

Development of Scaling Criteria and Numerical Simulation Study of Steam Flooding Process

A Thesis

Submitted to the School of Graduate Studies

In Partial Fulfillment of the Requirements for the Degree of

Master of Engineering

In

Oil and Gas Engineering

Faculty of Engineering and Applied Science

Memorial University of Newfoundland

By

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May 2018

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Abstract

Canada contains reserves of oil sand and heavy oil resources considered to be the largest amount of unconventional hydrocarbons deposited in unfavorable conditions. It needs more efforts and technological advancement to recover oil from such reserves. Steam flooding enhanced oil recovery technique is applied for more than 70% of heavy oil reservoirs to extract the oil. Three-dimensional (3D) displacement model can represent an appropriate approach and model for the steam flooding process. However, their physical limitations make it impossible to duplicate the real behavior of a reservoir in larger scale. So, it is important to develop scaling criteria for depicting the actual fluid behavior for unconventional reservoirs.

Scaled physical models have the unique advantage of capturing all physical phenomena occurring in a particular process by transforming the parameters into dimensionless numbers. This concept is applicable to fluid flow through porous media, where continuous alteration of rock and fluid properties can be characterized by various dimensionless numbers. In this study a set of dimensionless groups were developed using both inspectional and dimensional analyses. The new groups of dimensionless numbers can be used to characterize the reservoir rock and fluid properties for better explanation of complex rock/fluid phenomena for the steam flooding process. It should be noted that the complete set of scaling criteria is very difficult to satisfy. Therefore, some of the similarity groups must be relaxed in order to satisfy the most important parameters of the specific reservoir activities. The choice of which requirements to relax depends on the particular process being modeled. Scaling of the phenomena considered to be least important to a particular process might be relaxed without significantly affecting the major features of the process. The choice of an approach depends on the importance of the phenomena that are not scaled by that approach. Major scaling groups were found by applying different elimination techniques. The effect of those dominant dimensionless groups on recovery was evaluated through the study of process controlling parameters. A new group which is called Dykstra-Parsons coefficient is introduced to incorporate the reservoir heterogeneity. A combined dimensionless group was proposed to characterize and evaluate the performance and found to have the largest effect on oil recovery. Sensitivity analysis of scaling numbers is performed to find out the relative effect of each dimensionless numbers on oil recovery. Finally, a numerical simulation study is performed to quantify the effect of steam quality and permeability variations for different reservoirs.

This research work leads to the development of a procedure that can be applied to design a steam flooding EOR process. This process allows the assessment of different parameters to aid in the selection of optimum additive concentration to account for the uncertainties due to reservoir heterogeneity. The process is flexible; it can be applied to wide range of reservoir types as there exists a physical commonality between laboratory and field scale.

DEDICATION

To my dearest parents, my beloved wife and daughter

ACKNOWLEDGEMENTS

This thesis becomes a reality with the kind support and help of many individuals. I would like to extend my sincere thanks to all of them.

First, I would like to offer this endeavor to our Almighty God for the wisdom He bestowed upon me, the strength, peace of mind and good health to finish this research.

I sincerely wish to acknowledge my academic adviser, Dr. M. Enamul Hossain for his excellence guidance, continuous support, constructive comments and encouragement throughout my M. Eng. studies at Memorial University of Newfoundland. I am highly indebted to my academic adviser, Dr. Salim Ahmed for his guideline, valuable advice, inspiration, help as well as his time and attention.

I would like to express my heartfelt appreciation to my family members for their trust, support and patience during the whole period of the study. I want to especially thank my beloved and supportive wife HAPPY, who is always by my side when I need her most and helped me in making this study, and my lovable daughter, ANEESHA who served as my inspiration to pursue this undertaking.

I would like to express my heartiest appreciation and gratitude to head as well as all the faculty members of the Department of Process Engineering, staff and fellow students for their support and help and to make this study enjoyable and fruitful.

I would like to acknowledge School of Graduate Studies of Memorial University of Newfoundland, Research & Development Corporation of Newfoundland and Labrador (RDC), and Statoil Canada Ltd. for providing financial support to accomplish this research.

I am also thankful to my wonderful research group members and friends. Thank you all for being with me when I need help and support.

CO-AUTHORSHIP STATEMENT

I, Arifur Rahman, hold the primary author status for all the chapters in the thesis. However, each manuscript is co-authored by my supervisor and co-researcher, whose contributions have facilitated the development of this work as described below.

- **Arifur Rahman, Fatema Akter Happy, Salim Ahmed, M. Enamul Hossain. “Development of scaling criteria for enhanced oil recovery: A review”, This article has been published in the Journal of Petroleum Science and Engineering.**

Statement: I, Arifur Rahman, the primary author and carried out the research and develop the literature review of scaling criteria development for different EOR process. I drafted the manuscript and incorporated the comments of the co-authors in the final manuscript. Co-authors helped in conceiving the idea and selection of appropriate approach for steam flooding process.

- **Arifur Rahman, Salim Ahmed, M. Enamul Hossain. “Development of Scaling Criteria for Steam Flooding Process using Rock and Fluid Memory Concept”, to be submitted to a journal.**

Statement: I, Arifur Rahman, the primary author and carried out the research and development of scaling criteria. I drafted the manuscript and incorporated the comments of the co-authors in the final manuscript. Co-authors helped in conceiving the idea and selection of appropriate approach for steam flooding process.

- **Arifur Rahman, Salim Ahmed, M. Enamul Hossain. “Scaled Physical Model Studies of Steam Flooding EOR Process”, to be submitted to a journal.**

Statement: I, Arifur Rahman, the primary author and carried out the research and development of scaled physical model of steam flooding EOR process. I drafted the manuscript and incorporated the comments of the co-authors in the final manuscript. Co-authors helped in conceiving the idea and improve the design of a steam flooding process.

- **Arifur Rahman, Salim Ahmed, M. Enamul Hossain. “Sensitivity Analysis of Scaled Model and Numerical Simulation Study of Steam Flooding Process”, to be submitted to a journal.**

Statement: I, Arifur Rahman, the primary author and carried out the research to study sensitivity analysis of scaled physical model and numerical simulation of steam flooding EOR process. I drafted the manuscript and incorporated the comments of the co-authors in the final manuscript. Co-authors helped in conceiving the idea and improve the quality of the manuscript.

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Chapter One

Introduction

1.1. Introduction

Heavy crude oils remain a major player in the business of future energy exploitation. Their volumes represent as much as the conventional energy resources. However, due to their limitations with recovery arising from high viscosity, the exploitation of heavy crude oil needs technological advancement as well as the adaptation of current means of the petroleum industry. The production from the unconventional or heavy oil reservoir is important for future energy demand fulfillment. However, it is very challenging to recover oil from those reservoirs which need advanced recovery techniques. The primary recovery which consists recovery from reservoirs with natural energy such as water encroachment and gas cap drive typically produces a small percentage of oil (10%-15%) and then reached its economic limit due to lack of driving force. The secondary recovery is usually performed using water flooding or gas injection to increase the reservoir pressure to sustain the oil-producing (Surguchev et al., 2005). After a certain time of gas and water injection, the oil production rate declines due to the high water-cut or gas-oil ratio. Then it is said that the secondary recovery technique enters its matured stage. To further increase the recovery from the remaining oil in the reservoir, tertiary or enhanced oil recovery (EOR) methods are applied (Ali and Meldau, 1979; Alvarado and Manrique, 2010). Generally, the injection of material that is not present in the reservoir is termed as enhanced oil recovery (EOR) (Lake, 1989). In general, EOR methods can be divided into two broad groups: non-thermal (miscible/immiscible, chemical, solvent or microbial flooding) and thermal methods (steam, cyclic steam, combustion, and hot water flooding) (Taber et al., 1997). Steam flooding can play a vital role in recovering oil from unconventional or heavy oil reservoirs. Scaled steam flooding model can characterize and evaluate the parameters which are involved in this process.

1.2. Steam flooding

Steam flooding is one of the main thermal flooding procedure applied to heavy oil reservoirs. This technique helps to improve the rate of production and ultimate recovery of a reservoir where injection and production wells are involved. The injected steam heats the formation near the wellbore and builds a steam zone that can propagate towards the production wells. It can reduce the viscosity and increases the sweep efficiency of reservoir oil and hence increase the oil production. There are two well-known methods available to inject steam into the reservoir

and make the oil less viscous. One is steam stimulation or cyclic injection of steam, and another one is steam flooding. In cyclic steam injection process, there is a consecutive period of steam injection, but in steam flooding process steam is continuously injected through the injection well. A special form of steam flooding is called steam-assisted gravity drainage (SAGD) in which reservoir fluid is produced based on gravity instead of viscous displacement.

Marx and Langenheim (1959) made a theoretical approach for reservoir heating through hot fluid injection into the reservoir. Most of the researcher used their solution technique to evaluate the steam-drive process. This solution technique neglected the growth of hot water zone ahead of the steam zone. Willman et al. (1961) predicted another analytical solution of the same problem which is comparable to Marx and Langenheim solution technique. Wilson and Root (1966) performed a numerical solution of the steam flood into the reservoir. Boberg (1966) introduced a model based on the work done by Marx and Langenheim. Experimental work was carried out by Baker (1969) using a sand pack for heat flow through steam flooding process. Newman (1975) developed a method which enables to predict the rate of steam zone thickness increases with areal extent. In addition, this model can estimate the volume of oil displacement from the steam zone and the underlying hot water zone. Myhill and Stegemeier (1978) introduced a method based on the energy relationships of Marx and Langenheim model. They calculated the growth of steam zone using a slightly modified version of Mandl and Volek method (1969). Gomma (1980) introduce a method which is based on oil recovery correlations for typical heavy oil reservoirs consisting unconsolidated sand. On the other hand, Jones (1981) presented a model based on the work done by Van Lookeren (1983) and Myhill-Stegemeier. Jones divided his work into two parts. The first parts of the model can calculate optimal steam injection rate. It is based on the given reservoir parameters provided by Van Lookeren method. The second part of the model need additional inputs to calculate optimal injection rate which will ultimately help to predict the production history. Beside modeling studies, several researchers investigated systematic experimental studies of steam flooding process (Sumnu et al., 1996; Mollaei et al., 2007; Souraki et al., 2011). Toma *et al.* (1984) performed an experimental study of cyclic steam flood for the horizontal well where axial and radial components of recovery significantly affect overall recovery. A numerical simulation study is implemented by Fernandez and Zerpa (1995) to inspect the performance of cyclic steam injection process. A new analytical model is developed by Gozde *et al.* (1989) by incorporating some major recovery mechanism which is applicable for steam stimulation. An improved model of SAGD process is presented by Reis (1992), where steam zone shape is predicted by

an inverted triangle of its vertex fixed at the production well. Oballa and Buchanan (1996) evaluated the effect of fluid characteristics on production for cyclic steam flooding and Escobar *et al.* (1997) presented beneficial effects of steam injection with additives. Marpriansyah (2003) investigated a comparative study of oil production for cyclic steam flooding of vertical and horizontal wells. Steam-assisted gravity drainage (Butler 1994), vapor extraction (Nasr *et al.*, 2003; Nasr and Ayodele, 2005 and 2006) and steam alternative solvent (Zhao 2004 and Zhao *et al.*, 2010) method are applied for a horizontal injection well with alternating production well.

1.3. Scaling steam flooding process

Scaling criteria derivation is a technique or procedure to extrapolate the results found in one scale (small scale) to another scale (large scale) (Buckingham, 1914; Rahman *et al.*, 2017; Shook *et al.*, 1992; Johnson, 1998; Gharbi, 2002; Lozada and Ali, 1987; Novakovic, 2002). Scaled models had been discussed in the literature (Leverett *et al.*, 1942; Langhaar, 1951; Rapoport, 1955; Perkins and Collins, 1960; Pujol and Boberg 1972; Greenkorn, 1964; Niko and Troost 1971) for many years, but no qualitative information had been published which indicate that scaling parameters have the greatest effect on results obtained from thermal flooding process. Steam flooding is one of the thermal flooding technique. A scaled model of steam flooding is studied by previous investigators. Ali and Redford (1977) reviewed different approaches to steam scaled model studies. Depending on the complexity of the process scaled steam flood model is divided into two broad categories; low-pressure model (low pressure than the field) and high-pressure model (operating at field pressure). Generally, low-pressure model is presented by Stegemeier *et al.*, (1977) and high-pressure model is presented by Pujol and Boberg (1972). Generally, in high-pressure models, same fluid is employed in model which is found in the prototype. On the other hand, in low-pressure models, a fluid is required which has different fluid properties found in the prototype to fulfill the scaling requirements. High-pressure models can better scale rock-fluid interactions, compressibility, fluid properties, gas solubility, emulsification, steam distillation, etc. Low-pressure models can scale temperature and velocity distribution and it is easy to operate. Huygen (1976) only consider the heat flow of a half five-spot model for scaling calculation which is similar work of Sheinman *et al.*, (1973). He investigated the effects of initial oil saturation, distillation residue and oil viscosity on recovery at high pressure (843 psia) which contain crushed sandstone with crude oil. Lo (1977) developed an intermediate pressure model (15 psig) for 1/12 of a seven-spot. He employed the Pujol and Boberg's model where mobility is considered instead of permeability.

1.4. Numerical simulation

Numerical reservoir simulation plays an important role in revealing the mechanism which can affect thermal flooding process. Numerical simulation of thermal EOR methods has gained acceptance over the years in oil and gas industry, because it can solve the problem in a way which cannot be solved by any other way (Staggs and Herbeck, 1971; Coats, 1980 and 1982; Rubin and Buchanan, 1983; Ali, 1984; Mattax and Dalton 1990). Therefore, the selection of appropriate process will be based on mathematical modeling of different EOR processes (Wilson and Casinader, 1978). Numerical modeling of steam flooding process is of great importance in understanding the complex phenomena and recovery mechanism that is involved in steam flooding process. Numerical simulator is the best tool in understanding and optimizing reservoir performance. Mathematical equations are used in numerical simulator which describe the physical behavior and characterize the process under investigation. Multiple simulations are run to test different options of field operations to check the sensitivity of the reservoir behavior under different rock and fluid properties. High-speed computers are used to fulfill the ultimate objectives. Generally, reservoir simulation models are used to obtain the necessary raw data and act as an ideal tool in understanding complicated steam flooding process.

1.5. Problem statement

Widespread research efforts have been applied in the field of EOR by thermal flooding, water flooding, and other recovery techniques (Alvarado and Manrique, 2010). Several researchers focused on water flooding, while other researchers give emphasis on comparative study of different EOR process. Scaling criteria development also accomplished by dimensional and inspectional analysis for different EOR approaches. There is not much work done for developing scaling laws for steam flooding process. As steam flooding is a complex process, it is a challenge to develop scaling criteria where solid-fluid and fluid-fluid interactions are involved. Another challenge is to satisfy process controlling parameters which should be the same function of dimensionless variables in the model and prototype. Rock and fluid memory concept is incorporated to meet the challenges and better explaining the rock-fluid interactions and reservoir performance.

1.6. Objectives

The main purposes of this study are given below

- To develop scaling criteria for steam flooding process.
- To perform dimensional and inspectional analysis.
- Perform different elimination techniques to find out the most appropriate dimensionless numbers.
- To study the effect of developed dimensionless numbers on oil recovery.
- To develop a new dimensionless number through the effective combination of dimensionless groups.
- To determine the dominant scaling groups through sensitivity analysis.
- To investigate the effect of different process controlling variables on steam flooding process through numerical reservoir simulation.

1.7. Structure of the thesis

The remainder of the thesis is organized as follows: Chapter 2 provides a review of the literature on scaling criteria development for different EOR processes with classification. Major contributions in this field are summarized which helped in identifying the research gap. Chapter 3 presents details about the development of scaling criteria for the steam flooding process. Five approaches are proposed, and their relative merits and demerits are presented and tabulated which can be used as a guideline for choosing steam flooding process. Chapter 4 presents primary, secondary, and tertiary elimination technique to find major scaling groups and their effects on oil recovery. Chapter 5 presents sensitivity studies of scaling groups to find out the dominant and secondary scaling groups and their relative effect on oil recovery. Numerical simulations are performed to find out the effects of permeability variations and steam quality on recovery. Chapter 6 concludes this thesis by highlighting major points and contributions of this research and recommendations for future research.

Chapter Two

Development of scaling criteria for enhanced oil recovery: A review

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Preface

*This paper has been published in the Journal of Petroleum Science and Engineering.

* Rahman, A., Happy, F.A., Ahmed, S. and Hossain, M.E., 2017. Development of scaling criteria for enhanced oil recovery: A review. Journal of Petroleum Science and Engineering, 158, pp.66-79.

Abstract

Scaling criteria are used to evaluate the performance of a reservoir by deriving dimensionless groups which affect a specific enhanced oil recovery (EOR) process. The relationships among different process controlling factors are investigated in this approach by comparing the dimensionless numbers. Scaling criteria can capture continuous alteration of rock and fluid properties related to fluid flow through porous media which can be characterized by different dimensionless groups. In this study, a critical review of scaling criteria development is made based on published inspectional and dimensional analyses of fluid flow through porous media for oil-water displacement processes. This paper provides the basic concepts of scaling and dimensionless groups along with the review of recent works on scaling criteria development for EOR processes. It also discusses how scaling criteria are developed using the existing techniques and reviews both their merits and demerits. The history of dimensional analysis is reviewed, starting with the first notions of dimensions to the powerful methods of recent times. This study reviews briefly some relevant analytical and semi-analytical works which are related to scaled model development for petroleum reservoirs. Understanding the basics of these mechanisms will assist petroleum engineers to analyze, design and evaluate EOR processes. This study will also help in developing dimensionless mathematical models for fluid flow through porous media

Keywords: Scaling criteria; Dimensional analysis; Inspectional analysis; Dimensionless group; Displacement process

2.1. Introduction

Scaled physical models have been extensively used in the field of engineering problems to reproduce the behavior of an actual system on a small-scale laboratory for many years (Doscher, 1980). This process is effective to simulate the behavior of a petroleum reservoir and efficient in evaluating the advantages of a recovery process (Purvis and Bentsen, 1988). Their significance has been demonstrated particularly for new processes whose mechanisms are not well understood or a mathematical description is difficult to formulate. The procedure for the development of scaled models will be accepted when dimensionless scaling groups would be known to scale up laboratory results to field conditions. The world has huge natural resources (e.g., fossil fuel). Most of the fossil fuel in the form of heavy oil reserves are found in Canada. These unconventional resources have been deposited in unfavorable conditions. Thus, it needs more efforts, technological advancements and energy to recover the reservoir fluid. In practice, three-dimensional (3D) displacement models can represent an appropriate well configuration. However, their physical limitations make it impossible to duplicate the real reservoirs under some conditions. Therefore, it is essential and of pragmatic significance to create scaling criteria for depicting the fluid behavior in unconventional reservoirs (Zhou, 2015). Although, recent advancements in numerical reservoir simulation processes are significant, however scaled physical models are presently favored because their capacity to capture the physical phenomena that can occur in a specific process. In the petroleum engineering, core flood experiments in the laboratory have been used for many years to understand and verify the reservoir behavior and numerical findings. The feasibility of EOR techniques are investigated through this process before they are attempted in the field application. Whatever information is obtained from a pore scale model, it should be presented in a way such that it will be appropriate for other systems rather than the one used. As results are described, it is practical to use the outcome of one scale to foresee the behavior of another scale. A series of connections should be developed to verify the approximations between the two configurations which are considered for the analyses. The developed connections between two systems are typically known as similarity laws, similarity requirements, or scaling laws. These scaling laws help to develop the specific EOR process which can affect the physical phenomena.

2.1.1. Enhanced oil recovery

EOR is the implementation of different kinds of secondary and tertiary recovery techniques. It can be employed for increasing the amount of crude oil that can be extracted from an oil field. Different types of technologically advanced EOR techniques have been developed over the last thirty years for mature and depleted type reservoirs (Ali, and Thomas, 1996). These techniques

greatly enhanced the effectiveness of oil recovery compared to the primary (i.e. pressure reduction), and the secondary (i.e. water flooding) recovery techniques. In the most recent times, EOR techniques have paid attention from the field development and research work stages to enhance the recovery of a specific field. This increased attention has been promoted by high oil price, increased demand, the expansion of oil fields around the world, and new well discoveries (Aladasani and Bai, 2010). Two-thirds of the oil volume in the reservoirs require unconventional EOR strategies for recovery (Green and Wilhite, 1998). Different types of reservoirs are available on earth. So, different types of EOR techniques are developed to improve the extraction of oil & gas from the reservoirs. Several techniques had been used so far to increase the recovery of oil. Gas and thermal flooding are the most widely used and successful recovery methods that consist of around 99% of EOR in the United States. Chemical and microbial EOR methods have research potential. However, these techniques require high operating cost with relatively low performance. Thermal EOR techniques are usually applied to heavy viscous crude oil reservoirs. This method involves the introduction of heat or thermal energy deep into the reservoir to raise the temperature of the reservoir fluid (e.g., oil). Thus, the viscosity of reservoir fluid will decrease which will ultimately increase the mobility ratio as well as sweep efficiency (Mozaffari et al., 2013). Many Laboratory experiments and analyses have been conducted over the years to accomplish this goal. Different types of experiments and analyses were conducted to study different mechanisms. Some analyses, known as numerical simulation were designed to present the results which can be extended to predict the field production. On the other hand, some other experiments known as scaled experiments were considered to permit the relative impact of other mechanisms observed in the laboratory experiments.

2.1.2. Scaled model studies

Scaled model studies provide an accurate method for forecasting reservoir fluid displacement. This method is used to study the impact of different factors on the recovery of hydrocarbon. The scaling technique utilizes the outcomes gained at one scale dimensions (laboratory research scale) to extrapolate at alternative scale dimensions (a large-scale method) (Buckingham, 1914; Lozada and Ali, 1987; Shook et al., 1992; Johnson, 1998; Gharbi, 2002; Novakovic, 2002). In case of isothermal or non-isothermal petroleum reservoirs, different scale models have been documented to describe multiphase fluid flow behavior. Scaling should be performed properly because unscaled laboratory experiments may be misleading when applied to field operations. Some variables in laboratory experiments might be unduly amplified, while other vital variables might be smothered. In recent years, complex numerical simulators have

been built with effective and dependable computational schemes. Similarly, high performance and CPU storage capacity computers are also available. These systems still suffer from computational time and storage. It is difficult for numerical simulators to give detailed descriptions of an extensive field containing heterogeneities. In contrary, it is relatively easy to implement the physical models. Therefore, in describing the physical process of a reservoir scheme, scaled models play a crucial role. This scale method can be used to verify computational strategies. It can provide information of certain physical phenomena which are not appropriately formulated in numerical simulators. The laboratory models have been used for many years to simulate the actual behavior of a reservoir during the thermal recovery schemes. The development of scaling criteria for thermal recovery processes are more difficult in small laboratory models. Many factors such as heat transfer, thermal effects on rocks and fluids, as well as capillary, gravity and viscous forces should be considered. The theory of similarity between model and prototype were considered as a base to outline a scaled physical model. In terms of geometric similarity, flow rate, pressure drop and time factor which are different for different approaches are exemplified by these processes. Depending on the variables used, each method has its distinctive benefits and shortcomings (Bansal and Islam, 1994). It is very challenging to fulfill a complete set of scaling principles prerequisite to design a thermal recovery process. Thus, some of the similitude numbers must be undisturbed to fulfill the most significant factor of a reservoir behaviors. The selection of which requirement should be relaxed be governed by the specific process being modeled. A specific process should be rested without essentially disturbing the significant element of the process which can be considered as a scaling phenomenon.

2.1.3. Dimensionless scaling group

The ultimate objective of the scaling technique is to forecast the behavior of rock and fluid properties which affect the physical phenomena from laboratory scale (i.e. small) to field scale (i.e. large). Dimensionless scaling groups are developed using appropriate parameters so that the dynamics of the physical system remain essentially unaffected. The scaled parameters have the connections between themselves which are assigned by different scaling techniques. Here, we considered the two methods. The first method is the classical scaling methodology which is known as a dimensional analysis process. It is constructed in dimensionless groups of parameters that can be set up by using the Buckingham PI-theorem. The second procedure involves governing equations with initial and boundary conditions. It can determine relationships among variables through scaling transformations.

2.1.4. Motivation and purposes

Widespread research efforts have been dedicated in the field of EOR by water flooding, steam flooding and other recovery techniques (Alvarado and Manrique, 2010). Several investigators focused on water flooding EOR techniques, while comparative studies of different EOR techniques have been done by others. Development of various types of dimensionless groups by dimensional and inspectional analyses has also been accomplished for different forms of EOR techniques. Those developed dimensionless groups were validated using the core flood experiments and numerical simulation. However, how these experiments were planned and performed to improve the mobility and sweep efficiency has not been presented properly. On the other hand, there is not much work done for developing scaling principles in the field of thermal flooding EOR techniques. As the scale of measurements from labs to reservoirs increases, steam flooding requirement increases rapidly, and the effects of reservoir heterogeneity are emphasized. Dimensionless scaling groups can be used to characterize the reservoir fluids and rocks properties for better explanation of the complex rock/fluid behavior. In the future, these dimensionless scaling groups can be employed in displacement process to augment the recovery technique and enhance the production of oil from the reservoirs.

2.2. Scaling approaches

The studies on the method of dimensional analysis or dimensionally scaled models have been applied to engineering problems for many years; especially in the field of heat and fluid flow along with structural design (Bridgman, 1931; Langhaar, 1951; Leverett et al., 1942; Mattax and Kyte, 1962; Murphy, 1950). A similar application for petroleum reservoir problems is relatively new but the application is increasing day by day (Bobek and Bail, 1961; Carpenter et al., 1962; Craig et al., 1955, 1957; Engelberts and Klinkenberg, 1951; Geertsma et al., 1956; Graham and Richardson, 1959; Henley et al., 1961; Leverett et al., 1942; Mattax and Kyte, 1962; Rapoport, 1955; Rapoport and Leas, 1953; Seve and Pottier, 1963; Van Meurs, 1956). Dimensionally scaled models are particularly important in deciding the behavior of reservoirs with unsymmetrical limits and different well-spacing patterns. These properly scaled physical model studies and their pertinent variables are the most important factor for complex fluid displacement processes in porous media. Dimensionless scaling groups provide a technique by which we can study analogous methods on diverse scales. Small-scale operations are carried out to simulate such approaches. Ultimately, it will help to understand or predict the larger scale (i.e., field) processes. It is important to generate a group of relationships starting from small scale laboratory studies towards larger scale field operations. These relationships will connect both systems which are known as scaling laws. Dimensionless numbers are used to

represent these scaling laws. In the literature, there are two existing methods available in finding dimensionless numbers, which are dimensional analysis (Buckingham, 1914; Bridgman, 1931; Langhaar, 1951; Focken, 1953; Nielsen and Tek, 1963; Sonin, 2001) and inspectional analysis (Ruark, 1935; Birkhoff, 1950; Bear, 1972; Shook et al., 1992; Novakovic, 2002).

2.2.1. Dimensional analysis

The procedure that combine different type of parameters or factors into a group which is essentially dimensionless and have an impact on a specific process is called dimensional analysis. The impact of a specific parameter is then considered in terms of a group instead of separate parameters within the group. Dimensional analysis remains as the most useful technique in areas where knowledge is developed through a middle stage. It can be applied when fundamental laws are now known, and the absence of capable techniques for solution. Bridgman's dimensional analysis (Bridgman, 1931) technique found widespread applications in engineering and physics. Rapoport (1955) proposed that if the proportion of dimensionless group on a smaller (laboratory) geometric scale to that on a larger (field) geometric scale is kept equivalent to unique, then the activities appearing on both scales should be analogous. Nonetheless, if both scales are geometrically related then the above description is correct. Dimensional analysis was first adopted in developing dimensionless groups for the investigation of reservoir behavior by Leverett et al. (1942). The procedure of dimensional analysis is shown in Fig. 2.1. First, each parameter that affect the specific process and their corresponding dimensions for performing dimensional analysis should be listed. Then the fundamental dimensions including length, mass, temperature, time, etc. for this specific process should be found out. Selection of variables should be equal to the number of fundamental dimensions. After that, the dimensional equations should be set up and combined the parameters to form dimensionless groups. Finally, check if the derived group is dimensionless or not. If the group is not dimensionless, then performed the previous step again to make it dimensionless.

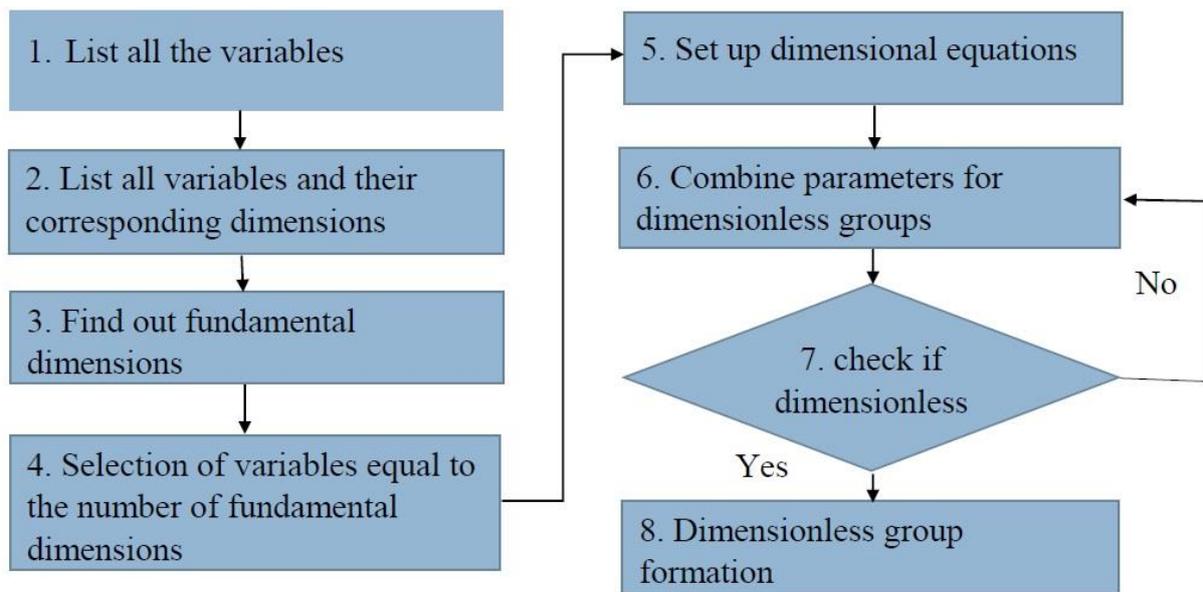


Figure 2.1. Principle procedure for dimensional analysis (Novakovic, 2002).

2.2.2. Inspectional analysis

Inspectional analysis is a procedure where the dimensional analysis procedure is expanded. This approach verified the dimensionless expression in contrast to the parameters it has been generated. We can develop the dimensionless groups experimentally without the help of governing equations for dimensional analysis. However, for inspectional analysis, governing equations should be derived with the help of initial and boundary conditions. It is a straightforward, easy and preferred technique for deriving the dimensionless scaling group in petroleum literature. All equations which describe the method of concern are considered to form a single differential equation. The parameters of the equation form the dimensionless groups. This method has a unique advantage that the developed scaling groups have a clear physical meaning. As inspectional analysis involves parameters rather than dimensions, so it can produce dependent dimensionless groups which affect a specific process. The procedure for inspectional analysis is presented in Fig. 2.2.

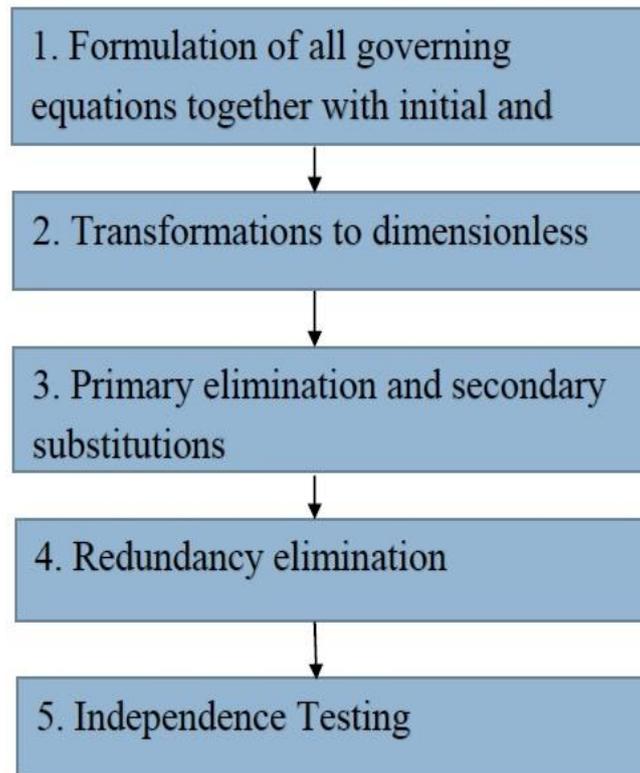


Figure 2.2. Principal procedure for inspectional analysis.

2.2.3. Comparison of scaling approaches

Dimensional analysis is useful in providing directions for initial analyses. It is particularly helpful when there is a lack of data and information. In this manner, the dimensional analysis technique is widely used than the inspectional analysis technique because it needs only a little theory to perform dimensional analysis. It can also provide an initial direction in setting up the investigations. Dimensional analysis is rapid and simple process. It often yields required information. There are scaling groups introduced using the dimensional analysis which would not be possible using inspectional analysis. Some of the variables were not considered in the formulation of the governing equations. On the other hand, dimensional analysis has some limitations. There may be extra groups formed by dimensional analysis which may not affect the physical process. The physical meaning of these groups may be quite obscure. For example, there are two groups which are related to inertia forces and these are Reynolds number $\left(\frac{\rho v k^{1/2}}{\mu}\right)$ and the ratio $\left(\frac{k}{l^2}\right)$ which is related to pore diameter and overall dimensions. For cases of practical interest, inertia effects may not be important, thus we can relax their scaling requirements (see Fig. 2.3).

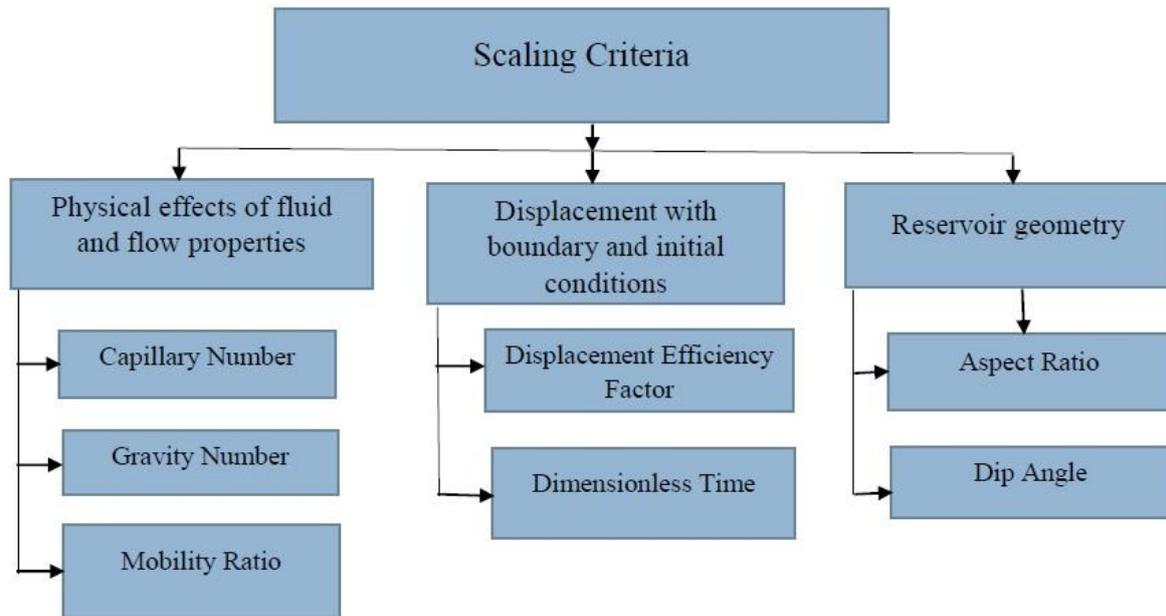


Fig. 2.3. Different scaling groups.

The inspectional analysis strategy is used for most reservoir engineering applications. The partial differential equations and boundary conditions are derived using the most important basic physical principles (Shook et al., 1992). The fluid flow equations should be incorporated in the analysis to explain the behavior of a reservoir more clearly. The principal objective of the inspectional analysis is to describe the natural phenomena which occur in the reservoir. This approach can use extended group of equations with the required boundary conditions. Usually, inspectional analysis can form dimensionless scaling groups whose physical significances are evident, and which will affect the physical process. On the other hand, inspectional analysis needs mathematically derived formulations for the study of the process involved. If such equations are not available, inspectional analysis cannot be used. Although, the inspectional scaling approach represents the derived equations with minimum parameters, implementation of this procedure is tedious and time consuming.

Finally, dimensional analysis involves generating dimensionless groups, irrespective of whether it is related to a specific process or not. Thus, we can get a meaning less result in terms of a specific process involved. In contrary, inspectional analysis produces dimensionless groups in a way that the developed groups can affect a specific process. In conclusion, if the initial and boundary conditions are chosen in a proper way to formulate the involved equations, then the difficulty level should be minimized.

2.3. Development of various scaling criteria

This review is based on various scaling criteria of fluid flow through porous media for fluid displacement processes within petroleum reservoirs. Scaling groups are very important in describing the influence of parameters on a specific EOR process. Accurate formulation and evaluation of dimensionless scaling groups are important because it can largely affect the physical process. Unscaled physical processes can give erroneous results. Table 1 lists the most widely used scaling groups relevant to EOR.

2.3.1. Capillary number

The ratio of viscous to capillary force force is termed as capillary number (Fulcher et al., 1985; Tang, 1992). Different forms of capillary number have been used in the existing literature (Cense and Berg, 2009). Foster (1973), Salager (1977), Green and Wilhite (1998), and Tiab and Donaldson (2015) defined the capillary number using the Darcy velocity of displacing fluid, the viscosity, porosity and the interfacial tension. Sheng (2010) omitted the porosity term and Lake (1989) included the contact angle term. The derivation of capillary number can be found in the literature (Johannesen and Graue, 2007). The capillary number provides satisfactory correlations of mobility of oil with respect to different values of viscosities (Morrow, 1979). The recovery factor is found to be dependent on the capillary factor (Fulcher et al., 1985).

Table 2.1: Various Scaling Dimensionless Numbers (Novakovic, 2002)

Dimensionless Scaling Type	Scaling Group	Formulation	Comment
Physical Effects of Flow and Fluid Properties Scaling	Capillary Number	$N_C = \frac{F_{viscous}}{F_{capillary}}$	Rock-fluid interaction, describes set-up at the small scale
	Gravity Number	$N_g = \frac{F_{gravity}}{F_{viscous}}$	Reservoir-fluid shape dependent, seizes the effect of resistant force
	Mobility Ratio	$M = \frac{\lambda_{displaced\ fluid}}{\lambda_{displacing\ fluid}}$	Fluid-rock-fluid communication effect on the flow performance
Displacement Techniques with Initial and Boundary Conditions Scaling	Displacement Efficiency Factor	$E_D = \frac{V_{Produced}}{V_{Reference}}$	Dimensionless production response
	Dimensionless Time	$t_D = \frac{V_{injected}}{V_{pore}}$	Forced injection boundary condition
Reservoir Geometry Scaling	Aspect Ratio	$N_A = \frac{L}{H}$	Reservoir shape description scale
	Dip Angle	$N_\alpha = \tan\alpha$	Dip angle scaling

2.3.2. Bond number

The ratio of the gravity force to the capillary force is called the Bond number. It is of great importance in vertical displacement processes in a reservoir-well system. The Bond number is usually useful for gravity assisted displacement processes. For immiscible displacement process oil recovery improves with increasing Bond number.

2.3.3. Gravity number

Gravity number which characterizes the ratio of gravity to viscous force is a dimensionless group. It does not detect the properties of the capillary forces. Gravity number depends on gravity, oil and gas density and viscosity, absolute permeability and the gravity drainage velocity of the fluid. The gravity number indicates that the gravity effects are larger in thicker reservoirs and higher the gravity number the better would be the recovery.

2.3.4. Mobility ratio

The ratio of effective permeability to phase viscosity of a fluid is expressed as the mobility ratio. The proportion of the mobility of displayed fluid by displacing fluid is termed as mobility ratio of one fluid by another in terms of displacement process. The fundamental mechanism behind the displacement of oil by water can be grasped through studying the mobilities of the individual fluids (Dake, 1978).

2.3.5. Displacement efficiency

The portion of movable oil that can be extracted from the reservoir using existing technology at any time is defined as the displacement efficiency. The microscopic displacement efficiency is dependent on the mobilization or dislocation of oil at the small scale. It can be a criterion for the preliminary oil saturation or remaining oil saturation in the area contacted by the moving fluid. On the other hand, macroscopic or volumetric displacement efficiency depends on the efficiency of the moving fluid in contact with the reservoir in a volumetric sense. The macroscopic displacement efficiency of a fluid can be measured in a way by which the displacing fluid is striking the reservoir volume both areally and vertically.

2.3.6. Dimensionless time

The scale-up time of a given prototype field is expressed by the dimensionless time. The expression of dimensionless time (t_D) can be found in the literature (Miguel-H et al., 2004), for the gravity drainage methods and is stated as:

$$t_D = \frac{k k_{ro} \Delta \rho g \left(\frac{K}{\phi} \right) / g_c}{h \phi \rho \mu_o (1 - S_{or} - S_{wi})} t \quad (1)$$

Equation (1) enables estimation of the time required in the reservoir to reach the same recovery as the scale-up of the run time (in minutes) in the physical model.

2.3.7. Aspect ratio

The proportion of a geometric shape magnitude in diverse dimension is called the aspect ratio of that shape. For illustration, the proportion of width to height or the ratio of longer side to shorter side is defined as the aspect ratio of a rectangle. The aspect ratio illustrates the proportion of time for a fluid to flow in vertical and horizontal axes of the reservoir, when the equal pressure difference is employed. The determination of flow regime in the advanced part of the investigation is performed by the help of this explanation. It is important to express the vertical scale along with the horizontal scale on a stratigraphic cross section to indicate significant details of stratigraphic variation or dip angle of a reservoir. It is imperative to understand the effect that this distortion has on reservoir area or geometry and angular relationships of formation surfaces. The small angular differences among stratigraphic horizons that can consider for thickness variations are strongly exaggerated in such a section.

2.4. Scaling classification

Based on the principles on which the scaling criteria are developed, they can be categorized as (a) Scaling criteria based on flow and fluid properties, (b) Scaling criteria based on displacement techniques and (c) Scaling criteria based on reservoir geometry. This review article will focus on these three types of scaling principles.

2.4.1. Flow and fluid properties

This type of scaling principles should be established depending on the fluid/reservoir interaction. It can distinguish wide-ranging flow performance which include equilibrium of capillary, gravity and viscous forces. The flow properties should also be considered for these forces which present the consequence of extrapolation from the initial scale to the scale of concern.

2.4.1.1. Multi-phase flow

The use of miscible and immiscible multiphase flow scaling has been investigated previously for different EOR techniques. Leverett et al. (1942) studied the dimensionless scaling numbers for immiscible water induced oil displacement process. The effect of water/oil viscosity ratio on immiscible displacement was studied by Croes and Schwarz (1955). The results found for linear displacement of oil by water is presented in the form of diagram for similar formations. The effect of gravity separation of five spot models for miscible and immiscible displacement was presented by Craig et al. (1957). It is difficult to build bridges between theoretical multiphase flow behavior and field applications for a hydrocarbon reservoir without simplifying assumptions which result in questionable conclusions (Rapoport, 1955). Rapoport developed the scaling laws for water-oil displacement process for an incompressible,

immiscible and two-phase flow system. Scaling groups including capillary and gravity number has been derived by inspectional analysis. Difficulties have been raised, when reproducing identical capillary pressure and similar relative permeability curves. The different types of model tests performed with different materials can study the water flooding process for a broad range of reservoir settings. In turn, for a specific reservoir, its behavior could be evaluated by interpolating its characteristics into the ranges covered by the scaled model studies. In contrast, Grattoni et al. (2001) described a succession of trials regarding the impacts of water saturation and wettability on multi-phase flow. They exceptionally considered the gravity-dominated environments of gas injection. The trials were conducted by instinctive gas injection and dispersion of oil in bead-pack models at very high and low water saturations. Different recovery rates of oil had been found. The procedure seemed to be less effective at irreducible water saturation for the case of oil-wet condition. Similar recoveries were monitored at residual oil saturation in both cases of water and oil wet condition, respectively. The authors found a straightline connection between the derived dimensionless group and all the analyzed conditions of overall recovery. Suzuki and Hewett (2002) demonstrated an innovative technique to scale up the multi-phase flow properties. It ultimately represented the proper boundary conditions in the upscale section. They depicted a technique to scale-up an entire finely-gridded model and decide the boundary conditions using injection tubes for two phase flows. This novel technique can correctly capture the fine-scale two-phase flow behavior, such as saturation distributions, inside each segregated coarse-grid domain. They presented that this method can be pertinent to both viscosity dominated, and gravity affected flows for reasonable gravity to viscous ratios. Later, Azoug and Tiab (2004) developed a comprehensive approach using the pseudo function for upscaling three dimensional anisotropic heterogeneous reservoirs. It was considered for multiphase flow with different capillary and gravity numbers. They compared the performance of several pseudo function techniques by considering diverse flow regimes. These are represented by different types of homogeneous small grid models. The researchers became successful to reproduce the oil production level and water cut of fine grid for equilibrium, viscous dominated and capillary controlled flows. On the other hand, the authors were unable to match the curves of fine grid using pseudo function techniques for the gravity-controlled flow. Finally, they became successful in upscaling small to large grid simulation for high flow rates using pseudo functions.

2.4.1.2. Two-phase flow

Artus and Noetinger (2004) reviewed the main upscaling techniques to derive different capillary and gravity numbers for heterogeneous reservoirs in terms of two-phase flow. They

investigated numerical fine to coarse grid methods. Additional physical methods were employed where the statistical arrangement of transport equations was emphasized. They showed a comprehensive logical and numerical study of the dynamic contrast of oil-water front through the study of viscous connection between the pressure and saturation. There was an extremely effective communication found between the steady or unsteady state character of the fluid flow displacement and heterogeneity of the reservoir. The connection of this type is reliant on a subjective and measurable alteration of the extensive scale conditions. It must be represented by any upscaling procedure. Later Zhang et al. (2005) demonstrated how conventional upscaling methods may deliver erroneous results and suggested a simple alternative. They reproduced single phase flow and greatly increased the coarse-scale two phase flow model using suitable boundary conditions. This method is slower than the local upscaling method and cannot consider the physical disruption caused by heterogeneity in the fine-scaled model. It is not suitable for small scale heterogeneities where capillary pressure has a significant impact on the fluid flow. Pfister and Chanson (2014) summarized the water air interfacial properties and the air entrainment rate under a Froude similitude. It represents the physical background of a pore physical model. The smallest values of Weber or Reynolds numbers were considered to limit the scale effects. Based on a literature review, they presented and discussed the existing limit, bringing about a progression of more moderate recommendations in terms of air concentration scaling. As the selection of criteria to examine the scale effects was crucial, it was observed that a couple of factors (e.g., bubble sizes, turbulent scales etc.) can be influenced by scale consequences, even in comparatively large laboratory models.

2.4.1.3. Capillary to viscous force

Hilfer and Øren (1996) reexamined the multiphase flow equations of small and large scale in porous media through the traditional dimensional analysis. Depending on the category of length scale, porous medium and saturation history, a macroscopic capillary number was presented that differs from a microscopic capillary number. The macroscopic number could be associated with the Leverett J-function. The microscopic number is the ratio of viscous pressure drop to capillary pressure. The sample calculations of desaturation curves are provided when the macroscopic number is equal or close to one for distinctive porous media. Finally, the analytical modification between residual oil saturation of laboratory experiments and field implementations were provided. On the other hand, Wibowo et al. (2004) studied the impact of the forces correlation in horizontal well production operation for bottom water drive reservoirs. They successfully constructed a scaled physical model. It can be simulated in the

production operation using dimensional analysis and showed that the linking of the reservoir forces increased as the proportion of gravity to viscous forces increases. The significant finding of their work was the well production performance of the reservoir. It will enhance as the capillary pressure is decreasing, and subsequently the increase of gravity to viscous force ratio will improve the oil recovery. Later, Jonoud and Jackson (2008) showed the capillary or viscous forces flow which validate the steady-state scaling techniques. They found that reservoir flow rates within a reasonable range were valid for viscous limit upscaling techniques. The capillary equilibrium limit technique was limited to exceptionally reduced rates, because it overestimates the amount of capillary entrapping. However, the authenticity of capillary equilibrium limit upscaling in a 3D model was not properly captured.

2.4.1.4. Fluid saturation and relative permeability

Perkins and Collins (1960) redefined the relative permeabilities and fluid saturations. Their definition permits one to have diverse relative permeability and capillary pressure relationships in the prototype and model. This work proposed a method to authorize a diverse relationship between relative permeability and fluid saturation with capillary pressure. This relationship helps to derive the modified capillary number. They demonstrated one simple example that clarifies how to derive modified scaling criteria. Astarita (1997) discussed the modern viewpoint of dimensional analysis. It is the basis of the theory of scaling to derive gravity and capillary number. The author illustrated several specific examples to show how scaling and dimensional analysis may generate actual important point for the solution of the problem. Finally, the author showed that using scaling, dimensional analysis and the estimation of the order of magnitude can be used to derive those dimensionless group. Durlofsky (1998) developed a coarse scale equation using a volume average saturation calculation of small scale in dissimilar reservoirs. It can be used for two phase flows to evaluate several approaches for the detailed upscaling method for reservoir characterization. The author discussed the strengths and limitations of each of these techniques. Especially the fundamental assumptions in those calculations using the volume-averaged equations as a framework equation. These equations were rearranged for the unit mobility ratio case and applied to the immediate solution of a coarse scale model issue. Wang et al. (2009) demonstrated the large error behind the conventional upscaling method. They established a novel approach for the upscaling method of the relative permeability curve. A large model upscaling method was used which best fits with the fine scaled model. The authors verified this method by constructing a three-dimensional, three-phase and extremely dissimilar reservoir model. As contrasted with the conventional method the new coarse scaled upscaling method demonstrated a more reasonable

result. The outcome can be attained by approximating the consequence of ambiguity through computational time, order and magnitudes quicker than the earlier methods. Tsakiroglou (2012) developed a model using a network type multi-scale analysis for immiscible displacement of both wetting and non-wetting phase fluid in dissimilar porous media. The author utilized these methods to decide the transient consequences of the axial dispersion of water saturation, pressure drop. Finally, the functions of relative permeability can be evaluated with its upscaled impact.

2.4.1.5. Rock and fluid memory

Hossain and Islam (2011) developed new scaling criteria incorporating memory concept using inspectional and dimensional analysis. They became successful to develop relationships between capillary pressure, saturation, velocities and fluid pressure for prototype and model. The authors identified a competent tactic for oil-water displacement process by deriving the sets of similitude groups. Hossain and Abu-Khamsin (2012a) developed new dimensionless groups using mathematical modeling of non-linear energy balance equations. The developed numbers were helpful to demonstrate the rheological behavior of fluid-rock interactions. Their proposed dimensionless numbers described the various types of heat transport mechanisms including convection and conduction in porous media for the processes of thermal recovery. These dimensionless numbers were found to be responsive to a large set of fluid and reservoir rock properties including densities, permeability, heat capacities, porosity, etc. Hossain and Abu-Khamsin (2012b) also developed new dimensionless numbers which can describe convective heat transfer between the fluid and rocks in continuously changing conditions using the memory concept. They employed an energy balance equation to develop the heat transfer coefficient by assuming the rock can attain the temperature of the fluid immediately. The developed new numbers correlate with the Nusselt and Prandtl numbers and the local Peclet number is observed to be responsive to memory.

2.4.1.6. Spontaneous imbibition

Mirzaei-Paiaman and Masihi (2013) developed scaling equations utilizing counter-current spontaneous imbibition method for oil and gas recovery from fractured porous media. Earlier scaling equations were defined systematically by linking the primary time squared recovery to squared pore volume. They showed that this settlement does not employ to general scaling performances and, if employed, it affects nontrivial sprinkle in the scaling designs. The authors proposed that throughout the expansion of any scaling equations, its reliability with mutual purposes should be measure which was neglected in the literature. The authors have rewritten scaling equations for two physically expressive numbers, namely, the Darcy number and the

Capillary number. It was authenticated by the investigation data from the literature. The authors scale up available data in an efficient way and represented different recovery curves by a single master curve.

2.4.1.7. Compositional flow simulation

Li and Durlofsky (2015) developed an upscaling procedure which is more precise and robust for the simulation of flow composition. They computed the functions related to coarse-scale boundary or block and the prerequisite upscaled factors by using a technique. This technique requires a global fine-scale compositional simulation. The authors introduced near-well behaviors along with a technique for enhancing the α -factors for both production and injection wells. It was combined further to upgrade the coarse-model appropriateness. Finally, they suggested that using their technique the produced upscaled models can be employed to lessen computational difficulties for different purposes including the optimization of well control.

2.4.2. Displacement techniques with initial and boundary conditions

Different type of scaling groups is derived depending on various displacement techniques along with their initial and boundary conditions. Major scaling groups derived using this technique are the dimensionless time and displacement efficiency factor. These scaling groups will represent the dimensionless production response of a reservoir. The development of scaling criteria is subdivided in the following subsections depending on different displacement techniques.

2.4.2.1. Immiscible displacements

Rojas (1985) performed scaled model studies for immiscible CO₂ flooding of substantial oil. Lozada and Ali (1987) displayed a group of scaling criteria including six groups of scaling processes. They concluded that a full set of scaling criteria might not be fulfilled at the same time. Thus, few groups had to be excluded to fulfill the major scaling conditions, including the vital factors of a specific method. The authors found that the nature of fluid/rock schemes, flow rate, pressure drop, model geometry and so forth were dissimilar contingent upon the methods exercised. Later, Lozada and Ali (1988) also developed partial differential equations of immiscible carbon dioxide flooding for the moderately heavy oil reservoir. The authors used different sets of scaling criteria to construct scaled models with different operating conditions. A series of similitude numbers was derived for the displacements of moderately heavy oil recovery by dimensional and inspectional analyses. The mass transfer between the phases were considered for immiscible carbon dioxide flooding. So, all the similarity groups were not satisfied in the case of recovery from moderately heavy oil reservoirs. They relaxed some of the groups which had less effect on the physical mechanism and hence found out the dominant

scaling groups. Peters et al. (1993) studied the saturation data through a dimensionless self-similitude parameter to develop the dimensionless representative response curve for variable core floods. The authors found that there is a considerable dissimilarity between the response function of oil wet to water wet reservoir. Finally, the results showed that the effectiveness of displacement could occur in water wet reservoir compared to oil wet reservoir. Zhou et al. (1997) defined three dimensionless groups, namely, gravity viscous ratio, shape factor and viscous capillary ratio. These dimensionless numbers help to detect influential flow regions at numerous situations. They demonstrated the comparative extents of energies in the scheme linked through the reservoir properties. The scaling groups and flow areas governing different kinds of flow performance in the schemes were examined with straightforward heterogeneity formulae. The authors considered three frequently used flow schemes such as immiscible displacement with layered reservoir in homogeneous media, miscible displacements in layered reservoir without scattering and fluid flow in the reservoir with high fracture.

2.4.2.2. Controlled gravity drainage

Zendehboudi et al. (2011) performed dimensional analysis for scaling the immiscible displacements of controlled gravity drainage (CGD) method. The authors obtained an empirical model in fracture dominated porous media by dimensional analysis using Buckingham π theorem to investigate the gravity drainage process. They developed a model to forecast the maximum withdrawal rate, the distance of fluid-gas interface locations, critical pumping rate and the recovery factor of fluid experiencing the CGD methods. The developed model delivers satisfactory predictions for the oil-gas drainage system.

2.4.2.3. Immiscible GAGD process

Sharma and Rao (2008) developed a scaled physical model of the gas assisted gravity drainage (GAGD) technique to describe the enhanced recovery method. They determined the impact of a few dimensionless scaled factors. For example, the Gravity number, Bond number and Capillary number effect on GAGD technique implementation. Sharma and Rao (2008) found that the Bond number significantly affects GAGD performance than any other numbers. Finally, they relate the run time of the model to the run time of field development to observe high recoveries. Dimensionless time indicated augmented rate of recovery when GAGD method is implemented in field projects. Farahi et al. (2014) developed a few scaling groups by performing inspectional analysis. These groups had analyzed the performance of reservoir fluid displacements by immiscible GAGD technique. They determined five matched scaling groups for homogeneous reservoirs. The authors found a coefficient for different reservoir which is called the coefficient of Dykstra-Parson. They determined another new set of

dimensionless groups in large scale that added altogether the prevailing energies. Finally, they evaluated and verified experimental results and found it consistent for rapid forecast of oil recovery for GAGD technique.

2.4.2.4. Miscible displacements

Gharbi et al. (1998) studied the miscible displacement scaling in permeable medium utilizing inspectional investigation to produce scaling sets. These sets influence displacement method in a 2D, similar, different cross-sectional formation. They derived nine groups of dimensionless numbers and from which only one number was found to have no impact on this displacement technique. Babadagli (2008) determined dimensionless scaling groups for miscible displacement utilizing inspectional analysis in a fractured porous and permeable medium. They proposed a new dimensionless number based on the dimensionless group they derived for better characterizing the efficiency of the method. The proposed new group which is called Matrix-Fracture Diffusion Number (NM-FD) was significant in assessing the efficiency of CO₂ sequestration, enhanced oil recovery, and pollutant transportation issues. The authors performed validated laboratory scale experiments, and physically interpreted the Matrix-Fracture Diffusion Number (NM-FD).

2.4.2.5. Water flooding

Carpenter et al. (1962) represented the outcomes of model analyses of water-oil displacements with water flooding scaling relationships in heterogeneous reservoirs with vertical communicating strata of different permeability. They showed the combined influence of viscous, gravitational and capillary forces on water-oil recovery behavior. The study was performed in a water-wet system where strong imbibition forces were present. The outcome of the study showed that these relationships can be successfully applied to the water flooding process. Finally, they found the effects of capillary imbibition would be varying for different wettability. Bai et al. (2005) determined a full group of scaling conditions of five-spotted pattern wells for water flooding reservoirs. They used three dimensional governing equations for this, including capillary and gravitational force along with oil, water, and rock compressibility. The authors estimated the impact of individual dimensionless factor on investigation outcomes using this approach. They sorted out the dominant scaling numbers with larger sensitivity factors ranging from 10^{-4} to 10^0 . Jin et al. (2009) developed dimensionless numbers using inspectional analysis for bottom water drive reservoir. They provided the procedure and technique involved in developing the dimensionless numbers. The description of the steps involved in deriving the groups and the problems associated with these groups had

also discussed. Finally, the authors validated these groups from the sensitivity analysis of reservoir well system without changing the values of involved parameters.

2.4.2.6. CO₂ flooding

Prosper and Ali (1991) presented a recovery mechanism comprising a two-dimensional and linear scaled model for the water-alternating-gas (WAG) and the low pressure immiscible carbon dioxide flooding. They compared the results of the Aberfeldi field using the same model at the same pressure and WAG ratios. The authors found the oil recovery of model involving linear analyses was about one half at 2.5 MPa pressure. The bottom recovery involving waterflood was 40% and the incremental recovery of 10% was due to the WAG process. On the other hand, the recovery for the two-dimensional model varied from 40% to 50%. Bansal and Islam (1994) performed a study of sequential scaled model by injecting carbon dioxide, propane and nitrogen gas in the reservoir. The gas injection is a principal method for the recovery of heavy oil reservoir in Alaska. Nearly 65% of oil initially in place is recovered; the same is indicated by their experimental outcome. For gravity drainage, although the final recovery was the same, it took longer time to recover the same amount of oil. They found the recovery mechanism was different for different gases and the highest recovery was obtained with carbon dioxide. Viscous fingering takes place with different degree of severity when applying different gas flooding techniques. It is considered harmless as the ultimate recovery is higher by gas injection.

2.4.2.7. Steam flooding

Pujol and Boberg (1972) presented different approaches for scaling the investigation of steam flooding process in viscous oil reservoirs. The scaling of capillary pressure was not considered essential to represent highly viscous oils. On the other hand, for intermediate viscosity oil (less than 10,000 cP), unscaled capillary pressures can predict the optimistic recovery of oil. They developed a method to convert capillary pressure into the scale and discovered that it can give qualitative enhancement as the recovery of oil is sensitive to flooding rates. The authors found oil recovery was mainly dependent on per unit volume of heat input to the formation. Kimber et al. (1988) developed novel dimensionless scaling numbers for the recovery of oil by steam or a steam improver and discussed their relative merits. They determined a group of similitude numbers which allow the utilization of similar fluid in prototype and model through inspectional and dimensional analyses. The authors also compared their approach with other approaches which were published in the literature and discussed their relative merits. They outlined a means of developing or selecting a process that best fits the most important characteristics of a specific recovery scheme. Doan et al. (1990) presented mathematical

models to derive dimensionless scaling groups of flow inside the horizontal wellbore for performing laboratory investigations. They used variable diameters of horizontal wellbore, and skin factors to conduct the experiments. They carried out a series of steam injection experiments through a development well. Pressure behavior and temperature distribution were controlled to explain the recoveries of oil. They evaluated oil recovery performance for various types of experiments to determine the effectiveness of different horizontal wells and the impact of perforated casing. Doan et al. (1997) performed steamflood tests utilizing a physical model of the Aberfeldy reservoir (Saskatchewan) to scale up and inspect the recovery of the steamflood technique for horizontal injection and production wells. They analyzed the results from two types of experiments: a base case run steamflooding of homogeneous reservoir and a reservoir having 20% net pay bottom water layer. They presented scaling up laboratory outcomes to predict the performance of a prototype. The diagnostic heat loss model demonstrated a 3.1% difference from experimental results. Scaled-up test information data for a base case run showed that approximately 20% of the oil initially in place was recovered after 0.8 PV of steam added. For a reservoir having 20% net pay, the increase in the oil recovery depends on how the energy contained in the fluid is managed.

4.2.8. Hot fluid injection

Willman et al. (1961) assessed the outcomes of laboratory investigations for steam, cold water and hot water injection. They studied different cell measurements with various permeabilities. The authors found cold water drive had less recovery than hot water and steam injection drive. Finally, they found the soaked steam with high temperature and pressure is more effective in terms of recovery than steam with low pressure. Moreover, all types of recovery have greatly improved if the temperature of the injected fluid is higher. Cheng and Cheng (2004) provided a fundamental idea of dimensional analysis scaling and reviewed the present research employing these ideas to model the quantities of instrumented indentation. They analyzed the indentation of pyramidal and conical shaping in various viscoelastic materials. They likewise indicated scaling approaches which were best fit for these processes and provide a superior understanding of instrumented indentation measurements. Heron et al. (2005) developed thermally improved remediation techniques which were favorable for the elimination of pollutants at intensely polluted places. They developed methods to incorporate invasion of hot air, high temperature steam or water using thermal wells or heat blankets; electrical heating with low frequency; microwave heating; etc. These techniques are also described by Hinchee and Smith (1992), Heron et al. (1998) and Davis (1997).

2.4.2.9. Solvent/chemical injection

Geertsma et al. (1956) extended the scaling theory to hot water drive and solvent injection by utilizing dimensional and inspectional analyses. They assumed uniform porosity and isotropic permeability. Since not all the scaling groups can be considered in building a model, a comprehensive discussion on which scaling groups are negligible were provided. Nonetheless, experimental studies were performed to verify the feasibility of neglecting some scaling groups. Sundaram and Islam (1994) presented a scaled physical model of petroleum pollutant removal using solutions of surfactants. They developed scaling principles for the decontamination process where viscous forces, aquifer geometry, and the proportion of the viscous to gravitational forces were used. Experiments were conducted to examine the type and concentration of surfactants and injection/production strategies. They found optimum surfactant concentration needed for the removal of a specific contaminant with surface tension. The outcomes of experiments showed that using this decontamination technique more than 90% of the contaminant originally in place may be removed. Basu and Islam (2009) performed a sequence of chemical adsorption experiments to provide most influential scale up form. The authors contrasted their outcomes with numerical simulation results. The numerical solutions were offered based on flow rates of the fluid, pore velocity, the amount of adsorbent used and the adsorption coefficient which were related to field environments. Finally, they developed a guideline to interpret the investigational outcomes and applied the scaling laws to forecast the field performance. Veedu et al. (2010) presented an upscaling methodology for chemical flooding by comparing results between coarse and fine grid method. Their technique was quite dissimilar than the other upscaling methods used for EOR process. They showed that for a heterogeneous reservoir the salinity gradient was not effectively picked up by the coarse grid method. It can lead to lower recovery than the simulations of the fine grid method. Finally, they recommended to use fine grid upscaling for better performance prediction of chemical flooding.

2.4.2.10. Polymer flooding

Islam and Ali (1989) obtained new dimensionless scaling groups which can incorporate the flow of foams, emulsions and polymers. They focused on the significance of mass transfer among phases, fractional flow, diffusion, adsorption, trapping, slug size and interfacial tension. New groups of scaling conditions were derived for co-surfactant improved polymer flooding with a mathematical explanation. The relative permeability and interfacial tension model were also obtained by Islam and Ali (1990). Bai et al. (2008) developed a group of scaling principles by taking into consideration many factors for polymer flooding in the reservoirs. They

evaluated the sensitivity analysis of each of the dimensionless numbers. A numerical approach was recommended to enumerate the sensitivity analysis of every dimensionless number. The researcher analyzed the influence of specific physical parameters, such as injection rate, oil viscosity and permeability, on the predominant level of the dimensionless numbers. Finally, they determined the leading ones for distinctive circumstances. Guo et al. (2012) identified the dimensionless leading scaling groups in heavy oil reservoirs for polymer flooding. They derived twenty-eight dimensionless scaling numbers and build up a mathematical model to authenticate the efficacy of these scaling numbers. The authors performed numerical sensitivity analysis of individual scaling numbers to find out their consequences on the recovery of oil. They identified nine dominant scaling numbers which were used to design field scale oil recovery experiments.

2.4.2.11. Micellar flooding

Thomas et al. (1997) discussed the design of micellar flooding experiments using scaling laws. They derived scaling criteria utilizing dimensional and inspectional analyses with six elements for three-phase flow. These criteria were derived in several ways. The partial differential equations, constitutive relations and initial and boundary conditions are used to form a mathematical model. Finally, the mathematical model was simplified, and a group of scaling principles was derived which was applicable to most laboratory conditions.

2.4.2.12. In-situ combustion

Garon et al. (1982) studied the three-dimensional physical models of tar sand fireflood reservoirs following a pre-heating to explore the reservoir heterogeneity. They used three types of heterogeneity, including communicating and non-communicating bottom water zones and a thin, simulating a fracture heated layer. They chose a symmetrical element pattern of overburden and under burden. It had the same thermal diffusivities as the field was used for the model. They employed actual field crude because its properties affect important features of fire flooding. They increased the characteristic flux in the model in direct proportion to scale for both diffusion and convection of heat and mass transfer. Islam and Ali (1992) provided valuable rules to construct a suitable scaling principle for in-situ combustion investigations. They used partial differential equations and imposed initial and boundary conditions to derive a set of scaling criteria. Fire tube tests were employed to investigate the authenticity of the resulting scaling criteria. Their results showed that among the developed scaling groups only a few groups had experimental validation. On the other hand, the outcomes of research test site fire tubes of wet combustion showed that the measured parameters can mislead the experiments. Kandlikar (2010) developed a local parameter model using scaling analysis of

critical heat flux (CHF) in micro channels and insignificant width tubes to estimate the secure working boundaries of refrigeration schemes using flow boiling. The author found a new non-dimensional group K_2 with Weber number and capillary number. It represents the proportion of vaporization motion to surface tension forces and rising as the principal sets in enumerating the thin conduit consequences on CHF. The coefficients in the model had found by calculating available experimental data. Finally, the author evaluated each data set for individual sets of constants. The outcome showed average inaccuracies of fewer than 10 out of a hundred for entire information groups.

2.4.3. Reservoir geometry

This type of scaling numbers can compare between identical configuration of reservoirs at diverse scale. It can detect the inaccuracy if the configuration of reservoir changes between the scales. It also depends on the dip angle of a reservoir to be drilled and the grid geometry of a specific reservoir.

2.4.3.1. Geometric factor

Van Daalen and Van Domselaar (1972) determined the scaling groups by applying inspectional analysis of macroscopic displacement processes. They pointed out that the geometric factor (length to thickness proportion) can ordinarily be ignored if no cross flow occurs. Lake and Srinivasan (2004) demonstrated the ambiguity in consigning scaled up assessments to a limited formation interval or a cell width for numerical simulation. They used the alteration of the average of an arbitrary factor to understand the scaling process. The authors used the variance of the mean of reasonable auto correction function to explain the modification in vertical and horizontal permeability with scale. Finally, they demonstrated the effect of scaling up on auto correction configuration in the field of simulation. De Souza Mendes (2007) introduced an alternative way for non-Newtonian fluid flow obstructions which uses governing equations for non-dimensionalization of the flow. In his alternative method, he found that the subsequent dimensionless rheological parameters are dimensionless rheological properties. Therefore, it is fixed for a specified flow material. Likewise, each set of estimations of these dimensionless rheological properties portray a class of rheologically equivalent materials. Finally, the author found that this alternative nondimensionalization technique was substantially more straightforward. It reduces both the utilization of dimensionless outcomes to production circumstances and the correlations between mathematical and investigation outcomes of systematic research. Polsinelli and Kavvas (2015) discussed modern lie scaling technique by means of the established scaling methods founded on different analyses techniques. They laid out the vital facts of the lie group concept and the exploitation of the lie scaling alteration.

Finally, Polsinelli and Kavvas explained the similarities, comparative powers and drawbacks of these two methods. Depending on the above-mentioned literature of scaling criteria development, the most widely used scaling groups are discussed below.

2.4. Small scale capillary number

Firstly, the small-scale capillary number was derived by Dombrowski and Brownell (1954) for synthetic media. The modeling of pore-scale is the primary and the smallest scale to consider for the derivation of two-phase flow dimensionless numbers (Moore and Slobod, 1956). The set of connections of wetting and non-wetting phase and the purpose of remaining saturation and scaling numbers which influence these numbers are the basic issue for pore-scale modeling. On the other hand, the medium resolution scale is the second type of scale at which point the subsequent production and flood front performance is detected (Dietz, 1953; Craig et al., 1957; Hagoort, 1980). The numerical models of medium scale and large-scale deals with many factors including flow property or barrier distribution (Peters et al., 1998; Willis and White, 2000), geometry and the parameters which affect the production. The authors with their corresponding scaling numbers are presented in Table 2.2:

Table 2.2: Small/Core/Pore-Size Scale Capillary Number (N_c)

Reference	Formulation	Comments
Dombrowski and Brownell (1954)	$N_c = \frac{k \cdot \bar{\nabla} \Phi }{\sigma \cos \theta}$	Synthetic media, distilled water-pure organics system
Moore and Slobod (1956)	$N_c = \frac{v \cdot \mu_1}{\sigma \cos \theta}$	Outcrop sandstone, brine-crude System
Taber (1969)	$N_c = \frac{v \cdot \mu_1}{\sigma \cos \theta}$	Berea sandstone, brine-soltrol System
Foster (1973)	$N_c = \frac{u \cdot \mu_1}{\sigma}$	Berea sandstone, brine-oil System
Lefebvre Du Prey (1973)	$N_c = \frac{u \cdot \mu_1}{\sigma}$	Synthetic media, water pure hydrocarbons system
Ehrlich <i>et al.</i> , (1974)	$N_c = \frac{u \cdot \mu_1}{\sigma}$	Outcrop sandstone, brine crude system
Abrams, (1975)	$N_c = \frac{v \cdot \mu_1}{\sigma \cdot \Delta S} \cdot \cos \theta \left(\frac{\mu_1}{\mu_2} \right)^{0.4}$	Outcrop sandstone, brine crude system

2.5. Large scale capillary number

Rapoport and Leas (1953) formed the flow regime guide during a large scale waterflood for scaling the capillary effects. Geertsma et al. (1956) consider the growth of large scale numbers for both thermal and water flood as identical as pore-scale one. Perkins and Collins (1960),

derived gravitational segregation capillary number analogous to dimensionless number derived by Craig et al. (1957). Shook et al. (1992) developed a scaling number identical to Van Daalen and Van Domselaar (1972) omitting the conventional capillary number. The authors with their corresponding scaling numbers are presented in Table 2.3:

Table 2.3: Medium (Inter-well)/Large (Reservoir) Scale Capillary Number

Reference	Formulation	Comments
Rapoport and Leas, (1953)	$N_{RL} = \sqrt{\frac{\phi}{k} \cdot \frac{\mu_1 \cdot u \cdot L_1}{k_{r1}^o \cdot \phi \cdot \sigma_{12} \cdot \cos\theta}}$	Capillary dominated regime indicator
Geertsma <i>et al.</i> , (1956)	$N_c = \frac{\sigma_{12} \cdot \cos\theta \cdot \sqrt{k \cdot \phi}}{u \cdot \mu_1 \cdot L}$	Identical to pore-scale N_c
Craig <i>et al.</i> , (1957)	$R_c = \frac{\mu_1 q_i L}{\sigma_{12} \cdot \cos\theta \cdot \sqrt{k_x}}$	Dimensionless scaling number
Perkins and Collins, (1960)	$S_c = \frac{k_{r1}^o \cdot \sigma}{u \cdot \mu_1 \cdot L_1} \sqrt{\left(\frac{\phi}{k}\right)}$	N_c corresponding similarity group
Van Daalen and Van Domselaar, (1972)	$N_{pc} = \frac{\lambda_{r2}^o \cdot \sigma}{L \cdot u_T} \sqrt{\phi \cdot k_x}$	Capillary scaling number
Shook <i>et al.</i> , (1992)	$N_{pc} = \frac{\lambda_{r2}^o \cdot \sigma}{L \cdot u_T} \sqrt{\phi \cdot k_x}$	Scaling dimensionless number of oil-water system

2.6. Gravity number

Gravity number for granular material was first derived by Engelberts and Klinkenberg (1951) for density variation of the system. The two-phase flow gravity number was developed by Rapoport (1955) for the case of petroleum reservoirs. Two different type of gravity number was considered by Geertsma et al. (1956) for unconsolidated sand. Gravity numbers that was surveyed in literature also differed from one source to another. Although, the reasonable selection to be considered for gravity number is considerable distinction of density (Craig et al., 1957; Hagoort, 1980), and comprehensive absconding in the structure of two-liquid scheme. Many researchers (Pozzi and Blackwell, 1963; Peters et al., 1998) have been concerned about the improvement of gravity number in two-liquid scheme. On the other hand, Carpenter et al. (1962) derived gravity number which was not dimensionless. Using WAG process Stone (1982) developed the dimensionless group which was different from Wellington and Vinegar (1985) carbon dioxide flooding process. Newley (1989) derived gravity number for solvent flooding and Sorbie et al. (1990) developed the number for miscible flooding process. Shook et al. (1992) have proved the consequence of geometric aspect ratio and dip

angle that significantly affect the gravity number. The authors with their corresponding scaling numbers are presented in Table 2.4.

Table 2.4: Gravity Number (N_g) for petroleum literature

References	Scaling Groups and Formulation	Comments
Engelberts and Klinkenberg, (1951), Croes and Schwarz, (1955)	$N_g = \frac{\Delta\rho \cdot k_x \cdot \lambda_{T1}}{u_T}$	Granular material
Rapoport, (1955)	$N_g = \frac{\Delta\rho \cdot k_x \cdot \lambda_{T1}}{u_T}$	Two-phase flow
Geertsma <i>et al.</i> , (1956)	$N_{g1} = \frac{\rho_1 \cdot g \cdot k_x \cdot \lambda_{T1}}{u_T}$ $N_{g2} = \frac{\rho_1}{\rho_2}$	Unconsolidated sand
Craig <i>et al.</i> , (1957), Spivak, (1974)	$N_g = \frac{u_T}{\Delta\rho \cdot g \cdot \sqrt{k_x \cdot k_z} \cdot \lambda_{T2}}$	Zero dip
Perkins and Collins, (1960)	$N_g = \frac{\Delta\rho \cdot g \cdot k_x \cdot \lambda_{T1}^0}{u_T} \cdot \frac{H}{L}$	Unconsolidated reservoir sand
Carpenter <i>et al.</i> , (1962)	$N_g = \frac{q}{\Delta\rho \cdot k_x \cdot \lambda_{T1} \cdot L^2}$	Not dimensionless
Pozzi and Blackwell, (1963)	$N_g = \frac{u_T}{\Delta\rho \cdot k_x \cdot \lambda_{T2}} \cdot \frac{L}{H}$	Dependent on viscosity ratio
Greenkorn, (1964)	$N_{g1} = \frac{\rho_2 \cdot g \cdot k_x \cdot \lambda_{T2}}{u_T}$ $N_{g2} = \frac{\rho_2}{\rho_s}$	Unconsolidated sand
Stone, (1982)	$N_g = \frac{u_T}{\Delta\rho \cdot g \cdot k_z \cdot (\lambda_1 + \lambda_3)} \cdot \frac{L}{H}$	WAG process (injected gas is phase 3)
Wellington and Vinegar, (1985)	$\frac{\Delta\rho \cdot g \cdot k_z \cdot \lambda_{T1}^0}{u_T} \cdot \frac{L}{H}$	CO ₂ injection
Newley (1989)	$N_g = \frac{u_T}{\Delta\rho g k_x \lambda_{se}} \cdot \sqrt{\frac{L}{H}}$	Derived for zero dip and solvent flooding
Lake, (1989)	$N_g = \frac{\Delta\rho \cdot g \cdot k_x \cdot \lambda_{f2}^0}{u_T}$	Derived using one-dimensional fractional flow theory
Sorbie <i>et al.</i> , (1990)	$N_g = \frac{\mu \cdot u_T}{\Delta\rho \cdot g \cdot k_x} \cdot \frac{L}{H}$	Miscible floods
Vortsos (1991)	$N_g = \frac{H k_x \Delta\rho g}{L u_T \mu_2}$	Granular material
Shook <i>et al.</i> , (1992)	$N_g = \frac{\Delta\rho \cdot g \cdot k_x \cdot \lambda_{f2}^0 \cdot \cos\alpha}{u_T} \cdot \frac{H}{L}$	Buoyancy number
Shook <i>et al.</i> , (1992)	$N_g = \frac{\Delta\rho g \left(\frac{K}{\phi}\right)}{\mu_o v_d}$	Gravity forces to viscous forces

2.7. Dimensionless scaling groups for GAGD

The most applicable combination of dimensionless scaling groups for gravity drainage oil recovery process are presented by Edwards et al. (1998), Grattoni et al. (2001), Kulkarni (2005), and Rostami et al. (2010). Grattoni et al. (2001) represented the scaled model as the combination of capillary and Bond number which excluded gravity number. This limitation was eliminated by Kulkarni (2005) with the inclusion of gravity number term and thereby factoring the density ratio in the combination model. Rostami et al. (2010) presented a scaled model with the combination of capillary and Bond number along with the inclusion of viscosity ratio term, but they neglect the gravity number term. The authors with their corresponding scaling numbers are presented in Table 2.5.

Table 2.5: Dimensionless Scaling Groups for GAGD EOR Process

Reference	Scaling Groups and Formulation	Comment
Edwards <i>et al.</i> , (1998)	$N_B = \frac{\Delta\rho g l^2}{\sigma}$ and $\frac{\Delta\rho g l^2}{\sigma \sqrt{\left(\frac{\phi}{k}\right)}}$	Gravity to capillary number
Grattoni <i>et al.</i> , (2001)	$N_G = \frac{\Delta\rho.g.k}{\Delta\mu.u}$	Gravity to viscous force
Grattoni <i>et al.</i> , (2001)	$N_C = \frac{v\mu}{\sigma}$ and $\frac{v\mu}{P_C R_A} 2\cos\theta$	Viscous forces to capillary forces
Kulkarni (2005)	$N_k = N_G + \left(\frac{\rho_G}{\rho_0} (N_C + N_B) \right)$	Improved characterization
Rostami <i>et al.</i> , (2010)	$N_{rostami} = \frac{N_B(\mu_r)^A}{(N_C)^B}$	Forced gravity drainage

2.8. Other scaling groups

Other dimensionless scaling groups are very important to describe the physical process which affect the model. Dimensionless time is one of the most important scaling group which was first derived by Rapoport (1955). Mattax and Kyte (1962) were the pioneer who scaled capillary force imbibition under some specific condition and proposed this number. In this scaling group, different author defined viscosity and core length differently (Kazemi et al., 1992; Mattax and Kyte, 1962). Even though, the authors applied distinctive equations to identify these factors, every single one of these equations utilized the squared representative length. Kantzas et al. (1988) and Blunt et al. (1995) described the fluid property group and their significance on displacement process. Miguel-H et al. (2004) developed the recent dimensionless time group which was used in different recovery processes. The authors along with their corresponding numbers are presented in Table 2.6:

Table 2.6: Other Scaling Groups

References	Scaling Groups and Formulation	Comments
Rapoport (1955)	$t_{DR} = \frac{k \frac{d}{ds_w}(p_c)}{u\mu_w L}$	Dimensionless time
Mattax and Kyte (1962)	$t_{DMK} = \frac{\sigma \sqrt{\frac{k}{\phi}}}{\mu_w L^2} t$	Dimensionless time
Kazemi <i>et al.</i> , (1992)	$t_{KGE} = \frac{\sigma \sqrt{\frac{k}{\phi}} F_{s,KGE}}{\mu_w} t$	Dimensionless time
Kantzas <i>et al.</i> (1988) and Blunt <i>et al.</i> (1995)	$\alpha = \frac{\rho_{ow}(\rho_o - \rho_g)}{\rho_{go}(\rho_w - \rho_o)}$	Fluid property group
Shook <i>et al.</i> , (1992)	$R_L = \frac{L}{H} \sqrt{\frac{k_V}{k_H}}$	Dimensionless geometric group
Edwards <i>et al.</i> , (1998)	$N_{DB} = \frac{\Delta\rho g k}{\sigma}$	Dombrowski Brownell Number
Grattoni <i>et al.</i> , (2001)	$N_B = \frac{\Delta\rho g (\frac{K}{\phi})}{\sigma}$	Gravity forces to capillary forces
Miguel-H <i>et al.</i> , (2004)	$t_D = \frac{k k_{ro} \Delta\rho g (\frac{K}{\phi}) / g_c}{h \phi \rho \mu_o (1 - S_{or} - S_{wi})} t$	Dimensionless time

2.5. Current research challenges and future directions

The usefulness and reliability of a scaled physical model depend upon the selection of recovery mechanisms. It also depends on how properly the dimensionless scaled numbers were developed. It is difficult to build a relationship between different theoretical flow properties and field implementation without considering the simplified assumptions which will result in questionable conclusions. Laboratory experiments can compensate the deficiencies in analytical solutions, but the difficulties remain which could entirely be misleading the analyses outcomes. Different displacement processes demand accurate capturing of rock and fluid properties depending on the process which selected for the analyses. Many factors such as viscosity, relative permeability, saturation, density and the mixing capacities can play a significant role for the recovery performance of a reservoir. The formulation of dimensionless scaling numbers plays a crucial role to capture the influence of rock and fluid properties that affect the physical system. Darcy's law is the basis of reservoir engineering as well as reservoir simulation. Governing equations for fluid flow through porous media is a combination of

physical principles, i.e., conservation of mass, momentum and energy along with the equations of state. Some simplified assumptions should be considered to formulate partial differential equations. The porous medium is homogeneous and isotropic, rock compressibility and thermal expansions are negligible, and the flow should be steady state etc. are desired assumptions. These simplified assumptions will provide erroneous results when implemented those scaling groups to field conditions. As these properties alter in terms of space and time, thus it should be considered the alteration of rock and fluid properties with respect to both time and space. This phenomenon is called the rock and fluid memory concept. Many authors (Ewing, 1997; Polubarinova-Kochina, 1962; Barry and Sposito, 1989; Kabala and Sposito, 1991; Dewers and Ortoleva, 1994; Indelman and Abramovich, 1994; Steefel and Lasaga, 1994; Caputo, 1997) have studied diagnostic and numerical models incorporating time and space dependent permeability in water, petroleum and hydrothermal and magmatic systems. However, incorporation of memory remains a challenge in terms of modeling and validation. Hossain et al. (2009) have considered memory concept for developing scaling principles by conducting small-scale laboratory experiments to simulate a drilling process. They recommended new scaling principles to derive the dimensionless scaling numbers. The authors validated this approach and dimensionless groups by investigating the dimensionless numbers through scaled physical models and experimental evidences. Another problem is that all derived dimensionless numbers do not fulfill the physical process as well-defined by the governing equations, conditions, constitutive relationships and constraints. Therefore, some of the scaling groups should be relaxed to fulfill some other most important conditional phenomena occurring in the system. The choice of which prerequisites should be relaxed, will depend on the specific process being modeled. In any case, a few or no literature is available that can completely describe the development of scaling principles and its practices depending on the displacement process incorporating the idea of rock and fluid memory. In future, memory concept should be incorporated with partial differential equations which will provide much validated dimensionless scaling groups that influence the physical process. This paper can guide to the development of new scaling criteria to diminish significant operating cost with different displacement process in an EOR process design. Memory concept can be included in deriving the basic fluid flow equations through porous media for the development of dimensionless scaling numbers. In future, this study will help to emphasize the development of scaling principles for different processes of fluid displacement for a widespread limit of reservoir types and their field implementation. This concept can be extended in different enhanced oil recovery processes where rocks and fluid properties are more complex in explaining their behavior. This

study leads to the progress of a recovery scheme which will be employed towards a widespread variety of reservoir categories given that there exists an interconnection concerning the small-scale laboratory and the large-scale field models.

Concluding remarks

In this study, review of different scaling criteria development procedure has been outlined for the performance of different EOR approaches. The principal contribution of this paper is to demonstrate the rigorous procedure of the scaling criteria development. Principle procedure or algorithm of dimensional and inspectional analyses are presented with a comparison. The classification of different scaling dimensional groups is presented in a convenient way. Important dimensionless numbers which are used in petroleum field are described and summarized. A novel approach is suggested where rock and fluid memory should be incorporated. Scaling of multiphase fluid flow for displacement process faced difficulty when implementing the theoretical multiphase flow behavior to field applications. Scaled physical model of water flooding is used extensively to derive scaling criteria. It is an effective recovery process, but there are some limitations for this process. Immiscible and miscible displacement approach is used for better defining the scaling approach. On the other hand, solvent and chemical injection approach methods have some variable results depending on the process being used. Immiscible GAGD technique performance largely determined by the proportion of gravity to capillary forces and found it reliable for fast oil recovery. Steam injection method causes considerably larger crude oil recovery, because the recovery of oil mainly dependent on the heat involvement for each unit volume of reservoir. When steam additives are added then it will significantly increase the recovery process. Countercurrent spontaneous imbibition process is very effective for oil and gas recovery from fractured porous media. The authors reviewed the existing literature of the scaling procedure using dimensional and inspectional analysis. The inspectional scaling tactic compromises numerous benefits compared to using the traditional π -theorem. Memory concept can be utilized to determine the dimensionless groups and their effective combination can greatly increase the recovery process. In future, this analysis technique can be applied to a variety of reservoirs to increase the hydrocarbon recovery and to characterize the behavior of a petroleum reservoir.

Acknowledgements

The authors would like to thank Natural Sciences and Engineering Research Council of Canada (NSERC); Research & Development Corporation of Newfoundland and Labrador (RDC), funding no. 210992; and Statoil Canada Ltd., funding no. 211162 for providing financial

t_D	Dimensionless time	GAGD	Gas-Assisted Gravity Drainage
R_L	Geometric aspect ratio	WAG	Water-Alternating Gas
g	Acceleration of gravity, m/s ²	CHF	Critical Heat Flux

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Chapter Three

Development of Scaling Criteria for Steam Flooding Process using Rock and Fluid Memory Concept

Abstract

Development of new scaling criteria for steam flooding process is presented in this paper. The mathematical development is done using modified Darcy's law, constitutive relationships, constraints, initial and boundary conditions. Dimensional and inspectional analyses are used to develop sets of dimensionless groups by incorporating rock and fluid memory concept. The variety of scaling criteria and their comparative advantages and limitations are discussed. Presently available scaling criteria for steam flooding processes used same fluid, same porous media in model and prototype. However, it requires a high-pressure model with different porous media which causes difficulties in scaling properties, and thus it largely depends on pressure and porous media. In this paper, different methods are presented which permit scaling of all properties dependent on pressure or temperature by relaxing the requirements of geometric similarity. A set of relaxed scaling criteria is determined to satisfy a major mechanism. A comparative study of different approaches and their relative merits and demerits are discussed. Approach 2 (Same Fluids, Same Pressure Drop, Same Porous Medium and Geometric Similarity) seems to be the most appropriate for steam flooding process, but gravitational forces cannot be scaled properly with this approach. Approach 3 (Same Fluids, Same Pressure Drop, Same Porous Media and Relaxed Geometric Similarity) is suitable for this process if the effect of transverse dispersion is considered negligible. Finally, a table is developed which can act as a guideline to select an appropriate approach which best scales a major mechanism for a specific steam flooding recovery process.

3.1. Introduction

Dimensionally scaled model studies are applied in engineering problems for many years; especially in the field of heat and fluid flow with structural design (Leverett et al., 1942; Mattax and Kyte, 1962; Bridgman, 1931; Langhaar, 1951; Murphy, 1950). Similar approach used in the field of petroleum engineering is relatively new, however, its application is increasing day by day (Leverett et al., 1942; Bobek and Bail, 1961; Mattax and Kyte, 1962; Carpenter et al., 1962; Graham and Richardson, 1959; Rapoport, 1955; Craig et al., 1955, 1957; Rapoport and Leas, 1953; Engelberts and Klinkenberg, 1951; Seve and Pottier, 1963; Greettsma et al., 1956; Van Meurs, 1956; Henley et al., 1961; Jadhawar, 2010; Rahman et al., 2017; Hossain, 2017).

It can reproduce the behavior of one scale process to another scale. Many researchers had demonstrated the importance of scaling criteria development in many ways (Kimber et al., 1988; Shook et al., 1992, Novakovic, 2002). However, the importance of scaling can be demonstrated for new processes whose mechanism are not known to us. Moreover, the mathematical description of these processes is difficult to formulate. Many small-scale models had been developed for multiphase flow behavior considering reservoir as either isothermal or non-isothermal process.

Laboratory models had been used for many years to extrapolate the behavior of the thermal recovery operations. It is unfortunate that the scaling of the thermal recovery process is difficult to formulate. A lot of factors are involved in thermal recovery processes. Heat transfer and thermal effects of fluid and rock properties as well as gravity, capillary, and viscous forces should be considered for the thermal recovery process. Steam flooding technique is usually used for heavy or viscous oil reservoirs.

The laboratory steam flooding process had been evolved during the last two decades from qualitative observations to the complicated scaled model. Researchers investigated many procedures for scaling steam flooding process. Ali and Redford (1977) reviewed the approach used by previous investigators. The different approaches show the different degree of complexity. Stegemeier *et al.* (1980) developed most widely used scaling technique for low-pressure models. On the other hand, Pujol and Boberg (1972) investigated the scaling technique for high-pressure models. In a high-pressure model, same fluids will be used in model and prototype. Low-pressure models are easy to generate and operate where different fluids will be used in model and prototype. Huygen (1976), and Huygen and Lowry (1983) developed a high-pressure model by considering heat flow in crudes and crushed sandstones. They investigated the effect of oil viscosity, distillation and initial oil saturation on recovery. Pursley (1974) developed the high pressure scaled model and studied the effect of bottom water, gas cap, heterogeneities, and steam quality on reservoir response. Ehrlich (1974) developed scaled model by using Pujol and Boberg's scaling laws for Wabasca, Alberta heavy oil. An intermediate pressure model had been constructed by Lo (1977) for 1/12 of a seven-spot. Singhal (1980) developed scaled model depending on steam quality including the enthalpy of vapor to liquid water. The author simulated Lloydminster type oil sand by material and energy balance equation.

This study focused on deriving scaling criteria using inspectional and dimensional analysis. A relaxed set of criteria is determined without significantly changing the process parameters. The geometric similarity is relaxed to satisfy other requirements for steam flooding process. Five different sets of scaling criteria are developed and performed their comparative study to discover which approach is most suitable for steam flooding process.

3.2. Development of Scaling Criteria

The application of scaling law is dependent on the concept of dimensional similarity. A perfectly scaled model requires physical, dynamic, and geometric similarity at each point between model and prototype (Poettmann et al., 1974). However, all physical and geometric variables are essentially proportional to a perfectly scaled model at any time and point. Moreover, governing equations and their initial and boundary conditions are also satisfied the similarity criteria regarding dimensionless parameters. There are two standard procedures for deriving scaling criteria for any system. These are inspectional analysis (Ruark, 1935; Birkhoff, 1950; Bear, 1972; Shook et al., 1992, Novakovic, 2002), and dimensional analysis (Buckingham, 1914; Bridgman, 1931; Langhaar, 1951; Focken, 1953; Nielsen and Tek, 1963; Sonin, 2001).

3.2.1. Dimensional Analysis

Dimensional analysis is a technique to form any dimensionless group using two or more variables. The impact of different variables is then studied in a group rather than individuals in the group. Dimensional analysis method combines variables that affect a process or system into fundamental dimensionless numbers. By this process, functions and experiments are simplified by the combination of the various variables which affect the process into single variable. When dimensionless groups are derived, it lumps together the numerous variables which affect a process since it would be cumbersome to run series of experiments to define how the parameters affect each other.

Two methods used for dimensional analysis include:

1. The Rayleigh Method and
2. The Buckingham PI Theorem

The choice of the above methods in the derivation of the dimensionless numbers depends largely on the number of variables involved in describing the phenomena. The Rayleigh's

method is utilized for processes involving few variables. For processes or system involving a large number of variables, the Buckingham PI theorem is used.

1. Rayleigh's Method

The procedure for the Rayleigh's method involves

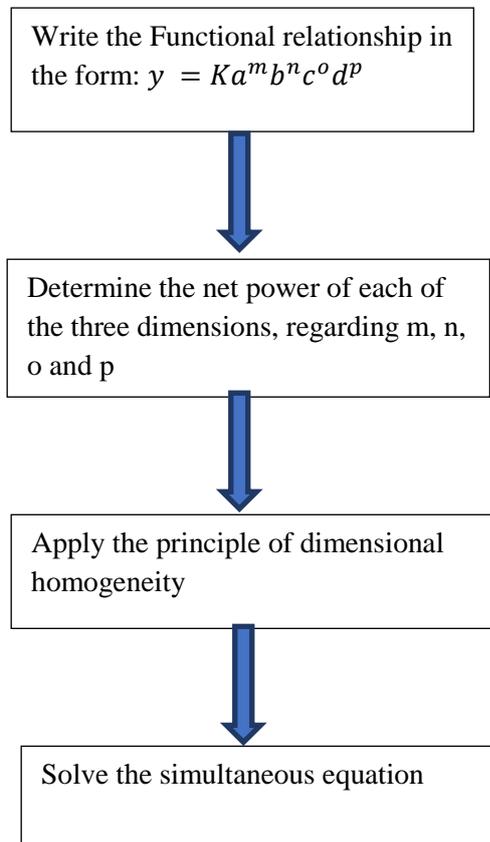


Figure 3.1: Rayleigh's Method

Where K is dimensionless constant, $a, b, c,$ and d are variables and m, n, o and p are arbitrary exponents as illustrated in Figure 3.1

2. Buckingham PI theorem

The procedure for the Buckingham PI theorem is given below:

1. List all variables (the independent variables)
2. Express each variable in fundamental dimensions
3. Determine the required number of PI terms

$$\pi s = n - r \tag{1}$$

n = number of physical relationships and r = number of reference dimensions required to describe the variables

4. Select r repeating variables by
 - i) Avoid dependent variables
 - ii) Ensuring that each is dimensionally independent and cannot be combined to form dimensionless numbers
5. Form the PI terms by multiplying the non-repeating variables by repeating variables to get dimensional numbers
 - i) Repeating variables can be raised to any power
 - ii) Non-repeating variables are raised to the power of 1

3.2.1.1 Mathematical formulation using PI-theorem

Leverett *et al.*, (1942) use dimensionless groups for the investigated of reservoir behavior by adopting dimensional analysis.

If any variable p_1 depends upon the independent variables, $p_2, p_3, p_4 \dots \dots \dots p_n$ then we may write:

$$p_1 = f(p_2, p_3, p_4 \dots \dots \dots p_n) \quad (2)$$

Where p_1 is the dependent parameter, and $p_2, p_3, p_4 \dots \dots \dots p_n$ are $(n - 1)$ numbers of the independent parameter. Since there exists a mathematical equilibrium between the dependent and the independent variables, they may be grouped into another functional relationship equal to zero:

$$g(p_1, p_2, p_3, p_4 \dots \dots \dots p_n) = 0. \quad (3)$$

Where g is an unspecified function, making the transformations to dimensionless form is simple and straightforward. Several steps have to be done to decide the required numbers of dimensionless groups. The primary step is to determine the total number of primary dimensions “ n ” which involve the physical processes. Then determine the number of repeating parameters assigned as “ m ”. To find out the value of “ m ”, it is required to determine the rank of the resulting dimensional matrix:

$$m = \begin{bmatrix} a_{11} & \dots & a_{n1} \\ \vdots & \ddots & \vdots \\ a_{1r} & \dots & a_{nr} \end{bmatrix} \quad (4)$$

According to Buckingham, the dimensionless form of the equation should satisfy the following functional form:

$$X((\pi_1, \pi_2, \pi_3, \pi_4 \dots \dots \dots \pi_{n-m})) = 0. \quad (5)$$

Where n-m denotes the minimum number of independent dimensionless groups which affect the physical process and is required to denote the dimensions of all parameters $p_1, p_2, p_3 \dots \dots \dots p_n$.

Table 3.1 shows the similarity group developed from dimensional analysis. The pertinent variables are selected depending on the processes and Buckingham PI-theorem is used to develop these dimensionless numbers. There are few new groups have been introduced through this approach which is not found by inspectional analysis. It happened because some of the variables are not considered in the formulation of governing equations. The new groups formed by dimensional analysis had an insignificant or negligible effect on this specific process, so their scaling requirements are relaxed.

Table 3.1: Dimensionless group from dimensional analysis

$\pi_1 = \frac{A}{L^2}$	$\pi_{11} = \frac{k^2}{L^2}$	$\pi_{21} = \frac{q_{prod}}{\sqrt{TC_{pf}}L^{5/2}}$	$\pi_{31} = \frac{u_w}{\sqrt{LTC_{pf}}}$	$\pi_{41} = \frac{\rho_g}{\rho_o}$	$\pi_{51} = \frac{k_r}{\rho_o L^{5/2} T^{1/2} C_{pf}^{5/2}}$
$\pi_2 = \frac{w^2}{L^2}$	$\pi_{12} = \frac{k_r^2}{L^2}$	$\pi_{22} = \frac{D_{Ta}}{\sqrt{TC_{pf}}L^{3/2}}$	$\pi_{32} = \frac{u_g}{\sqrt{LTC_{pf}}}$	$\pi_{42} = \frac{\rho_w}{\rho_o}$	$\pi_{52} = \frac{C_{pg}}{C_{pf}}$
$\pi_3 = \frac{h^2}{L^2}$	$\pi_{13} = \frac{P_i}{\rho_o LTC_{pf}}$	$\pi_{23} = \frac{D_{La}}{\sqrt{TC_{pf}}L^{3/2}}$	$\pi_{33} = \frac{V_r}{L^3}$	$\pi_{43} = \frac{V\rho}{\rho_o}$	$\pi_{53} = \frac{C_{pr}}{C_{pf}}$
$\pi_4 = \frac{\rho_o L^4 c_r}{T C_{pf}}$	$\pi_{14} = \frac{P_o}{\rho_o LTC_{pf}}$	$\pi_{24} = S_g$	$\pi_{34} = \frac{v_f}{L^3}$	$\pi_{44} = \frac{r^2}{L^2}$	$\pi_{54} = \frac{C_{pw}}{C_{pf}}$
$\pi_5 = \frac{\rho_o L^4 c_f}{T C_{pf}}$	$\pi_{15} = \frac{P_w}{\rho_o LTC_{pf}}$	$\pi_{25} = S_o$	$\pi_{35} = \frac{\sigma_{go}}{\rho_o^{3/2} L^2 T C_{pf}}$	$\pi_{45} = \frac{g}{T C_{pf}}$	$\pi_{55} = \frac{h_w}{L T C_{pf}}$
$\pi_6 = \frac{\rho_o L^4 c_0}{T C_{pf}}$	$\pi_{16} = \frac{P_g}{\rho_o LTC_{pf}}$	$\pi_{26} = S_w$	$\pi_{36} = \frac{\sigma_{ow}}{\rho_o^{3/2} L^2 T C_{pf}}$	$\pi_{46} = \tau$	$\pi_{56} = \frac{h_o}{L T C_{pf}}$

π_7 $= \frac{\rho_o L^4 c_g}{T C_{pf}}$	π_{17} $= \frac{P_{cgo}}{\rho_o L T C_{pf}}$	$\pi_{27} = \theta$	π_{37} $= \frac{\sqrt{T C_{pf}}}{L^{-3/2}} v$	π_{47} $= \frac{k_f}{\rho_o L^{5/2} T^{1/2} C_{pf}^{5/2}}$	$\pi_{57} = \frac{h_g}{L T C_{pf}}$
π_8 $= \frac{\rho_o L^4 c_w}{T C_{pf}}$	π_{18} $= \frac{P_{cow}}{\rho_o L T C_{pf}}$	$\pi_{28} = \frac{\sqrt{T} t}{\sqrt{A C_{pf}}}$	$\pi_{38} = \frac{T \mu_o}{\rho_o L^2}$	π_{48} $= \frac{k_g}{\rho_o L^{5/2} T^{1/2} C_{pf}^{5/2}}$	$\pi_{58} = \frac{h_r}{L T C_{pf}}$
π_9 $= \frac{\rho_o L^4 c_t}{T C_{pf}}$	π_{19} $= \frac{q_i}{\sqrt{T C_{pf}} L^{5/2}}$	π_{29} $= \frac{U}{\sqrt{L T C_{pf}}}$	$\pi_{39} = \frac{T \mu_w}{\rho_o L^2}$	π_{49} $= \frac{k_w}{\rho_o L^{5/2} T^{1/2} C_{pf}^{5/2}}$	$\pi_{59} = \frac{L_v}{L T C_{pf}}$
$\pi_{10} = \phi$	π_{20} $= \frac{q_{ia}}{\sqrt{T C_{pf}} L^{5/2}}$	π_{30} $= \frac{u_o}{\sqrt{L T C_{pf}}}$	$\pi_{40} = \frac{T \mu_g}{\rho_o L^2}$	π_{50} $= \frac{k_o}{\rho_o L^{5/2} T^{1/2} C_{pf}^{5/2}}$	$\pi_{60} = \frac{\xi}{t}$

3.2.2. Inspectional analysis

The inspectional analysis involves the formulation of the governing partial differential equations, initial and boundary conditions to derive dimensionless groups. Constitutive relationships and constraint were also formulated to derive these dimensionless groups. Derived dimensionless groups are written in terms of dimensionless variables with their reference quantities. Some of the dimensionless groups are eliminated which have little or no effects on the specific process. In the inspectional analysis, the mathematical equation of a given problem is reduced to non-dimensional units of space, time and mass. The process like the dimensional analysis approach generates sets of non-dimensional numbers appearing as coefficients in the governing equations.

The process involves:

1. Changing the physical equation to non-dimensional equations. Non-dimensional equations are obtained by dividing each term in the equation by variables or constants whose product have same dimensions.
2. Generation of non-dimensional parameters: In the process of making equations non-dimensional, non-dimensional parameters can be generated. The dimensionless

parameters include sets of dimensional variables, non-dimensional variables and dimensional constants in the problem.

The process involves in three-phase flows (i.e., oleic, aqueous, gaseous). Mass and energy balance takes place among distinct phases and additives. Modified Darcy's law and Fourier law are used in deriving the dimensionless groups.

3.2.2.1. Mathematical formulation using inspectional analysis

Let us consider steam flooding process by considering modified Darcy's law for three-phase flows during the production. A model was derived using memory concept for the development of scaling criteria of steam flooding process. The relationship between different process controlling parameters was developed through the effective combination of those dimensionless groups. Finally, a model equation has been developed for displacement of oil by steam flood using modified Darcy's law with incorporating memory concept (Hossain et al. 2007; Hossain et al. 2008; Hossain et al. 2009b). The flow equation can be written as

The flow equation can be written as

$$u_x = -\eta \left[\frac{\partial^\alpha}{\partial t^\alpha} \left(\frac{\partial p}{\partial x} \right) \right] \quad (6)$$

$$\text{where } \frac{\partial^\alpha}{\partial t^\alpha} [p(x, t)] = \frac{1}{\Gamma(1-\alpha)} \int_0^t (t-\xi)^{-\alpha} \frac{\partial}{\partial \xi} [p(x, t)] d\xi, \text{ with } 0 \leq \alpha < 1 \quad (6.1)$$

Equation (6) can be written as:

$$u_x = -\frac{\eta}{\Gamma(1-\alpha)} \int_0^t (t-\xi)^{-\alpha} \frac{\partial^2 p}{\partial \xi \partial x} d\xi \quad (7)$$

Equation (7) can be written for oil, water and gas phase in the direction of x and z-axes.

$$u_{xo} = -\frac{\eta_o}{\Gamma(1-\alpha)} \int_0^t (t-\xi)^{-\alpha} \frac{\partial^2 p_o}{\partial \xi \partial x} d\xi \quad (8)$$

$$u_{zo} = -\frac{\eta_o}{\Gamma(1-\alpha)} \int_0^t (t-\xi)^{-\alpha} \frac{\partial^2 p_o}{\partial \xi \partial z} d\xi \quad (9)$$

$$u_{xw} = -\frac{\eta_w}{\Gamma(1-\alpha)} \int_0^t (t-\xi)^{-\alpha} \frac{\partial^2 p_w}{\partial \xi \partial x} d\xi \quad (10)$$

$$u_{zw} = -\frac{\eta_w}{\Gamma(1-\alpha)} \int_0^t (t-\xi)^{-\alpha} \frac{\partial^2 p_w}{\partial \xi \partial z} d\xi \quad (11)$$

$$u_{xg} = -\frac{\eta_g}{\Gamma(1-\alpha)} \int_0^t (t-\xi)^{-\alpha} \frac{\partial^2 p_g}{\partial \xi \partial x} d\xi \quad (12)$$

$$u_{zg} = -\frac{\eta_g}{\Gamma(1-\alpha)} \int_0^t (t-\xi)^{-\alpha} \frac{\partial^2 p_g}{\partial \xi \partial z} d\xi \quad (13)$$

Now the mass balance equation for different phases are written as

Mass balance of aqueous phase

$$\begin{aligned} & \frac{\partial}{\partial x} u_{xw} E_{w1} + \frac{\partial}{\partial z} u_{zw} E_{w1} + \frac{\partial}{\partial x} u_{xw} E_{w3} + \frac{\partial}{\partial z} u_{zw} E_{w3} + \frac{\partial}{\partial x} u_{xw} E_{w4} + \frac{\partial}{\partial z} u_{zw} E_{w4} + \phi E_{Lw1} \frac{\partial^2}{\partial x^2} E_{w1} + \phi E_{Tw1} \frac{\partial^2}{\partial z^2} E_{w1} + \\ & \phi D_{Lw3} \frac{\partial^2}{\partial x^2} E_{w3} + \phi D_{Tw3} \frac{\partial^2}{\partial z^2} E_{w3} + \phi D_{Lw4} \frac{\partial^2}{\partial x^2} E_{w4} + \phi D_{Tw4} \frac{\partial^2}{\partial z^2} E_{w4} = \phi \frac{\partial}{\partial t} s_w E_{w1} + \phi \frac{\partial}{\partial t} s_w E_{w3} + \phi \frac{\partial}{\partial t} s_w E_{w4} \end{aligned} \quad (14)$$

Mass balance of oleic phase

$$\begin{aligned} & \frac{\partial}{\partial x} u_{ox} E_{o1} + \frac{\partial}{\partial z} u_{oz} E_{o1} + \frac{\partial}{\partial x} u_{ox} E_{o2} + \frac{\partial}{\partial z} u_{oz} E_{o2} + \frac{\partial}{\partial x} u_{ox} E_{o4} + \frac{\partial}{\partial z} u_{oz} E_{o4} + \phi E_{Lo1} \frac{\partial^2}{\partial x^2} E_{o1} + \phi E_{To1} \frac{\partial^2}{\partial z^2} E_{o1} + \\ & \phi E_{Lo2} \frac{\partial^2}{\partial x^2} E_{o2} + \phi D_{To2} \frac{\partial^2}{\partial z^2} E_{o2} + \phi D_{Lo4} \frac{\partial^2}{\partial x^2} E_{o4} + \phi D_{To4} \frac{\partial^2}{\partial z^2} E_{o4} = \phi \frac{\partial}{\partial t} s_o E_{o1} + \phi \frac{\partial}{\partial t} s_o E_{o2} + \phi \frac{\partial}{\partial t} s_o E_{o4} \end{aligned} \quad (15)$$

Mass balance of gaseous phase

$$\frac{\partial}{\partial x} u_{xg} E_{g1} + \frac{\partial}{\partial z} u_{zg} E_{g1} = \phi \frac{\partial}{\partial t} s_g E_{g1} \quad (16)$$

The detail derivation of model equation is given in appendix A of chapter 4. For two-dimensional flow, we can write the displacement equation as:

$$\begin{aligned} & (1 - f_{xo} - f_{xw}) \left[-\frac{(\eta_o + \eta_w + \eta_g)}{\Gamma(1-\alpha)} \int_0^t (t - \xi)^{-\alpha} \left[\frac{\partial^2 p_w}{\partial \xi \partial x} \right] d\xi - \frac{(\eta_o + \eta_g)}{\Gamma(1-\alpha)} \int_0^t (t - \xi)^{-\alpha} \left[\frac{\partial}{\partial \xi} \left(\frac{\partial p_{cow}}{\partial s_w} \frac{\partial s_w}{\partial x} \right) \right] d\xi - \frac{\eta_g}{\Gamma(1-\alpha)} \int_0^t (t - \xi)^{-\alpha} \left[\frac{\partial}{\partial \xi} \left(\frac{\partial p_{cgo}}{\partial s_g} \frac{\partial s_g}{\partial x} \right) \right] d\xi \right] E_{w1} \frac{\partial}{\partial x} (1 - f_{xo} - f_{xw}) + (1 - f_{xo} - f_{xw}) \left[-\frac{(\eta_o + \eta_w + \eta_g)}{\Gamma(1-\alpha)} \int_0^t (t - \xi)^{-\alpha} \left[\frac{\partial^2 p_w}{\partial \xi \partial x} \right] d\xi - \right. \\ & \left. \frac{(\eta_o + \eta_g)}{\Gamma(1-\alpha)} \int_0^t (t - \xi)^{-\alpha} \left[\frac{\partial}{\partial \xi} \left(\frac{\partial p_{cow}}{\partial s_w} \frac{\partial s_w}{\partial x} \right) \right] d\xi - \frac{\eta_g}{\Gamma(1-\alpha)} \int_0^t (t - \xi)^{-\alpha} \left[\frac{\partial}{\partial \xi} \left(\frac{\partial p_{cgo}}{\partial s_g} \frac{\partial s_g}{\partial x} \right) \right] d\xi \right] E_{w3} \frac{\partial}{\partial x} (1 - f_{xo} - f_{xw}) + \\ & (1 - f_{xo} - f_{xw}) \left[-\frac{(\eta_o + \eta_w + \eta_g)}{\Gamma(1-\alpha)} \int_0^t (t - \xi)^{-\alpha} \left[\frac{\partial^2 p_w}{\partial \xi \partial x} \right] d\xi - \frac{(\eta_o + \eta_g)}{\Gamma(1-\alpha)} \int_0^t (t - \xi)^{-\alpha} \left[\frac{\partial}{\partial \xi} \left(\frac{\partial p_{cow}}{\partial s_w} \frac{\partial s_w}{\partial x} \right) \right] d\xi - \frac{\eta_g}{\Gamma(1-\alpha)} \int_0^t (t - \xi)^{-\alpha} \left[\frac{\partial}{\partial \xi} \left(\frac{\partial p_{cgo}}{\partial s_g} \frac{\partial s_g}{\partial x} \right) \right] d\xi \right] E_{w4} \frac{\partial}{\partial x} (1 - f_{xo} - f_{xw}) + (1 - f_{zo} - f_{zw}) \left[-\frac{(\eta_o + \eta_w + \eta_g)}{\Gamma(1-\alpha)} \int_0^t (t - \xi)^{-\alpha} \left[\frac{\partial^2 p_w}{\partial \xi \partial z} \right] d\xi - \right. \\ & \left. \frac{(\eta_o + \eta_g)}{\Gamma(1-\alpha)} \int_0^t (t - \xi)^{-\alpha} \left[\frac{\partial}{\partial \xi} \left(\frac{\partial p_{cow}}{\partial s_w} \frac{\partial s_w}{\partial z} \right) \right] d\xi - \frac{\eta_g}{\Gamma(1-\alpha)} \int_0^t (t - \xi)^{-\alpha} \left[\frac{\partial}{\partial \xi} \left(\frac{\partial p_{cgo}}{\partial s_g} \frac{\partial s_g}{\partial z} \right) \right] d\xi \right] E_{w1} \frac{\partial}{\partial z} (1 - f_{zo} - f_{zw}) + \\ & (1 - f_{zo} - f_{zw}) \left[-\frac{(\eta_o + \eta_w + \eta_g)}{\Gamma(1-\alpha)} \int_0^t (t - \xi)^{-\alpha} \left[\frac{\partial^2 p_w}{\partial \xi \partial z} \right] d\xi - \frac{(\eta_o + \eta_g)}{\Gamma(1-\alpha)} \int_0^t (t - \xi)^{-\alpha} \left[\frac{\partial}{\partial \xi} \left(\frac{\partial p_{cow}}{\partial s_w} \frac{\partial s_w}{\partial z} \right) \right] d\xi - \frac{\eta_g}{\Gamma(1-\alpha)} \int_0^t (t - \xi)^{-\alpha} \left[\frac{\partial}{\partial \xi} \left(\frac{\partial p_{cgo}}{\partial s_g} \frac{\partial s_g}{\partial z} \right) \right] d\xi - \right. \\ & \left. \frac{(\eta_o + \eta_g)}{\Gamma(1-\alpha)} \int_0^t (t - \xi)^{-\alpha} \left[\frac{\partial}{\partial \xi} \left(\frac{\partial p_{cow}}{\partial s_w} \frac{\partial s_w}{\partial z} \right) \right] d\xi - \frac{\eta_g}{\Gamma(1-\alpha)} \int_0^t (t - \xi)^{-\alpha} \left[\frac{\partial}{\partial \xi} \left(\frac{\partial p_{cgo}}{\partial s_g} \frac{\partial s_g}{\partial z} \right) \right] d\xi \right] E_{w3} \frac{\partial}{\partial z} (1 - f_{zo} - f_{zw}) + (1 - f_{zo} - f_{zw}) \left[-\frac{(\eta_o + \eta_w + \eta_g)}{\Gamma(1-\alpha)} \int_0^t (t - \xi)^{-\alpha} \left[\frac{\partial^2 p_w}{\partial \xi \partial z} \right] d\xi - \right. \\ & \left. \frac{(\eta_o + \eta_g)}{\Gamma(1-\alpha)} \int_0^t (t - \xi)^{-\alpha} \left[\frac{\partial}{\partial \xi} \left(\frac{\partial p_{cow}}{\partial s_w} \frac{\partial s_w}{\partial z} \right) \right] d\xi - \frac{\eta_g}{\Gamma(1-\alpha)} \int_0^t (t - \xi)^{-\alpha} \left[\frac{\partial}{\partial \xi} \left(\frac{\partial p_{cgo}}{\partial s_g} \frac{\partial s_g}{\partial z} \right) \right] d\xi \right] E_{w4} \frac{\partial}{\partial z} (1 - f_{zo} - f_{zw}) + \\ & \phi D_{Lw1} \frac{\partial^2}{\partial x^2} E_{w1} + \phi D_{Lw3} \frac{\partial^2}{\partial x^2} E_{w3} + \phi D_{Lw4} \frac{\partial^2}{\partial x^2} E_{w4} + \phi D_{Tw1} \frac{\partial^2}{\partial z^2} E_{w1} + \phi D_{Tw3} \frac{\partial^2}{\partial z^2} E_{w3} + \phi D_{Tw4} \frac{\partial^2}{\partial z^2} E_{w4} = \phi \frac{\partial}{\partial t} s_w E_{w1} + \\ & \phi \frac{\partial}{\partial t} s_w E_{w3} + \phi \frac{\partial}{\partial t} s_w E_{w4} \end{aligned} \quad (17)$$

Thermal energy balance equation can be written in integral form over the steam zone modified from Yortsos (1979)

$$\begin{aligned} & \Delta T \frac{d}{dt} \int_{v(t)} M_1 dv + \int_{A_{c(t)}} \left(-K_{nc} \frac{\partial T}{\partial x} \right) dA + \int_{A_{sf(t)}} \left(-K_h \frac{\partial T}{\partial x} \right) dA + \Delta T \left[\sum_{i=w,o} C_i \int_{A_{sf(t)}} \rho_i (u_{ix} - \phi s_i v_x) dA - (1 - \phi) C_r \int_{A_{sf(t)}} \rho_r v_x dA \right] = m_s [f_s L_v + C_w \Delta T] \end{aligned} \quad (18)$$

Here volumetric integral covers the steam zone volume $v(t)$ and the areal integrals are evaluated over steam front area $A_{f(t)}$ to the steam zone area $A_{c(t)}$ contacting adjacent formation. $\frac{\partial T}{\partial x}$ represents the temperature gradient normal to the steam front, v_x is the steam front velocity, and M_1 is the volumetric heat capacity of the steam zone.

$$M_1 = (1 - \phi) \rho_r c_r + \phi (c_w \rho_w s_w + c_o \rho_o s_o + c_g \rho_g s_g) + \frac{\phi L_v \rho_g s_g}{\Delta T} \quad (19)$$

Detail derivation of the dimensionless groups are given in in appendix A of chapter 4.

3.3. Dimensionless groups

The dimensionless groups from the inspectional analysis are given in table 3.2. Different assumptions, initial and boundary conditions are used along with constitutive relationships and constraints to derive those groups. Capillary number, gravity number, geometric aspect ratio, longitudinal and transverse Peclet number, dimensionless time, conductivity ratio, dispersion factor, mobility ratio and other groups are derived using inspectional analysis. These are the primary dimensionless groups which is derived from steam flooding process. After the primary, secondary and tertiary elimination of groups the desired dimensionless groups will be found which will ultimately affect the steam flooding process.

Table 3.2: Dimensionless groups from inspectional analysis

$\pi_1 = \frac{t_R u_{xWR}}{\phi x_R S_{WR}}$	$\pi_{45} = \frac{\eta_{gr} p_{cOWR}}{\Gamma(1-\alpha)t_R^{\alpha-1}\phi_R S_{WR} x_R^2}$	$\pi_{89} = \frac{\eta_{WR} p_{WR}}{\Gamma(1-\alpha)t_R^{\alpha-1}\phi_R S_{WR} z_R^2}$	$\pi_{133} = \frac{S_{gi}}{S_{gR}}$
$\pi_2 = \frac{t_R u_{zWR}}{\phi z_R S_{WR}}$	$\pi_{46} = \frac{f_{xOR}\eta_{OR} p_{cOWR}}{\Gamma(1-\alpha)t_R^{\alpha-1}\phi_R S_{WR} x_R^2}$	$\pi_{90} = \frac{\eta_{gr} p_{WR}}{\Gamma(1-\alpha)t_R^{\alpha-1}\phi_R S_{WR} z_R^2}$	$\pi_{134} = \frac{S_{oi}}{S_{oR}}$
$\pi_3 = \frac{D_{LW1R} t_R}{x_R^2 S_{WR}}$	$\pi_{47} = \frac{f_{xOR}\eta_{gr} p_{cOWR}}{\Gamma(1-\alpha)t_R^{\alpha-1}\phi_R S_{WR} x_R^2}$	$\pi_{91} = \frac{f_{xOR}\eta_{OR} p_{WR}}{\Gamma(1-\alpha)t_R^{\alpha-1}\phi_R S_{WR} z_R^2}$	$\pi_{135} = \frac{E_{2i}}{E_{o2R}}$
$\pi_4 = \frac{D_{TW1R} t_R}{z_R^2 S_{WR}}$	$\pi_{48} = \frac{f_{xWR}\eta_{OR} p_{cOWR}}{\Gamma(1-\alpha)t_R^{\alpha-1}\phi_R S_{WR} x_R^2}$	$\pi_{92} = \frac{f_{xOR}\eta_{WR} p_{WR}}{\Gamma(1-\alpha)t_R^{\alpha-1}\phi_R S_{WR} z_R^2}$	$\pi_{136} = \frac{E_{3i}}{E_{w3R}}$
$\pi_5 = \frac{D_{LW3R} t_R}{x_R^2 S_{WR}}$	$\pi_{49} = \frac{f_{xWR}\eta_{OR} p_{cOWR}}{\Gamma(1-\alpha)t_R^{\alpha-1}\phi_R S_{WR} x_R^2}$	$\pi_{93} = \frac{f_{xOR}\eta_{gr} p_{WR}}{\Gamma(1-\alpha)t_R^{\alpha-1}\phi_R S_{WR} z_R^2}$	$\pi_{137} = \frac{E_{1j}}{E_{g1R}}$
$\pi_6 = \frac{D_{TW3R} t_R}{z_R^2 S_{WR}}$	$\pi_{50} = \frac{\eta_{gr} p_{cgoR}}{\Gamma(1-\alpha)t_R^{\alpha-1}\phi_R S_{WR} x_R^2}$	$\pi_{94} = \frac{f_{xWR}\eta_{OR} p_{WR}}{\Gamma(1-\alpha)t_R^{\alpha-1}\phi_R S_{WR} z_R^2}$	$\pi_{138} = \frac{E_{4j}}{E_{w4R}}$
$\pi_7 = \frac{D_{LW4R} t_R}{x_R^2 S_{WR}}$	$\pi_{51} = \frac{f_{xOR}\eta_{gr} p_{cgoR}}{\Gamma(1-\alpha)t_R^{\alpha-1}\phi_R S_{WR} x_R^2}$	$\pi_{95} = \frac{f_{xWR}\eta_{WR} p_{WR}}{\Gamma(1-\alpha)t_R^{\alpha-1}\phi_R S_{WR} z_R^2}$	$\pi_{139} = \frac{\Delta p_{gr}}{p_{gr}}$
$\pi_8 = \frac{D_{TW4R} t_R}{z_R^2 S_{WR}}$	$\pi_{52} = \frac{f_{xWR}\eta_{gr} p_{cgoR}}{\Gamma(1-\alpha)t_R^{\alpha-1}\phi_R S_{WR} x_R^2}$	$\pi_{96} = \frac{f_{xWR}\eta_{gr} p_{WR}}{\Gamma(1-\alpha)t_R^{\alpha-1}\phi_R S_{WR} z_R^2}$	$\pi_{140} = \frac{\rho_{gr} g_R H_R}{p_{gr}}$
$\pi_9 = \frac{t_R u_{xOR}}{\phi x_R S_{OR}}$	$\pi_{53} = \frac{p_{WR}}{p_{cOWR}}$	$\pi_{97} = \frac{\eta_{OR} p_{cOWR}}{\Gamma(1-\alpha)t_R^{\alpha-1}\phi_R S_{WR} z_R^2}$	$\pi_{141} = \frac{\rho_{gr} g_R z_R}{p_{gr}}$
$\pi_{10} = \frac{t_R u_{zOR}}{\phi z_R S_{OR}}$	$\pi_{54} = \frac{x_R^2}{z_R^2}$	$\pi_{98} = \frac{\eta_{gr} p_{cOWR}}{\Gamma(1-\alpha)t_R^{\alpha-1}\phi_R S_{WR} z_R^2}$	$\pi_{142} = \frac{\Delta p_{OR}}{p_{OR}}$
$\pi_{11} = \frac{D_{Lo1R} t_R}{x_R^2 S_{OR}}$	$\pi_{55} = \frac{p_{WR} x_R^2}{p_{cOWR} z_R^2}$	$\pi_{99} = \frac{f_{xOR}\eta_{OR} p_{cOWR}}{\Gamma(1-\alpha)t_R^{\alpha-1}\phi_R S_{WR} z_R^2}$	$\pi_{143} = \frac{\rho_{OR} g_R H_R}{p_{OR}}$
$\pi_{12} = \frac{D_{To1R} t_R}{z_R^2 S_{OR}}$	$\pi_{56} = \frac{p_{WR}}{p_{cgoR}}$	$\pi_{100} = \frac{f_{xOR}\eta_{gr} p_{cOWR}}{\Gamma(1-\alpha)t_R^{\alpha-1}\phi_R S_{WR} z_R^2}$	$\pi_{144} = \frac{\rho_{OR} g_R z_R}{p_{OR}}$
$\pi_{13} = \frac{D_{Lo2R} t_R}{x_R^2 S_{OR}}$	$\pi_{57} = \frac{p_{WR} x_R^2}{p_{cgoR} z_R^2}$	$\pi_{101} = \frac{f_{xWR}\eta_{OR} p_{cOWR}}{\Gamma(1-\alpha)t_R^{\alpha-1}\phi_R S_{WR} z_R^2}$	$\pi_{145} = \frac{\Delta p_{WR}}{p_{WR}}$
$\pi_{14} = \frac{D_{To2R} t_R}{z_R^2 S_{OR}}$	$\pi_{58} = \frac{p_{cOWR}}{p_{cgoR}}$	$\pi_{102} = \frac{f_{xWR}\eta_{OR} p_{cOWR}}{\Gamma(1-\alpha)t_R^{\alpha-1}\phi_R S_{WR} z_R^2}$	$\pi_{146} = \frac{\rho_{WR} g_R H_R}{p_{WR}}$

$\pi_{15} = \frac{D_{L04R}t_R}{x_R^2 s_{0R}}$	$\pi_{59} = \frac{p_{c0WR}x_R^2}{p_{c0GR}z_R^2}$	$\pi_{103} = \frac{\eta_{GR}p_{c0GR}}{\Gamma(1-\alpha)t_R^{\alpha-1}\phi_R s_{WR}z_R^2}$	$\pi_{147} = \frac{\rho_{WR}g_R z_R}{p_{WR}}$
$\pi_{16} = \frac{D_{T04R}t_R}{z_R^2 s_{0R}}$	$\pi_{60} = \frac{f_{x0R}p_{WR}}{p_{c0WR}}$	$\pi_{104} = \frac{f_{x0R}\eta_{GR}p_{c0GR}}{\Gamma(1-\alpha)t_R^{\alpha-1}\phi_R s_{WR}z_R^2}$	$\pi_{148} = \frac{HU_t}{z_R u_{gxR}z_R}$
$\pi_{17} = \frac{u_{xgR}t_R}{\phi x_R s_{gR}}$	$\pi_{61} = \frac{f_{x0R}x_R^2}{z_R^2}$	$\pi_{105} = \frac{f_{xWR}\eta_{GR}p_{c0GR}}{\Gamma(1-\alpha)t_R^{\alpha-1}\phi_R s_{WR}z_R^2}$	$\pi_{149} = \frac{z_R^2 D_{L01R}}{x_R^2 D_{T01R}}$
$\pi_{18} = \frac{u_{zgR}t_R}{\phi z_R s_{gR}}$	$\pi_{62} = \frac{f_{x0R}p_{WR}x_R^2}{p_{c0WR}z_R^2}$	$\pi_{106} = \frac{t_R D_{LW1R}}{s_{WR}x_R^2}$	$\pi_{150} = \frac{z_R^2 D_{L02R}}{x_R^2 D_{T02R}}$
$\pi_{19} = \frac{u_{x0R}}{U_{xR}}$	$\pi_{63} = \frac{f_{x0R}p_{WR}}{p_{c0GR}}$	$\pi_{107} = \frac{t_R D_{LW3R}}{s_{WR}x_R^2}$	$\pi_{151} = \frac{z_R^2 D_{L04R}}{x_R^2 D_{T04R}}$
$\pi_{20} = \frac{u_{xWR}}{U_{xR}}$	$\pi_{64} = \frac{f_{x0R}p_{WR}x_R^2}{p_{c0GR}z_R^2}$	$\pi_{108} = \frac{t_R D_{LW4R}}{s_{WR}x_R^2}$	$\pi_{152} = \frac{z_R^2 D_{LW1R}}{x_R^2 D_{TW1R}}$
$\pi_{21} = \frac{u_{xgR}}{U_{xR}}$	$\pi_{65} = \frac{f_{x0R}p_{c0WR}}{p_{c0GR}}$	$\pi_{109} = \frac{t_R D_{TW1R}}{s_{WR}z_R^2}$	$\pi_{153} = \frac{z_R^2 D_{LW2R}}{x_R^2 D_{TW2R}}$
$\pi_{22} = \frac{u_{z0R}}{U_{zR}}$	$\pi_{66} = \frac{f_{x0R}p_{c0WR}x_R^2}{p_{c0GR}z_R^2}$	$\pi_{110} = \frac{t_R D_{TW3R}}{s_{WR}z_R^2}$	$\pi_{154} = \frac{z_R^2 D_{LW4R}}{x_R^2 D_{TW4R}}$
$\pi_{23} = \frac{u_{zWR}}{U_{zR}}$	$\pi_{67} = \frac{f_{xWR}p_{WR}}{p_{c0WR}}$	$\pi_{111} = \frac{t_R D_{TW4R}}{s_{WR}z_R^2}$	$\pi_{155} = \frac{H}{z_R}$
$\pi_{24} = \frac{u_{zgR}}{U_{zR}}$	$\pi_{68} = \frac{f_{xWR}x_R^2}{z_R^2}$	$\pi_{112} = \frac{k_{xWR}\lambda_{xWR}p_{WR}}{x_R u_{xWR}}$	$\pi_{156} = \frac{L}{x_R}$
$\pi_{25} = \frac{u_{x0R}}{f_{x0R}U_{xR}}$	$\pi_{69} = \frac{f_{xWR}p_{WR}x_R^2}{f_{xWR}p_{c0WR}z_R^2}$	$\pi_{113} = \frac{k_{xWR}\lambda_{xWR}\rho_{WR}g_R z_R \sin\theta_R}{x_R u_{xWR}}$	$\pi_{157} = \frac{HU_t}{u_{gxR}z_R}$
$\pi_{26} = \frac{u_{z0R}}{f_{z0R}U_{zR}}$	$\pi_{70} = \frac{f_{xWR}p_{WR}}{p_{c0GR}}$	$\pi_{114} = \frac{k_{x0R}\lambda_{x0R}p_{0R}}{x_R u_{x0R}}$	$\pi_{158} = \frac{K_{hr}TAt}{L\Delta TM_1 V}$
$\pi_{27} = \frac{u_{xWR}}{f_{xWR}U_{xR}}$	$\pi_{71} = \frac{f_{xWR}p_{WR}x_R^2}{p_{c0GR}z_R^2}$	$\pi_{115} = \frac{k_{x0R}\lambda_{x0R}\rho_{0R}g_R z_R \sin\theta_R}{x_R u_{x0R}}$	$\pi_{159} = \frac{K_{hr}TAt}{L\Delta TM_1 V}$
$\pi_{28} = \frac{u_{zWR}}{f_{zWR}U_{zR}}$	$\pi_{72} = \frac{f_{xWR}p_{c0WR}}{p_{c0GR}}$	$\pi_{116} = \frac{k_{xgR}\lambda_{xgR}p_{gR}}{x_R u_{xgR}}$	$\pi_{160} = \frac{tC_{p0}\rho_0 u_{ox}A}{M_1 V}$
$\pi_{29} = \frac{u_{xgR}}{f_{xgR}U_{xR}}$	$\pi_{73} = \frac{f_{xWR}p_{c0WR}x_R^2}{p_{c0GR}z_R^2}$	$\pi_{117} = \frac{k_{xgR}\lambda_{xgR}\rho_{gR}g_R z_R \sin\theta_R}{x_R u_{xgR}}$	$\pi_{161} = \frac{tC_{pw}\rho_w u_{wx}A}{M_1 V}$
$\pi_{30} = \frac{f_{x0R}}{f_{xgR}}$	$\pi_{74} = \frac{f_{z0R}p_{WR}x_R^2}{p_{c0WR}z_R^2}$	$\pi_{118} = \frac{k_{zWR}\lambda_{zWR}p_{WR}}{z_R u_{zWR}}$	$\pi_{162} = \frac{tC_{p0}\rho_0 \phi S_0 v_x A}{M_1 V}$
$\pi_{31} = \frac{f_{xWR}}{f_{xgR}}$	$\pi_{75} = \frac{f_{z0R}p_{WR}}{p_{c0GR}}$	$\pi_{119} = \frac{k_{zWR}\lambda_{zWR}\rho_{WR}g_R z_R \sin\theta_R}{z_R u_{zWR}}$	$\pi_{163} = \frac{tC_{pw}\rho_w \phi S_w v_x A}{M_1 V}$
$\pi_{32} = \frac{u_{zgR}}{f_{zgR}U_{zR}}$	$\pi_{76} = \frac{f_{z0R}p_{WR}x_R^2}{p_{c0WR}z_R^2}$	$\pi_{120} = \frac{k_{z0R}\lambda_{z0R}p_{0R}}{z_R u_{z0R}}$	$\pi_{164} = \frac{(1-\phi)C_{pr}t\rho_r v_x A}{\Delta TM_1 V}$
$\pi_{33} = \frac{f_{z0R}}{f_{zgR}}$	$\pi_{77} = \frac{f_{z0R}p_{WR}}{p_{c0GR}}$	$\pi_{121} = \frac{k_{z0R}\lambda_{z0R}\rho_{0R}g_R z_R \sin\theta_R}{z_R u_{z0R}}$	$\pi_{165} = \frac{m_s f_s L_v t}{\Delta TM_1 V}$
$\pi_{34} = \frac{f_{zWR}}{f_{zgR}}$	$\pi_{78} = \frac{f_{z0R}p_{WR}x_R^2}{p_{c0GR}z_R^2}$	$\pi_{122} = \frac{k_{zgR}\lambda_{zgR}p_{WR}}{z_R u_{zgR}}$	$\pi_{166} = \frac{m_s C_{pw} t}{M_1 V}$
$\pi_{35} = \frac{\eta_{0R}p_{WR}}{\Gamma(1-\alpha)t_R^{\alpha-1}\phi_R s_{WR}x_R^2}$	$\pi_{79} = \frac{f_{z0R}p_{c0WR}}{p_{c0GR}}$	$\pi_{123} = \frac{k_{zgR}\lambda_{zgR}\rho_{gR}g_R z_R \sin\theta_R}{z_R u_{zgR}}$	$\pi_{167} = \frac{(1-\phi)\rho_r C_{pr}}{M_1}$

$\pi_{36} = \frac{\eta_{WR} p_{WR}}{\Gamma(1-\alpha) t_R^{\alpha-1} \phi_R S_{WR} x_R^2}$	$\pi_{80} = \frac{f_{xOR} p_{cOWR} x_R^2}{p_{cgoR} z_R^2}$	$\pi_{124} = \frac{\sigma_{owR} J_R(S_w) \cos \theta_R \sqrt{\frac{\phi_R}{k_R}}}{p_{cOWR}}$	$\pi_{168} = \frac{\phi C_{pw} \rho_w S_w}{M_1}$
$\pi_{37} = \frac{\eta_{gR} p_{WR}}{\Gamma(1-\alpha) t_R^{\alpha-1} \phi_R S_{WR} x_R^2}$	$\pi_{81} = \frac{f_{xWR} p_{WR}}{p_{cOWR}}$	$\pi_{125} = \frac{\sigma_{goR} J_R(S_g) \cos \theta_R \sqrt{\frac{\phi_R}{k_R}}}{p_{cgoR}}$	$\pi_{169} = \frac{\phi C_{po} \rho_o S_o}{M_1}$
$\pi_{38} = \frac{f_{xOR} \eta_{OR} p_{WR}}{\Gamma(1-\alpha) t_R^{\alpha-1} \phi_R S_{WR} x_R^2}$	$\pi_{82} = \frac{f_{xWR} x_R^2}{z_R^2}$	$\pi_{126} = \frac{S_{OR}}{S_{WR}}$	$\pi_{170} = \frac{\phi C_{pg} \rho_g S_g}{M_1}$
$\pi_{39} = \frac{f_{xOR} \eta_{WR} p_{WR}}{\Gamma(1-\alpha) t_R^{\alpha-1} \phi_R S_{WR} x_R^2}$	$\pi_{83} = \frac{f_{xWR} p_{WR} x_R^2}{f_{xWR} p_{cOWR} z_R^2}$	$\pi_{127} = \frac{S_{gR}}{S_{WR}}$	$\pi_{171} = \frac{\phi L_v \rho_g S_g}{M_1 \Delta T}$
$\pi_{40} = \frac{f_{xOR} \eta_{gR} p_{WR}}{\Gamma(1-\alpha) t_R^{\alpha-1} \phi_R S_{WR} x_R^2}$	$\pi_{84} = \frac{f_{xWR} p_{WR}}{p_{cgoR}}$	$\pi_{128} = \frac{S_o - S_{or}}{1 - S_{wi} - S_{or}}$	$\pi_{172} = \frac{K_{hw} S_w}{K_{hf}}$
$\pi_{41} = \frac{f_{xWR} \eta_{OR} p_{WR}}{\Gamma(1-\alpha) t_R^{\alpha-1} \phi_R S_{WR} x_R^2}$	$\pi_{85} = \frac{f_{xWR} p_{WR} x_R^2}{p_{cgoR} z_R^2}$	$\pi_{129} = \frac{S_w - S_{wi}}{1 - S_{wi} - S_{or}}$	$\pi_{173} = \frac{K_{ho} S_o}{K_{hf}}$
$\pi_{42} = \frac{f_{xWR} \eta_{WR} p_{WR}}{\Gamma(1-\alpha) t_R^{\alpha-1} \phi_R S_{WR} x_R^2}$	$\pi_{86} = \frac{f_{xWR} p_{cOWR}}{p_{cgoR}}$	$\pi_{130} = \frac{S_g - S_{gc}}{1 - S_{wi} - S_{or}}$	$\pi_{174} = \frac{K_{hg} S_g}{K_{hf}}$
$\pi_{43} = \frac{f_{xWR} \eta_{gR} p_{WR}}{\Gamma(1-\alpha) t_R^{\alpha-1} \phi_R S_{WR} x_R^2}$	$\pi_{87} = \frac{f_{xWR} p_{cOWR} x_R^2}{p_{cgoR} z_R^2}$	$\pi_{131} = \frac{U_t t}{L \phi (1 - S_{wi} - S_{or})}$	$\pi_{175} = \frac{\phi K_{hf}}{K_{he}}$
$\pi_{44} = \frac{\eta_{OR} p_{cOWR}}{\Gamma(1-\alpha) t_R^{\alpha-1} \phi_R S_{WR} x_R^2}$	$\pi_{88} = \frac{\eta_{OR} p_{WR}}{\Gamma(1-\alpha) t_R^{\alpha-1} \phi_R S_{WR} z_R^2}$	$\pi_{132} = \frac{S_{wi}}{S_{wD}}$	$\pi_{176} = \frac{(1-\phi) K_{hr}}{K_{he}}$

3.4 Approaches to satisfy scaling groups

The dimensionless groups derived in the previous section should be satisfied with the scaling process which is governed by the governing equations, initial and boundary conditions, constitutive relationships, and constraints. The similarity groups should be analogous in model and prototype. It is very difficult to satisfy a complete set of scaling criteria, so several groups should be rested to fulfill the scaling criteria. Figure 3.2 describes the different approaches to satisfy a specific process. These approaches are applicable for high-pressure reservoir fluids where both reservoir pressure-temperature conditions and different pressure-temperature conditions are used. Approach 2, 3 and 4 are used for porous reservoir medium with reservoir pressure, temperature conditions and approach 1 and 5 are applicable for other pressure, temperature conditions.

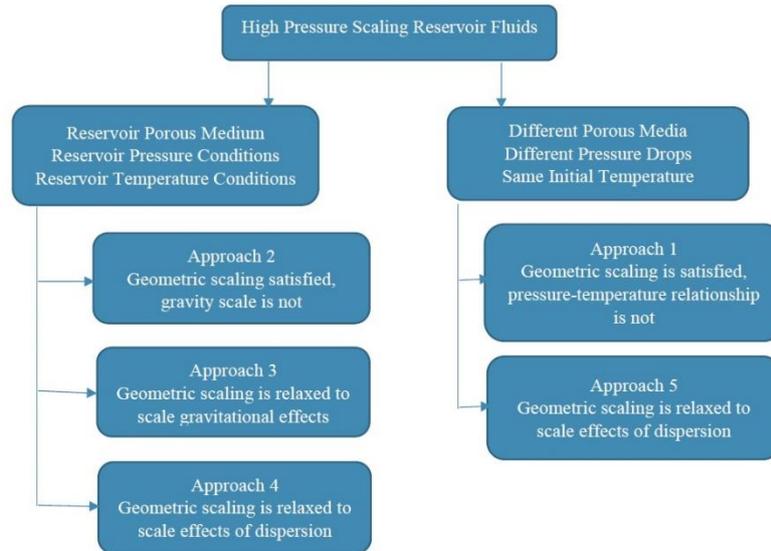


Figure 3.2: Scaling Approaches

Approach 1 same fluid, different porous media, different pressure drop, and geometric similarity

Geometric similarity groups can be satisfied by considering pressure drop, gravitational and viscous forces which are different for model and prototype. This condition requires different porous media. Pujol and Boberg (1972) proposed this approach which allows scaling requirements should be satisfied if violates some constitutive relationships, constraints, and boundary conditions. Saturation pressure and saturation temperature relationship for steam flooding process cannot be properly scaled by this method, which will ultimately mislead the heat losses from the steam zone. Different steam properties which largely depend on pressure will not be scaled properly. As different porous medium is considered, so the fluid saturations and relative permeability are not scaled accurately. In addition, capillary forces and dispersion effects are not properly scaled.

The implementation of these scaling criteria for a model can reduce the length by a scaling factor of a .

1. The value of ϕ , s_w , s_o , s_g , E_w , E_g , T , ΔT remain same
2. The values of H , Δp should be reduced by a factor of a
3. The value of k should be increased by a factor of a
4. The value of t should be reduced by a factor of a^2

If the gravitational force is important, then this technique is suitable only for the steam flooding process. This approach is unable to scale additive accurately. Relaxed and satisfied scaling groups are given in table 3.3.

Approach 2 same fluids, same pressure drop, same porous medium, geometric similarity

The difficulties raised in approach 1 should be overcome by considering the maximum pressure and temperature difference, and the initial pressure and temperature are same for model and prototype. This assumption has allowed the properties to depend on pressure and temperature which are properly scaled. As the same porous medium is used here, so the fluid saturations and relative permeabilities are properly scaled. In addition, viscous forces, diffusion effects, and heat transfers are properly scaled due to these changes. The limitation of this approach is that it cannot accurately scale gravitational forces. Another limitation is that it cannot scale dispersion effects if the flow rate is very high.

The implementation of these scaling criteria for a model can reduce the length by a scaling factor of ‘ a ’.

1. The value of ϕ , s_w , s_o , s_g , Δp , T , ΔT remain same.
2. The values of H , U_t should be reduced by a factor of a
3. The value of t should be reduced by a factor of $a^{\left(\frac{2}{\alpha-1}\right)}$

This approach is restricted to processes where the gravitational force is not much important such as thin formations with high flow rates. Diffusion effects and PVT properties are scaled well for steam flooding with additives. Relaxed and satisfied scaling groups are given in table 3.3.

Approach 3 same fluids, same pressure drop, same porous media, relaxed geometric similarity

The advantage of using same porous medium, same fluid and similar pressure and temperature conditions help to scale gravitational forces properly but allows the geometric similarity to be relaxed. If the pressure gradient is low due to capillary and viscous forces, then capillary and viscous forces can be scaled for the horizontal well. The vertical direction heat conduction, dispersion effects, and capillary number are not properly scaled.

The implementation of these scaling criteria for a model can reduce the length by a scaling factor of ‘ a ’. The value of ϕ , s_w , s_o , s_g , Δp , p_{wR} , T , ΔT remain same

1. The values of H should be reduced by a factor of ‘ a ’
2. The reservoir should be horizontal
3. The value of t should be reduced by a factor of $a^{\left(\frac{2}{\alpha-1}\right)}$

This approach is restricted to steam and steam additive processes where a significant reduction of reservoir thickness is considered. Relaxed and satisfied scaling groups are given in table 3.3.

Approach 4, same fluids, same porous media, same pressure drop, relaxed geometric similarity

The previous approaches had been not attempted to consider the dispersion effect for the case of high flow rates scaling. It is difficult to scale dispersion effects. This approach objective is to scale transverse dispersion effects. Gravitational and capillary effects are not properly scaled, but viscous and dispersion effects are scaled properly. The merit of this approach is to satisfy all other dimensionless numbers and boundary conditions except capillary and gravity forces. This rigorous method is not suitable when considering the scaling of steam flooding process.

The implementation of these scaling criteria for a model can reduce the length by a scaling factor of ‘ a ’.

1. The value of ϕ , s_w , s_o , s_g , Δp , p_{wR} , T , ΔT , k remain same
2. The values of H should be reduced by a factor of a
3. The values of U_t should be reduced by a factor of $a^{\left(\frac{1}{2}\right)}$
4. The value of t should be reduced by a factor of a^2

This approach is restricted to a process where dispersion effects are considered by relaxing gravitational forces. Hot water flooding with a liquid additive is a good option for this approach. In addition, this approach is restricted to thin formations because only small reduction in thickness is considered. Relaxed and satisfied scaling groups are given in table 3.3.

Approach 5 same fluid, different pressure drops, different porous media, relaxed geometric similarity

The main shortcoming of approach 4 is the relaxation of gravitational forces, but this approach tries to satisfy viscous and gravitational forces while still scaling transverse dispersion effects. As different porous medium and different pressure drop are used, the limitation of approach 1 comes into place. Here, time is scaled by a four-fifth power of the scaling factor rather than squares indicating the longer period of experimental time. Capillary forces and heat conduction are not properly scaled. In addition, saturation pressure and boundary temperature for steam flood is poorly scaled. Relaxed and satisfied scaling groups are given in table 3.3.

The implementation of these scaling criteria for a model can reduce the length by a scaling factor of ' a '.

1. The value of ϕ , s_w , s_o , s_g , T , ΔT remain same
2. The values of H should be reduced by a factor of a
3. The values of k should be increased by a factor of a
4. The value of t should be reduced by a factor of a^2

3.5. Comparison of different scaling approaches

Table 2.3 lists dimensionless numbers and how their effects can change the model for steam flooding process. Numerous previous researchers used scaling approach 1 to scale viscous to gravitational force. This approach can precisely have scaled the ratio of viscous to gravitation forces, but it had faced difficulty in scaling saturation temperature, saturation pressure, steam injection rate, steam density, the energy stored in the steam phase and latent heat of vaporization. As different porous medium is used, the relative permeabilities and irreducible saturations can alter also.

Approach 2 would be considered a suitable approach for the steam flooding process where gravitational does not play a vital role. When the process is dominated by viscous force, then this approach comes into play a vital role. The effects of gravitational force have been reduced in the model by employing this approach. When this approach creates a significant error under certain conditions which are not studied well, it is restricted to certain conditions for steam flooding process. In a study of immiscible isothermal displacement of heavy oil by CO₂ flooding, Rojas (1985) found that the recovery of oil is independent of model prototype ratio

when gravitational to viscous forces ratio is less than 5. There should have an upper and lower limit for this approach. The upper limit may represent a point where dispersion effects can be scaled more effectively. On the other hand, the lower limit of gravitational forces can be scaled more rigorously.

Approach 3 may overcome the limitations of approach 1. As the same fluid and same porous medium is used, thus it can ensure the irreducible saturations, and relative permeabilities can be scaled properly. It can also properly scale saturation temperature, saturation pressure, steam injection rate, steam density, the energy stored in the steam phase and latent heat of vaporization. This approach cannot scale capillary forces along with the vertical conduction of energy. Baker (1969, 1973) investigated that the heat losses are a function of time only, it does not depend on injection rate. The effect of transverse dispersion effects will be enhanced in the model.

Approach 4 may scale the transverse dispersion effects, but gravitational and capillary forces aren't properly scaled. It cannot scale vertical conduction of energy properly. The scaling requirements of irreducible saturations, relative permeabilities, steam density, heat stored in steam, saturation temperature-saturation pressure relationship and injection temperature are satisfied.

Approach 5 may satisfy the requirements for gravitational forces and balanced it with dispersive and viscous forces. However, it has several drawbacks like other approaches. It has required a significant reduction in pressure drop as well as a reduction in time scale factor to satisfy the scale conduction. Therefore, approach 5 may be poorly scaled conduction.

The various aspects of recovery are largely depended on the selection of appropriate approaches. The selection of appropriate approach is particularly depended on the properties which are involved within this approach. In approach 2, 3 and 4 same fluid, same pressure drops, and the same porous medium are used, but the temperature change has a significant effect in simulating these properties even though they have not been properly scaled. There are some important phenomena such as gas solubility, emulsification, distillation, etc. which are not considered here during scaling. The significance of a phenomenon is used as a selection criterion which is not scaled by the selected approach. If capillary force is a prime factor for a process, it is unlikely that approach 3 and approach 4 would be satisfied. Similarly, for the case of gravitational forces, approach 2 and approach 4 would not be satisfied. Another issue is the selection of relative significance of a phenomenon. If a phenomenon is considered insignificant

for a process, it should remain insignificant in the model also. For selecting a scaling process, the effects of transverse dispersion are considered to be minor in prototype for the case of approach 3. If it remains insignificant in the model, then it would be considered as a suitable approach for this process.

Table 3.3: Influence of different dimensionless groups on each approach.

Dimensionless Groups	Approaches					Dimensionless Groups	Approaches				
	1	2	3	4	5		1	2	3	4	5
$\pi_1 = \frac{t_R u_{xWR}}{\phi x_R s_{WR}}$	×	↓a	√	√	×	$\pi_{89} = \frac{\eta_{WR} P_{WR}}{\Gamma(1-\alpha) t_R^{\alpha-1} \phi_R s_{WR} z_R^2}$	×	√	√	√	×
$\pi_2 = \frac{t_R u_{zWR}}{\phi z_R s_{WR}}$	×	↓a	√		×	$\pi_{90} = \frac{\eta_{GR} P_{WR}}{\Gamma(1-\alpha) t_R^{\alpha-1} \phi_R s_{WR} z_R^2}$	×	√	√	√	×
$\pi_3 = \frac{D_{LW1R} t_R}{x_R^2 s_{WR}}$	×	×	×	√	×	$\pi_{91} = \frac{f_{xOR} \eta_{OR} P_{WR}}{\Gamma(1-\alpha) t_R^{\alpha-1} \phi_R s_{WR} z_R^2}$	×	↓a ² / _{α-1}	↓a ² / _{α-1}	√	×
$\pi_4 = \frac{D_{TW1R} t_R}{z_R^2 s_{WR}}$	×	×	↑	√	×	$\pi_{92} = \frac{f_{xOR} \eta_{WR} P_{WR}}{\Gamma(1-\alpha) t_R^{\alpha-1} \phi_R s_{WR} z_R^2}$	×	↓a ² / _{α-1}	↓a ² / _{α-1}	√	×
$\pi_5 = \frac{D_{LW3R} t_R}{x_R^2 s_{WR}}$	×	×	×	√	×	$\pi_{93} = \frac{f_{xOR} \eta_{GR} P_{WR}}{\Gamma(1-\alpha) t_R^{\alpha-1} \phi_R s_{WR} z_R^2}$	×	↓a ² / _{α-1}	↓a ² / _{α-1}	√	×
$\pi_6 = \frac{D_{TW3R} t_R}{z_R^2 s_{WR}}$	×	×	↑	√	×	$\pi_{94} = \frac{f_{xWR} \eta_{OR} P_{WR}}{\Gamma(1-\alpha) t_R^{\alpha-1} \phi_R s_{WR} z_R^2}$	×	↓a ² / _{α-1}	↓a ² / _{α-1}	√	×
$\pi_7 = \frac{D_{LW4R} t_R}{x_R^2 s_{WR}}$	×	×	×	√	×	$\pi_{95} = \frac{f_{xWR} \eta_{WR} P_{WR}}{\Gamma(1-\alpha) t_R^{\alpha-1} \phi_R s_{WR} z_R^2}$	×	↓a ² / _{α-1}	↓a ² / _{α-1}	√	×
$\pi_8 = \frac{D_{TW4R} t_R}{z_R^2 s_{WR}}$	×	×	↑	√	×	$\pi_{96} = \frac{f_{xWR} \eta_{GR} P_{WR}}{\Gamma(1-\alpha) t_R^{\alpha-1} \phi_R s_{WR} z_R^2}$	×	↓a ² / _{α-1}	↓a ² / _{α-1}	√	×
$\pi_9 = \frac{t_R u_{xOR}}{\phi x_R s_{OR}}$	×	↓a	√	√	×	$\pi_{97} = \frac{\eta_{OR} P_{COWR}}{\Gamma(1-\alpha) t_R^{\alpha-1} \phi_R s_{WR} z_R^2}$	×	√	√	√	×
$\pi_{10} = \frac{t_R u_{zOR}}{\phi z_R s_{OR}}$	×	↓a	√	√	×	$\pi_{98} = \frac{\eta_{GR} P_{COWR}}{\Gamma(1-\alpha) t_R^{\alpha-1} \phi_R s_{WR} z_R^2}$	×	√	√	√	×
$\pi_{11} = \frac{D_{LO1R} t_R}{x_R^2 s_{OR}}$	×	×	×	√	×	$\pi_{99} = \frac{f_{xOR} \eta_{OR} P_{COWR}}{\Gamma(1-\alpha) t_R^{\alpha-1} \phi_R s_{WR} z_R^2}$	×	√	√	√	×
$\pi_{12} = \frac{D_{TO1R} t_R}{z_R^2 s_{OR}}$	×	×	↑	√	×	$\pi_{100} = \frac{f_{xOR} \eta_{GR} P_{COWR}}{\Gamma(1-\alpha) t_R^{\alpha-1} \phi_R s_{WR} z_R^2}$	×	√	√	√	×
$\pi_{13} = \frac{D_{LO2R} t_R}{x_R^2 s_{OR}}$	×	×	×	√	×	$\pi_{101} = \frac{f_{xWR} \eta_{OR} P_{COWR}}{\Gamma(1-\alpha) t_R^{\alpha-1} \phi_R s_{WR} z_R^2}$	×	√	√	√	×
$\pi_{14} = \frac{D_{TO2R} t_R}{z_R^2 s_{OR}}$	×	×	↑	√	×	$\pi_{102} = \frac{f_{xWR} \eta_{GR} P_{COWR}}{\Gamma(1-\alpha) t_R^{\alpha-1} \phi_R s_{WR} z_R^2}$	×	√	√	√	×

$\pi_{15} = \frac{D_{LO4R}t_R}{x_R^2 S_{OR}}$	×	×	×	√	×	$\pi_{103} = \frac{\eta_{gR} p_{cgoR}}{\Gamma(1-\alpha)t_R^{\alpha-1}\phi_R S_{WR} Z_R^2}$	×	√	√	√	×
$\pi_{16} = \frac{D_{TO4R}t_R}{z_R^2 S_{OR}}$	×	×	↑	√	×	$\pi_{104} = \frac{f_{xoR}\eta_{gR} p_{cgoR}}{\Gamma(1-\alpha)t_R^{\alpha-1}\phi_R S_{WR} Z_R^2}$	×	√	√	√	×
$\pi_{17} = \frac{u_{xgR}t_R}{\phi x_R S_{gR}}$	×	↓a	√	√	×	$\pi_{105} = \frac{f_{xwR}\eta_{gR} p_{cgoR}}{\Gamma(1-\alpha)t_R^{\alpha-1}\phi_R S_{WR} Z_R^2}$	×	√	√	√	×
$\pi_{18} = \frac{u_{zgR}t_R}{\phi z_R S_{gR}}$	×	↓a	√	√	×	$\pi_{106} = \frac{t_R D_{LW1R}}{S_{WR} x_R^2}$	×	×	×	√	×
$\pi_{19} = \frac{u_{xoR}}{U_{xR}}$	√	↓a	√	√	√	$\pi_{107} = \frac{t_R D_{LW3R}}{S_{WR} z_R^2}$	×	×	×	√	×
$\pi_{20} = \frac{u_{xwR}}{U_{xR}}$	√	↓a	√	√	√	$\pi_{108} = \frac{t_R D_{LW4R}}{S_{WR} x_R^2}$	×	×	×	√	×
$\pi_{21} = \frac{u_{xgR}}{U_{xR}}$	√	↓a	√	√	√	$\pi_{109} = \frac{t_R D_{TW1R}}{S_{WR} z_R^2}$	×	×	↑	√	×
$\pi_{22} = \frac{u_{zoR}}{U_{zR}}$	√	↓a	√	√	√	$\pi_{110} = \frac{t_R D_{TW3R}}{S_{WR} z_R^2}$	×	×	↑	√	×
$\pi_{23} = \frac{u_{zwR}}{U_{zR}}$	√	↓a	√	√	√	$\pi_{111} = \frac{t_R D_{TW4R}}{S_{WR} z_R^2}$	×	×	↑	√	×
$\pi_{24} = \frac{u_{zgR}}{U_{zR}}$	√	↓a	√	√	√	$\pi_{112} = \frac{k_{xwR}\lambda_{xwR}p_{wR}}{x_R u_{xwR}}$	↑a	√	√	√	↑a
$\pi_{25} = \frac{u_{xoR}}{f_{xoR}U_{xR}}$	√	√	√	√	√	$\pi_{113} = \frac{k_{xwR}\lambda_{xwR}\rho_{wR}g_R z_R \sin\theta_R}{x_R u_{xwR}}$	↑a	×	√	×	↑a
$\pi_{26} = \frac{u_{zoR}}{f_{zoR}U_{zR}}$	√	√	√	√	√	$\pi_{114} = \frac{k_{xoR}\lambda_{xoR}p_{oR}}{x_R u_{xoR}}$	↑a	√	√	√	↑a
$\pi_{27} = \frac{u_{xwR}}{f_{xwR}U_{xR}}$	√	√	√	√	√	$\pi_{115} = \frac{k_{xoR}\lambda_{xoR}\rho_{oR}g_R z_R \sin\theta_R}{x_R u_{xoR}}$	↑a	×	√	×	↑a
$\pi_{28} = \frac{u_{zwR}}{f_{zwR}U_{zR}}$	√	√	√	√	√	$\pi_{116} = \frac{k_{xgR}\lambda_{xgR}p_{gR}}{x_R u_{xgR}}$	↑a	√	√	√	↑a
$\pi_{29} = \frac{u_{xgR}}{f_{xgR}U_{xR}}$	√	√	√	√	√	$\pi_{117} = \frac{k_{xgR}\lambda_{xgR}\rho_{gR}g_R z_R \sin\theta_R}{x_R u_{xgR}}$	↑a	×	√	×	↑a
$\pi_{30} = \frac{f_{xoR}}{f_{xgR}}$	√	√	√	√	√	$\pi_{118} = \frac{k_{zwR}\lambda_{zwR}p_{wR}}{z_R u_{zwR}}$	↑a	√	√	√	↑a
$\pi_{31} = \frac{f_{xwR}}{f_{xgR}}$	√	√	√	√	√	$\pi_{119} = \frac{k_{zwR}\lambda_{zwR}\rho_{wR}g_R z_R \sin\theta_R}{z_R u_{zwR}}$	↑a	×	√	×	↑a
$\pi_{32} = \frac{u_{zgR}}{f_{zgR}U_{zR}}$	√	√	√	√	√	$\pi_{120} = \frac{k_{zoR}\lambda_{zoR}p_{oR}}{z_R u_{zoR}}$	↑a	√	√	√	↑a
$\pi_{33} = \frac{f_{zoR}}{f_{zgR}}$	√	√	√	√	√	$\pi_{121} = \frac{k_{zoR}\lambda_{zoR}\rho_{oR}g_R z_R \sin\theta_R}{z_R u_{zoR}}$	↑a	×	√	×	↑a
$\pi_{34} = \frac{f_{zwR}}{f_{zgR}}$	√	√	√	√	√	$\pi_{122} = \frac{k_{zgR}\lambda_{zgR}p_{wR}}{z_R u_{zgR}}$	↑a	×	√	√	↑a
$\pi_{35} = \frac{\eta_{oR}p_{wR}}{\Gamma(1-\alpha)t_R^{\alpha-1}\phi_R S_{WR} x_R^2}$	×	√	√	√	×	$\pi_{123} = \frac{k_{zgR}\lambda_{zgR}\rho_{gR}g_R z_R \sin\theta_R}{z_R u_{zgR}}$	↑a	×	√	×	↑a

$\pi_{36} = \frac{\eta_{WR} p_{WR}}{\Gamma(1-\alpha)t_R^{\alpha-1}\phi_R s_{WR} x_R^2}$	x	✓	✓	✓	x	$\pi_{124} = \frac{\sigma_{oWR} J_R(s_w) \cos\theta_R \sqrt{\frac{\phi_R}{k_R}}}{p_{cOWR}}$	x	✓	x	x	x
$\pi_{37} = \frac{\eta_{GR} p_{WR}}{\Gamma(1-\alpha)t_R^{\alpha-1}\phi_R s_{WR} x_R^2}$	x	✓	✓	✓	x	$\pi_{125} = \frac{\sigma_{goR} J_R(s_g) \cos\theta_R \sqrt{\frac{\phi_R}{k_R}}}{p_{cgoR}}$	x	✓	x	x	x
$\pi_{38} = \frac{f_{xOR}\eta_{OR}p_{WR}}{\Gamma(1-\alpha)t_R^{\alpha-1}\phi_R s_{WR} x_R^2}$	x	$\downarrow a^{\frac{2}{\alpha-1}}$	$\downarrow a^{\frac{2}{\alpha-1}}$	✓	x	$\pi_{126} = \frac{s_{oR}}{s_{wR}}$	x	✓	✓	✓	x
$\pi_{39} = \frac{f_{xOR}\eta_{WR}p_{WR}}{\Gamma(1-\alpha)t_R^{\alpha-1}\phi_R s_{WR} x_R^2}$	x	$\downarrow a^{\frac{2}{\alpha-1}}$	$\downarrow a^{\frac{2}{\alpha-1}}$	✓	x	$\pi_{127} = \frac{s_{gR}}{s_{wR}}$	x	✓	✓	✓	x
$\pi_{40} = \frac{f_{xOR}\eta_{GR}p_{WR}}{\Gamma(1-\alpha)t_R^{\alpha-1}\phi_R s_{WR} x_R^2}$	x	$\downarrow a^{\frac{2}{\alpha-1}}$	$\downarrow a^{\frac{2}{\alpha-1}}$	✓	x	$\pi_{128} = \frac{s_o - s_{or}}{1 - s_{wi} - s_{or}}$	x	✓	✓	✓	x
$\pi_{41} = \frac{f_{xWR}\eta_{OR}p_{WR}}{\Gamma(1-\alpha)t_R^{\alpha-1}\phi_R s_{WR} x_R^2}$	x	$\downarrow a^{\frac{2}{\alpha-1}}$	$\downarrow a^{\frac{2}{\alpha-1}}$	✓	x	$\pi_{129} = \frac{s_w - s_{wi}}{1 - s_{wi} - s_{or}}$	x	✓	✓	✓	x
$\pi_{42} = \frac{f_{xWR}\eta_{WR}p_{WR}}{\Gamma(1-\alpha)t_R^{\alpha-1}\phi_R s_{WR} x_R^2}$	x	$\downarrow a^{\frac{2}{\alpha-1}}$	$\downarrow a^{\frac{2}{\alpha-1}}$	✓	x	$\pi_{130} = \frac{s_g - s_{gc}}{1 - s_{wi} - s_{or}}$	x	✓	✓	✓	x
$\pi_{43} = \frac{f_{xWR}\eta_{GR}p_{WR}}{\Gamma(1-\alpha)t_R^{\alpha-1}\phi_R s_{WR} x_R^2}$	x	$\downarrow a^{\frac{2}{\alpha-1}}$	$\downarrow a^{\frac{2}{\alpha-1}}$	✓	x	$\pi_{131} = \frac{U_t t}{L\phi(1 - s_{wi} - s_{or})}$	$\downarrow a^2$				
$\pi_{44} = \frac{\eta_{OR} p_{cOWR}}{\Gamma(1-\alpha)t_R^{\alpha-1}\phi_R s_{WR} x_R^2}$	x	✓	✓	✓	x	$\pi_{132} = \frac{s_{wi}}{s_{wD}}$	x	✓	✓	✓	x
$\pi_{45} = \frac{\eta_{GR} p_{cOWR}}{\Gamma(1-\alpha)t_R^{\alpha-1}\phi_R s_{WR} x_R^2}$	x	✓	✓	✓	x	$\pi_{133} = \frac{s_{gi}}{s_{gR}}$	x	✓	✓	✓	x
$\pi_{46} = \frac{f_{xOR}\eta_{OR}p_{cOWR}}{\Gamma(1-\alpha)t_R^{\alpha-1}\phi_R s_{WR} x_R^2}$	x	✓	✓	✓	x	$\pi_{134} = \frac{s_{oi}}{s_{oR}}$	x	✓	✓	✓	x
$\pi_{47} = \frac{f_{xOR}\eta_{GR}p_{cOWR}}{\Gamma(1-\alpha)t_R^{\alpha-1}\phi_R s_{WR} x_R^2}$	x	✓	✓	✓	x	$\pi_{135} = \frac{E_{2i}}{E_{o2R}}$	x	x	x	✓	✓
$\pi_{48} = \frac{f_{xWR}\eta_{OR}p_{cOWR}}{\Gamma(1-\alpha)t_R^{\alpha-1}\phi_R s_{WR} x_R^2}$	x	✓	✓	✓	x	$\pi_{136} = \frac{E_{3i}}{E_{w3R}}$	x	x	x	✓	✓
$\pi_{49} = \frac{f_{xWR}\eta_{GR}p_{cOWR}}{\Gamma(1-\alpha)t_R^{\alpha-1}\phi_R s_{WR} x_R^2}$	x	✓	✓	✓	x	$\pi_{137} = \frac{E_{1j}}{E_{g1R}}$	x	x	x	✓	✓
$\pi_{50} = \frac{\eta_{GR} p_{cgoR}}{\Gamma(1-\alpha)t_R^{\alpha-1}\phi_R s_{WR} x_R^2}$	x	✓	✓	✓	x	$\pi_{138} = \frac{E_{4j}}{E_{w4R}}$	x	x	x	✓	✓
$\pi_{51} = \frac{f_{xOR}\eta_{GR}p_{cgoR}}{\Gamma(1-\alpha)t_R^{\alpha-1}\phi_R s_{WR} x_R^2}$	x	✓	✓	✓	x	$\pi_{139} = \frac{\Delta p_{gR}}{p_{gR}}$	x	✓	✓	✓	✓
$\pi_{52} = \frac{f_{xWR}\eta_{GR}p_{cgoR}}{\Gamma(1-\alpha)t_R^{\alpha-1}\phi_R s_{WR} x_R^2}$	x	✓	✓	✓	x	$\pi_{140} = \frac{\rho_{gR} g_R H_R}{p_{gR}}$	✓	x	✓	x	✓
$\pi_{53} = \frac{p_{WR}}{p_{cOWR}}$	x	✓	✓	✓	✓	$\pi_{141} = \frac{\rho_{gR} g_R z_R}{p_{gR}}$	✓	x	✓	x	✓
$\pi_{54} = \frac{x_R^2}{z_R^2}$	$\downarrow a$	$\downarrow a$	$\downarrow a$	$\downarrow a$	$\downarrow a$	$\pi_{142} = \frac{\Delta p_{oR}}{p_{oR}}$	x	✓	✓	✓	✓

$\pi_{55} = \frac{P_{WR}X_R^2}{P_{COWR}Z_R^2}$	×	√	√	√	√	$\pi_{143} = \frac{\rho_{OR}g_R H_R}{\rho_{OR}}$	√	×	√	×	√
$\pi_{56} = \frac{P_{WR}}{P_{CGOR}}$	×	√	√	√	√	$\pi_{144} = \frac{\rho_{OR}g_R Z_R}{\rho_{OR}}$	√	×	√	×	√
$\pi_{57} = \frac{P_{WR}X_R^2}{P_{CGOR}Z_R^2}$	×	√	√	√	√	$\pi_{145} = \frac{\Delta P_{WR}}{P_{WR}}$	√	√	√	√	√
$\pi_{58} = \frac{P_{COWR}}{P_{CGOR}}$	×	√	√	√	√	$\pi_{146} = \frac{\rho_{WR}g_R H_R}{P_{WR}}$	√	×	√	×	√
$\pi_{59} = \frac{P_{COWR}X_R^2}{P_{CGOR}Z_R^2}$	×	√	√	√	√	$\pi_{147} = \frac{\rho_{WR}g_R Z_R}{P_{WR}}$	√	×	√	×	√
$\pi_{60} = \frac{f_{XOR}P_{WR}}{P_{COWR}}$	×	√	√	√	√	$\pi_{148} = \frac{HU_t}{u_{gXR}X_R}$	√	√	√	√	√
$\pi_{61} = \frac{f_{XOR}X_R^2}{Z_R^2}$	↓a	√	√	√	√	$\pi_{149} = \frac{Z_R^2 D_{L01R}}{X_R^2 D_{T01R}}$	×	×	×	√	×
$\pi_{62} = \frac{f_{XOR}P_{WR}X_R^2}{P_{COWR}Z_R^2}$	×	√	√	√	√	$\pi_{150} = \frac{Z_R^2 D_{L02R}}{X_R^2 D_{T02R}}$	×	×	×	√	×
$\pi_{63} = \frac{f_{XOR}P_{WR}}{P_{CGOR}}$	×	√	√	√	√	$\pi_{151} = \frac{Z_R^2 D_{L04R}}{X_R^2 D_{T04R}}$	×	×	×	√	×
$\pi_{64} = \frac{f_{XOR}P_{WR}X_R^2}{P_{CGOR}Z_R^2}$	×	√	√	√	√	$\pi_{152} = \frac{Z_R^2 D_{LW1R}}{X_R^2 D_{TW1R}}$	×	×	×	√	×
$\pi_{65} = \frac{f_{XOR}P_{COWR}}{P_{CGOR}}$	×	√	√	√	√	$\pi_{153} = \frac{Z_R^2 D_{LW2R}}{X_R^2 D_{TW2R}}$	×	×	×	√	×
$\pi_{66} = \frac{f_{XOR}P_{COWR}X_R^2}{P_{CGOR}Z_R^2}$	×	√	√	√	√	$\pi_{154} = \frac{Z_R^2 D_{LW4R}}{X_R^2 D_{TW4R}}$	×	×	×	√	×
$\pi_{67} = \frac{f_{XWR}P_{WR}}{P_{COWR}}$	×	√	√	√	√	$\pi_{155} = \frac{H}{Z_R}$	↓a	↓a	↓a	↓a	↓a
$\pi_{68} = \frac{f_{XWR}X_R^2}{Z_R^2}$	↓a	√	√	√	√	$\pi_{156} = \frac{L}{X_R}$	↓a	↓a	↓a	↓a	↓a
$\pi_{69} = \frac{f_{XWR}P_{WR}X_R^2}{f_{XWR}P_{COWR}Z_R^2}$	×	√	√	√	√	$\pi_{157} = \frac{HU_t}{u_{gXR}Z_R}$	√	√	√	√	×
$\pi_{70} = \frac{f_{XWR}P_{WR}}{P_{CGOR}}$	×	√	√	√	√	$\pi_{158} = \frac{K_{hr}TAt}{L\Delta T M_1 V}$	×	√	×	√	×
$\pi_{71} = \frac{f_{XWR}P_{WR}X_R^2}{P_{CGOR}Z_R^2}$	×	√	√	√	√	$\pi_{159} = \frac{K_{hr}TAt}{L\Delta T M_1 V}$	×	√	×	√	×
$\pi_{72} = \frac{f_{XWR}P_{COWR}}{P_{CGOR}}$	×	√	√	√	√	$\pi_{160} = \frac{tC_{p0}\rho_0 u_{ox}A}{M_1 V}$	×	√	×	√	×
$\pi_{73} = \frac{f_{XWR}P_{COWR}X_R^2}{P_{CGOR}Z_R^2}$	×	√	√	√	√	$\pi_{161} = \frac{tC_{pw}\rho_w u_{wx}A}{M_1 V}$	×	√	×	√	×
$\pi_{74} = \frac{f_{ZOR}P_{WR}X_R^2}{P_{COWR}Z_R^2}$	×	√	√	√	√	$\pi_{162} = \frac{tC_{p0}\rho_0 \phi S_o v_x A}{M_1 V}$	×	√	×	√	×
$\pi_{75} = \frac{f_{ZOR}P_{WR}}{P_{CGOR}}$	×	√	√	√	√	$\pi_{163} = \frac{tC_{pw}\rho_w \phi S_w v_x A}{M_1 V}$	×	√	×	√	×
$\pi_{76} = \frac{f_{ZOR}P_{WR}X_R^2}{P_{COWR}Z_R^2}$	×	√	√	√	√	$\pi_{164} = \frac{(1-\phi)C_{pr}t\rho_r v_x A}{\Delta T M_1 V}$	×	√	×	√	×
$\pi_{77} = \frac{f_{ZOR}P_{WR}}{P_{CGOR}}$	×	√	√	√	√	$\pi_{165} = \frac{m_s f_s L_v t}{\Delta T M_1 V}$	×	√	×	√	×

$\pi_{78} = \frac{f_{zOR}P_{WR}X_R^2}{P_{cgoR}Z_R^2}$	×	√	√	√	√	$\pi_{166} = \frac{m_s C_{pw} t}{M_1 V}$	×	√	×	√	×
$\pi_{79} = \frac{f_{zOR}P_{cOWR}}{P_{cgoR}}$	×	√	√	√	√	$\pi_{167} = \frac{(1-\phi)\rho_r C_{pr}}{M_1}$	×	√	×	√	×
$\pi_{80} = \frac{f_{xWR}P_{cOWR}X_R^2}{P_{cgoR}Z_R^2}$	×	√	√	√	√	$\pi_{168} = \frac{\phi C_{pw} \rho_w S_w}{M_1}$	×	√	×	√	×
$\pi_{81} = \frac{f_{xWR}P_{WR}}{P_{cOWR}}$	×	√	√	√	√	$\pi_{169} = \frac{\phi C_{po} \rho_o S_o}{M_1}$	×	√	×	√	×
$\pi_{82} = \frac{f_{xWR}X_R^2}{Z_R^2}$	×	√	√	√	√	$\pi_{170} = \frac{\phi C_{pg} \rho_g S_g}{M_1}$	×	√	×	√	×
$\pi_{83} = \frac{f_{xWR}P_{WR}X_R^2}{f_{xWR}P_{cOWR}Z_R^2}$	×	√	√	√	√	$\pi_{171} = \frac{\phi L_v \rho_g S_g}{M_1 \Delta T}$	×	√	×	√	×
$\pi_{84} = \frac{f_{xWR}P_{WR}}{P_{cgoR}}$	×	√	√	√	√	$\pi_{172} = \frac{K_{hw} S_w}{K_{hf}}$	×	√	×	√	×
$\pi_{85} = \frac{f_{xWR}P_{WR}X_R^2}{P_{cgoR}Z_R^2}$	×	√	√	√	√	$\pi_{173} = \frac{K_{ho} S_o}{K_{hf}}$	×	√	×	√	×
$\pi_{86} = \frac{f_{xWR}P_{cOWR}}{P_{cgoR}}$	×	√	√	√	√	$\pi_{174} = \frac{K_{hg} S_g}{K_{hf}}$	×	√	×	√	×
$\pi_{87} = \frac{f_{xWR}P_{cOWR}X_R^2}{P_{cgoR}Z_R^2}$	×	√	√	√	√	$\pi_{175} = \frac{\phi K_{hf}}{K_{he}}$	×	√	×	√	×
$\pi_{88} = \frac{\eta_{OR} P_{WR}}{\Gamma(1-\alpha) t_R^{\alpha-1} \phi_R S_{WR} Z_R^2}$	×	√	√	√	×	$\pi_{176} = \frac{(1-\phi) K_{hr}}{K_{he}}$	×	√	×	√	×

√ indicates the dimensionless group is satisfied for scaling criteria development process

×

↓ indicates the group is reduced for scaling criteria development process

↑ indicates the group is increased for scaling criteria development process

α indicate the dimension of scaling factor by which the model is reduced from prototype.

Conclusions

A complete set of dimensionless groups is derived from steam flooding process using dimensional and inspectional analysis. Modified Darcy equation incorporating rock and fluid memory, constitutive relationships, constraints, initial and boundary conditions have been developed. All the requirements should not be satisfied with a process, so some of the groups should be relaxed. Five sets of scaling criteria are selected, and each set consists of variables for satisfying the scaling criteria by relaxing different scaling phenomena. The different approaches selected different parameters to be relaxed to satisfy the specific requirements. For example, vertical geometry scale is relaxed to satisfy the viscous and gravitational forces using the concept of same fluid and same porous medium. Selecting the appropriate approach to use

is largely depend on the specific process being modeled. To choose a proper approach two main factors have to be considered. First, the selection of major mechanism should be correctly scaled. Second, minor mechanism should not have the significant effect on selected approach. The best way to select a suitable approach is the comparison of different approaches. This comparison indicates which mechanism is scaled and which are not with an order of degree. This study will help to select an appropriate steam flooding technique with the minimum number of most influential dimensionless scaling groups.

Acknowledgements

The authors would like to thank Research & Development Corporation of Newfoundland and Labrador (RDC), funding no. 210992; and Statoil Canada Ltd., funding no. 211162 for providing financial support to accomplish this research under Statoil Chair in Reservoir Engineering and SGS of Memorial University of Newfoundland, St. John's, NL, Canada.

Nomenclature

A	Area, m^2	V_f	Fluid Volume, m^3
L	Reservoir Length, m	σ_{go}	Interfacial Tension between Gas and Oil Phase, kg/s^2
W	Reservoir Width, m	σ_{ow}	Interfacial Tension between Oil and Gas Phase, kg/s^2
H	Reservoir Thickness, m	ν	Dynamic Viscosity, s/m^2
c	Compressibility, m^2/kg	μ	Viscosity, kg/ms
ϕ	Porosity, Fraction	ρ	Density, kg/m^3
k	Permeability, m^2	r	Pore Throat Radius, m
k_r	Relative Permeability, m^2/m^2	g	Gravitational Acceleration, m/s^2
P	Pressure, kg/ms^2	τ	Tortuosity
q_i	Injection Rate, m^3/s	K	Thermal Conductivity, $W/m.K$
q_{ia}	Injection Rate of Additive, m^3/s	C_p	Specific Heat Capacity, $j/kg.K$
q_{prod}	Production Rate, m^3/s	h	Enthalpy, j/kg
D_{Ta}	Transverse Dispersion of Additive, m^2/s	L_v	Latent Heat, j/kg
D_{La}	Longitudinal Dispersion of Additive, m^2/s	ξ	Dummy variable for time, s
S	Saturation		Subscript
θ	Contact Angle	f	Fluid

t	Time, s	o	Oil Phase
T	Reservoir Temperature, $^{\circ}C$	w	Water Phase
E	Additive Concentration	g	Gaseous Phase
U	Total Velocity, m/s	i	Initial
u	Velocity, m/s	r	Rock or Reservoir
V_r	Reservoir Volume, m^3	t	Total

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CHAPTER FOUR

Scaled Physical Model Studies of Steam Flooding EOR Process

Abstract

Scaling is used extensively in engineering problems for many years to reproduce the behavior of one scale (i.e., laboratory) to another scale (i.e., field). Scaling criteria development of a steam flooding process leads us to a better understanding of the process. This study focused on development, evaluation, and validation of scaling groups for the steam flooding enhanced oil recovery (EOR) process. The inspectional and dimensional analysis procedure is used with the incorporation of rock and fluid memory concept to obtain the dimensionless groups. Synthetic reservoir and laboratory scaled models are used to validate the dimensionless numbers and evaluate their effect on oil recovery. The existing scaling methods for evaluating dimensionless groups correspond to homogeneous system. Therefore, Dykstra-Parsons coefficient is introduced to incorporate the heterogeneity of the system and the evaluation of additive requirements. A novel dimensionless group is proposed in this study to characterize and evaluate the performance of scaled steam flooding process. This research work leads to the improvement of a procedure that can be applied to design a steam flooding EOR process. The process is flexible; it can be applied to wide range of reservoir types as there exists a physical commonality between field and laboratory scale.

4.1. Introduction

Scaling criteria development for EOR is a widely used technique for predicting the performance of a reservoir. Scaled model experiments had been used for many years to reproduce the behavior of a specific process (Rahman et al., 2017). Process controlling parameters are implemented by these dimensionless scaling groups. Core flood experiments and numerical simulation are performed to understand and verify the behavior of a reservoir. The feasibility of a specific EOR process had been studied through this process before they are attempted in the field. The unscaled model can lead to an erroneous result. So, it is important to develop appropriate pore scaled model which can represent the behavior of another scale (field).

Steam flooding is one of the proven methods of EOR. It is an important thermal recovery method which is employed in many parts of the world on a commercial scale. Steam injection process was analyzed as a displacement process through experimental investigation under

laboratory and field conditions (Willman et al., 1961; Blevins et al., 1969; Johnson et al., 1971; Baker, 1973; Blevins and Billingsley, 1975; Wu, 1977). Mathematical models had been employed along with laboratory and field tests to aid in understanding and designing the steam flooding process (Marx and Langenheim, 1959; Mandl and Volek, 1969; Shutler, 1969 and 1970; Abdalla, and Coats, 1971; Shutler and Boberg, 1972; Coats et al., 1974; Neuman, 1975; Coats, 1976; Van Lookeren, 1983). Many laboratory experiments had been performed to improve the efficiency of this method. Most of the physical model of steam flooding had been conducted to investigate the type of flow, saturation, displacement and sweep efficiency along with temperature distribution. Fractional oil recovery with production behavior as a function of time can be presented for a specific steam flooding process.

Scaling theory had been discussed for many years in the literature (Pujol and Boberg 1972; Greenkorn, 1964; Perkins and Collins, 1960; Leverett et al., 1942; Rapoport, 1955; Langhaar, 1951; Niko and Troost 1971), but no qualitative information has been published for scaled thermal flooding process. The scaled steam flooding process had been used extensively for last two decades. Many researchers investigated different scaled model steam flooding process. Stegemeier et al., (1980) developed an approach for a scaled model of steam flooding which operates at sub-atmospheric pressure and used fluids was different from field fluids. If same fluids were used, then the same temperature and pressure conditions should be employed to laboratory scale. Ali and Redford (1977) reviewed the previous scaled steam flooding approach in detail. There are two broad categories of steam flooding: one is high-pressure approach developed by Pujol and Boberg (1972), and another one is low-pressure approach presented by Stegemeier et al., (1980). The temperature and pressure used in a high-pressure approach model are same as in the prototype. Several investigators (Ali and Redford, 1977; Willman et al., 1961; Wu, 1977; Ehrlich, 1977) found that the residual oil left behind the steam front is lower than the residual oil found for hot water drive which is again lower than the cold-water drive. Ehrlich (1977) found that the residual oil of a steam flooding process does not depend on initial oil saturation and the quality of the steam. The assumptions of Marx-Langenheim was relaxed by Ali (1966) to consider the identical flow properties of base and cap rocks. Mandl and Volek (1969) investigated the effects of convective heat transfer from steam zone to the oil-water region. Willman et al., (1961) conducted a series of core flooding experiments saturated with different crude and refined oils for steam flooding process. The authors combined the Buckley-Leverett solution to the Marx-Langenheim equations for the radial steam drive. Hutchinson *et al.* (1992) investigated a study on steam foam mechanism at residual oil saturation under

different conditions. Valera *et al.* (1999) presented stimulation technique output for the case of a new reservoir and reentry of wells with steam and surfactant.

The ultimate objectives of deriving scaling criteria for steam flooding process is to forecast the behavior of rock and fluid properties which affect this process from laboratory scale to field scale. A modified Darcy's law is used with time and space diffusion derivative to develop the scaling criteria. The relationship among different process controlling parameters is studied through this scaling approach. It can capture the continuous alteration of different rock and fluid properties which is characterized by those dimensionless numbers. Finally, dominant scaling groups are determined through the studies of those dimensionless numbers to design a scaled experiment.

Memory formalism is used to derive the dimensionless groups for the case of a steam flood process. In petroleum field, simplified assumptions are used to derive a physical model of the steamflooding technique. These models are simplified by assuming constant rock and fluid properties throughout the reservoir. However, in practice, rock and fluid properties change with time and space (Rahman *et al.*, 2017). These alteration effects are captured by this memory formalism.

This study focused on deriving scaling criteria using inspectional and dimensional analysis. Some of the dimensionless groups are eliminated through different processes. Eighteen dimensionless groups are found which can particularly affect the steam flooding process. Synthetic reservoir properties with laboratory scaled model are used to validate those dimensionless groups and evaluate their effect on recovery. CMG STARS thermal simulation software is used to develop a model of steam flooding process.

4.2. Scaling procedure

The physical model of steam flooding process is based on the concept of dimensional similarity. A model can be considered as perfect if it can follow the physical, dynamic and geometric similarity at each point between model and prototype. In a perfectly scaled model studies, all relevant physical and geometric properties should be proportional for any scaled model at homologous space and time (Langhaar, 1951). Moreover, governing equations and their initial and boundary conditions should be satisfied the similarity criteria which are used to derive those dimensionless groups. There are two universally accepted methods which are available for deriving dimensionless groups. Those are dimensional analysis (Buckingham,

1914; Bridgman, 1931; Langhaar, 1951; Focken, 1953; Nielsen and Tek, 1963; Sonin, 2001) and inspectional analysis (Ruark, 1935; Birkhoff, 1950; Bear, 1972; Shook et al., 1992, Novakovic, 2002). The advantages and drawbacks of each approach are discussed in many kinds of literatures (Geertsma et al., 1956; Loomis and Crowell, 1964; Rahman et al., 2017) which will not be repeated here. The inspectional analysis is preferred because it has a significant impact on process control parameters.

4.2.1. Dimensional Analysis

Dimensional analysis is a simple technique to develop dimensionless groups by using two or more variables. It is a very simple and easy technique to develop dimensionless groups. Buckingham π –theorem can be used to develop the dimensionless groups. The variables are selected depending on the process being modeled. The effect of selected parameters is studied in terms of a group rather than separate parameters in the group. Leverett et al., (1942) first investigated to develop a dimensionless group of reservoir behavior using dimensional analysis. Dimensionless groups from a dimensional analysis are given in table 4.1. First, the parameters which affect the steam flooding process are listed. Then fundamental dimensions such as mass, length, time and temperature are selected where selection variables should be equal to fundamental dimensions. The dimensional equations should be formulated and combine the selected parameters to derive dimensionless groups. If the derived group is not dimensionless, then performed the previous step and made it dimensionless. Sixty-four parameters are selected for this process, and four selected variables with fundamental dimensions are L, T, ρ_o, C_{pf} . Sixty dimensionless groups had been derived from dimensional analysis listed in table 4.1. Geometric aspect ratio, density number, pressure group, flow rate group, saturation group, dispersion group and other numbers are developed through dimensional analysis. There are some new groups which are not found through inspectional analysis. This can have happened because of not selecting some parameters in formulating inspectional analysis equations. These groups have a little or insignificant effect on the specific process that is why the requirements of these groups had been relaxed.

Table 4.1: Dimensionless group from dimensional analysis

$\pi_1 = \frac{A}{L^2}$	$\pi_{11} = \frac{k^2}{L^2}$	$\pi_{21} = \frac{q_{prod}}{\sqrt{TC_{pf}}L^{5/2}}$	$\pi_{31} = \frac{u_w}{\sqrt{LTC_{pf}}}$	$\pi_{41} = \frac{\rho_g}{\rho_o}$	$\pi_{51} = \frac{k_r}{\rho_o L^{5/2} T^{1/2} C_{pf}^{5/2}}$
$\pi_2 = \frac{w^2}{L^2}$	$\pi_{12} = \frac{k_r^2}{L^2}$	$\pi_{22} = \frac{D_{Ta}}{\sqrt{TC_{pf}}L^{3/2}}$	$\pi_{32} = \frac{u_g}{\sqrt{LTC_{pf}}}$	$\pi_{42} = \frac{\rho_w}{\rho_o}$	$\pi_{52} = \frac{C_{pg}}{C_{pf}}$
$\pi_3 = \frac{h^2}{L^2}$	$\pi_{13} = \frac{P_i}{\rho_o LTC_{pf}}$	$\pi_{23} = \frac{D_{La}}{\sqrt{TC_{pf}}L^{3/2}}$	$\pi_{33} = \frac{V_r}{L^3}$	$\pi_{43} = \frac{V\rho}{\rho_o}$	$\pi_{53} = \frac{C_{pr}}{C_{pf}}$
$\pi_4 = \frac{\rho_o L^4 c_r}{T C_{pf}}$	$\pi_{14} = \frac{P_o}{\rho_o LTC_{pf}}$	$\pi_{24} = S_g$	$\pi_{34} = \frac{V_f}{L^3}$	$\pi_{44} = \frac{r^2}{L^2}$	$\pi_{54} = \frac{C_{pw}}{C_{pf}}$
$\pi_5 = \frac{\rho_o L^4 c_f}{T C_{pf}}$	$\pi_{15} = \frac{P_w}{\rho_o LTC_{pf}}$	$\pi_{25} = S_o$	$\pi_{35} = \frac{\sigma_{go}}{\rho_o^{3/2} L^2 TC_{pf}}$	$\pi_{45} = \frac{g}{TC_{pf}}$	$\pi_{55} = \frac{h_w}{LTC_{pf}}$
$\pi_6 = \frac{\rho_o L^4 c_o}{T C_{pf}}$	$\pi_{16} = \frac{P_g}{\rho_o LTC_{pf}}$	$\pi_{26} = S_w$	$\pi_{36} = \frac{\sigma_{ow}}{\rho_o^{3/2} L^2 TC_{pf}}$	$\pi_{46} = \tau$	$\pi_{56} = \frac{h_o}{LTC_{pf}}$
$\pi_7 = \frac{\rho_o L^4 c_g}{T C_{pf}}$	$\pi_{17} = \frac{P_{cgo}}{\rho_o LTC_{pf}}$	$\pi_{27} = \theta$	$\pi_{37} = \frac{\sqrt{TC_{pf}}}{L^{-3/2}} \nu$	$\pi_{47} = \frac{k_f}{\rho_o L^{5/2} T^{1/2} C_{pf}^{5/2}}$	$\pi_{57} = \frac{h_g}{LTC_{pf}}$
$\pi_8 = \frac{\rho_o L^4 c_w}{T C_{pf}}$	$\pi_{18} = \frac{P_{cow}}{\rho_o LTC_{pf}}$	$\pi_{28} = \frac{\sqrt{T} t}{\sqrt{AC_{pf}}}$	$\pi_{38} = \frac{T\mu_o}{\rho_o L^2}$	$\pi_{48} = \frac{k_g}{\rho_o L^{5/2} T^{1/2} C_{pf}^{5/2}}$	$\pi_{58} = \frac{h_r}{LTC_{pf}}$
$\pi_9 = \frac{\rho_o L^4 c_t}{T C_{pf}}$	$\pi_{19} = \frac{q_i}{\sqrt{TC_{pf}}L^{5/2}}$	$\pi_{29} = \frac{U}{\sqrt{LTC_{pf}}}$	$\pi_{39} = \frac{T\mu_w}{\rho_o L^2}$	$\pi_{49} = \frac{k_w}{\rho_o L^{5/2} T^{1/2} C_{pf}^{5/2}}$	$\pi_{59} = \frac{L_v}{LTC_{pf}}$
$\pi_{10} = \phi$	$\pi_{20} = \frac{q_{ia}}{\sqrt{TC_{pf}}L^{5/2}}$	$\pi_{30} = \frac{u_o}{\sqrt{LTC_{pf}}}$	$\pi_{40} = \frac{T\mu_g}{\rho_o L^2}$	$\pi_{50} = \frac{k_o}{\rho_o L^{5/2} T^{1/2} C_{pf}^{5/2}}$	$\pi_{60} = \frac{\xi}{t}$

4.2.2 Inspectional Analysis

The inspectional analysis is a technique by which dimensional analysis is expanded. This technique can verify the dimensionless groups where a specific process is involved. The mathematical formulation can be developed by using partial differential equations, initial and boundary conditions, constitutive relationships, and constraints. Derived dimensionless groups

are written in terms of dimensionless variables and with their reference quantities. Some of the dimensionless groups are eliminated which one has little or no effect on the specific process.

Rock and fluid memory concept are incorporating with fundamental equations to derive the dimensionless groups. This technique has a unique advantage over dimensional analysis. The developed dimensionless group has a clear physical meaning. The inspectional analysis involves parameters rather than dimensions, so it can produce dependent dimensionless groups for a specific process.

4.2.2.1. Mathematical formulation

Steam flooding process is considered by considering modified Darcy's law for three-phase flows during the production. A model is developed using all partial differential equations and their initial and boundary conditions. Finally, a model equation has been developed for displacement of oil by steam flooding technique using modified Darcy's law with incorporating memory concept (Hossain et al. 2007; Hossain et al. 2008; Hossain et al. 2009b). The flow equations and the derivation of model equations are given in Chapter 3.

The energy balance equation is written in a differential form to derive the dimensionless numbers. However, there exists a different level of inherent difficulties to match the dimensionless groups in model and prototype. This inconsistency can be happened when facing difficulties in selecting the characteristic quantities which are involved in the specific process. These problems arise because we have to scale complex steam flooding process in differential form. This differential form can provide detail local information about the process and requires more data to describe the local process. As it is not possible to satisfy every element of scaling requirements, it can be easier to satisfy the scaling requirements in integral form. The dimensionless groups derived from integral approach have some advantages over the differential approach to scale time and steam quality. The integral approach can create somewhat different pictures of saturation and temperature distribution in the reservoir, but it can show a correct behavior compared to differential approach. The different parameters such as oil recovery, efficiency, the steam-oil ratio is in integral form so that this approach can work more consistently than any other approaches.

$$M_1 = (1 - \phi)\rho_r c_r + \phi(c_w \rho_w s_w + c_o \rho_o s_o + c_g \rho_g s_g) + \frac{\phi L_v \rho_g s_g}{\Delta T} \quad (14)$$

This equation represents the summation of following terms such as:

Rate of heat stored in the steam zone + Conductive heat flux to adjacent formations+
 Conductive heat flux to the liquid zone + Convective heat flux to the liquid zone = Rate of heat
 injection

Based on the above equations (9, 10, 11, 12, 13 and 14) that are involved in the process, the
 detailed derivation of dimensionless groups is given in Appendix A.

4.3. Dimensionless groups

Dimensionless groups from the inspectional analysis are given in table 4.2. The dominant
 scaling groups for steam flooding process is reported in table 4.2. Different elimination
 techniques are used to select those numbers from 176 dimensionless groups as previously given
 in table 3.2. Peclet numbers, mobility ratio, capillary number, gravity number, fluid movement
 ratio, geometric aspect ratio, heat capacity ratio, thermal conductivity ratio, etc. groups are
 listed in table 4.2.

Table 4.2: Dimensionless Groups from Inspectional Analysis.

$G_1 = \frac{\phi D_{Lo1R}}{LU_t}$	$G_6 = \frac{f_R \eta_R \rho_{wR}}{\Gamma(1 - \alpha) t_R^{\alpha-1} \phi_R S_R L H}$	$G_{11} = \frac{\sigma_{owR} k_{rw} \cos \theta_R \sqrt{\phi_R k_{xw}}}{LU_t \mu_w}$	$G_{16} = \frac{\phi K_{hf}}{K_{he}}$
$G_2 = \frac{\phi D_{To1R} L}{H^2 U_t}$	$G_7 = \frac{L^2 D_{To1R}}{H^2 D_{Lo1R}}$	$G_{12} = \frac{(1 - \phi) \rho_r C_{pr}}{\phi C_{pw} \rho_w S_w}$	$G_{17} = \frac{(1 - \phi) K_{hr}}{K_{he}}$
$G_3 = \frac{\mu_o k_{rw}}{\mu_w k_{ro}}$	$G_8 = \frac{k_{xwR} \lambda_{xwR} \Delta \rho_{woR} g_R H \sin \theta_R}{LU_t}$	$G_{13} = \frac{m_s f_s L_v t}{\Delta T M_1 L^3}$	$G_{18} = \frac{U_t t}{L \phi (1 - s_{wi} - s_{or})}$
$G_4 = \frac{\mu_o k_{rg}}{\mu_g k_{ro}}$	$G_9 = \frac{k_{xwR} \lambda_{xwR} \Delta \rho_{ogR} g_R H \sin \theta_R}{LU_t}$	$G_{14} = \frac{m_s t}{\phi \rho_w S_w L^3}$	
$G_5 = \frac{f_R \eta_R \rho_{wR}}{\Gamma(1 - \alpha) t_R^{\alpha-1} \phi_R S_R L^2}$	$G_{10} = \frac{L^2 k_z}{H^2 k_x}$	$G_{15} = \frac{\phi L_v \rho_g S_g}{M_1 \Delta T}$	

The dimensionless groups reported in table 4.2 can be described in terms of established some
 available dimensionless numbers as:

$$\text{Longitudinal Peclet Number: } \frac{1}{G_1} = N_{PLo1} = \frac{LU_t}{\phi D_{Lo1R}}$$

$$\text{Transverse Peclet Number: } \frac{1}{G_2} = N_{PTO1} = \frac{H^2 U_t}{\phi D_{TO1R} L}$$

$$\text{Water-Oil Mobility Ratio: } G_3 = M_{ow} = \frac{\mu_o k_{rw}}{\mu_w k_{ro}}$$

$$\text{Gas-oil Mobility Ratio: } G_4 = M_{go} = \frac{\mu_o k_{rg}}{\mu_g k_{ro}}$$

$$\text{Gravity to Longitudinal Fluid Movement Ratio: } \frac{1}{G_5} = N_{LG} = \frac{\Gamma(1-\alpha) t_R^{\alpha-1} \phi_R S_R L^2}{f_R \eta_R \rho_{wR}}$$

$$\text{Gravity to Transverse Fluid Movement Ratio: } \frac{1}{G_6} = N_{TG} = \frac{\Gamma(1-\alpha) t_R^{\alpha-1} \phi_R S_R L H}{f_R \eta_R \rho_{wR}}$$

$$\text{Dispersion Factor: } \sqrt{G_7} = Q_L = \frac{L}{H} \sqrt{\frac{D_{TO1R}}{D_{LO1R}}}$$

$$\text{Water-Oil Gravity Number: } G_8 = N_{Gwo} = \frac{k_{xwR} \lambda_{xwR} \rho_{woR} g_R H \sin \theta_R}{L U_t}$$

$$\text{Gas-Oil Gravity Number: } G_9 = N_{Gog} = \frac{k_{xoR} \lambda_{xoR} \rho_{ogR} g_R H \sin \theta_R}{L U_t}$$

$$\text{Effective Aspect Ratio: } \sqrt{G_{10}} = R_L = \frac{L}{H} \sqrt{\frac{k_z}{k_x}}$$

$$\text{Oil-Water Capillary Number: } \frac{1}{G_{11}} = N_C = \frac{L U_t \mu_w}{\sigma_{owR} k_{rw} \cos \theta_R \sqrt{\phi_R k_{xw}}}$$

$$\text{Volumetric heat capacity ratio: } G_{12} = N_R = \frac{(1-\phi) \rho_r c_{pr}}{\phi c_{pw} \rho_w S_w}$$

$$\text{Heat Injected to Heat Stored Ratio: } G_{13} = Q_N = \frac{m_s f_s L v t}{\Delta T M_1 L^3}$$

$$\text{Mass Flux of Steam to Water: } G_{14} = N_S = \frac{m_s t}{\phi \rho_w S_w L^3}$$

$$\text{Heat Enthalpy to Heat Stored Ratio: } G_{15} = N_E = \frac{\phi L v \rho_g S_g}{M_1 \Delta T}$$

$$\text{Fluid Thermal Conductivity to Effective Thermal Conductivity Ratio: } G_{16} = N_F = \frac{\phi K_{hf}}{K_{he}}$$

$$\text{Rock Thermal Conductivity to Effective Thermal Conductivity Ratio: } G_{17} = N_T = \frac{(1-\phi) K_{hr}}{K_{he}}$$

$$\text{Dimensionless Time: } G_{18} = t_D = \frac{U_t t}{L \phi (1-s_{wi}-s_{or})}$$

4.4. Synthetic reservoir model

Synthetic reservoir properties are used for history matching of 18 dimensionless groups derived from the inspectional analysis. Different rock and fluid properties are considered here in table 4.3 to study the effect of different dimensionless numbers on oil recovery. The effective permeability, relative permeability, thermal conductivity of different phases, surface tension, heat capacity, steam quality and other properties are reported in table 4.3. A different dimension of the reservoirs with same dimensionless numbers can have the same response to

dimensionless numbers. Here, those dimensionless groups are used to evaluate whose values are same for 4 different cases.

Table 4.3: Dimensional parameters are tabulated here for core experiments and synthetic reservoir

Parameters	Values	Parameters	values	Parameters	Values
k_z (mD)	800	K_w =(Kj/h-m-k)	3.7758	C_{pw} (Kj/kg-k)	4.1868
k_x (mD)	800	K_g =(Kj/h-m-k)	0.0143	f_R	0.2
k_{rg}	0.150	K_{hf} =(Kj/h-m-k)	1.7288	m_s (ft ² /s)	17.20
k_{ro}	0.085	K_{he} =(Kj/h-m-k)	6.7936	L_v (Btu/lb)	837.3
k_{rw}	0.400	h_L (Kj/h-m ² k)	280.87	M_1 (Btu/ft ³ °F)	3.69
g (cm/s ²)	980.7	p_i (pa)	1.7×10^7	η_R	0.35
σ_{ow} (dyne/cm)	49.0	C_{pg} (Kj/kg-k)	29.7263	α	0.2
K_r =(Kj/h-m-k)	9.346	C_{pr} (Kj/kg-k)	0.8792	f_s	0.8
K_o =(Kj/h-m-k)	1.3962	C_{po} (Kj/kg-k)	2.0934	C_{pw} (Kj/kg-k)	4.1868

Four different cases are studied, and their properties are reported in table 4.4. Case 1 is considered for small or core flooding scale. Here the length of the core is considered 7.65 cm and height of the core is 2.56 cm. Case 2, 3 and 4 is considered for reservoir scale. Different properties with their corresponding values are also tabulated. These values are considered for 0.1% additive concentration.

Table 4.4: Dimensional parameters for 0.1% wt. additive concentration of core experiments and synthetic reservoirs

Parameters	Case 1	Case 2	Case 3	Case 4
L, cm (ft)	7.65	1500 (49.2)	1800 (59.0)	3735 (122.5)
H, cm (ft)	2.56	502 (16.5)	602.4 (19.8)	1250 (41.0)
U_T , ft/s	3.36×10^{-4}	1.71×10^{-5}	1.43×10^{-5}	2.50×10^{-6}
D_{Lo1R} , ft ² /s	1.12×10^{-4}	1.12×10^{-3}	9.67×10^{-4}	3.38×10^{-4}
D_{To1R} , ft ² /s	3.53×10^{-6}	3.53×10^{-5}	3.05×10^{-5}	1.067×10^{-5}
ϕ	0.332	0.332	0.385	0.400

μ_w at 2500 psi, cP	0.99	0.99	0.99	0.99
μ_o at 2500 psi, cP	1.03	1.03	1.03	1.03
μ_g at 2500 psi, cP	0.125	0.125	0.125	0.125
ρ_w at 2500 psi, g/cm ³	1.020	1.005	1.005	1.005
ρ_o at 2500 psi, g/cm ³	0.683	0.988	0.991	0.998
ρ_g at 2500 psi, g/cm ³	0.942	1.001	1.002	1.003
ρ_r at 2500 psi, g/cm ³	2.680	2.681	2.682	2.683

Similar to table 4.4, table 4.5 reported different properties of four cases which is applicable for 0.5% additive concentration. The only difference between this two table is the value of total velocity and longitudinal and transverse dispersion value due to the change in additive concentration.

Table 4.5: Dimensional parameters for 0.5% wt. additive concentration of core experiments and synthetic reservoirs

Parameters	Case 1	Case 2	Case 3	Case 4
L, cm (ft)	7.65	1500 (49.2)	1800 (59.0)	3735 (122.5)
H, cm (ft)	2.56	502 (16.5)	602.4 (19.8)	1250 (41.0)
U_T , ft/s	2.85×10^{-4}	1.45×10^{-5}	1.21×10^{-5}	5.84×10^{-6}
D_{Lo1R} , ft ² /s	1.12×10^{-5}	1.12×10^{-4}	9.67×10^{-5}	9.31×10^{-4}
D_{To1R} , ft ² /s	3.53×10^{-7}	3.53×10^{-6}	3.05×10^{-6}	2.93×10^{-5}
ϕ	0.332	0.332	0.385	0.400
μ_w at 2500 psi, cP	0.99	0.99	0.99	0.99
μ_o at 2500 psi, cP	1.03	1.03	1.03	1.03
μ_g at 2500 psi, cP	0.210	0.210	0.210	0.210
ρ_w at 2500 psi, g/cm ³	1.020	1.005	1.005	1.003
ρ_o at 2500 psi, g/cm ³	0.683	0.988	0.991	0.998
ρ_g at 2500 psi, g/cm ³	0.942	1.001	1.002	1.005
ρ_r at 2500 psi, g/cm ³	2.680	2.681	2.682	2.682

In table 4.6, dominant dimensionless groups values of 1% wt. additive concentration is reported for four different cases. From this table, it is observed that ten different dimensionless numbers and each of them provide the same value for four different cases. Based on these values and considering other dimensionless numbers are constant, the effect of those ten-dimensionless numbers on oil recovery is determined.

Table 4.6: Dimensional numbers for 0.1% wt. additive concentration core experiments and synthetic reservoir

Dimensionless Numbers	Case 1	Case 2	Case 3	Case 4
N_{PLo1}	69	69	69	69
N_{PTo1}	245	245	245	245
M_{ow}	4.9	4.9	4.9	4.9
M_{go}	14.5	14.5	14.5	14.5
N_{LG}	1.13×10^{-2}	433	723	3235
N_{TG}	3.77	145	242	1083
Q_L	0.531	0.531	0.531	0.531
N_{Gwo}	2.66×10^8	2.66×10^8	2.66×10^8	2.66×10^8
N_{Ggo}	4.19×10^7	4.19×10^7	4.19×10^7	4.19×10^7
R_L	2.99	2.99	2.99	2.99
N_C	2.90×10^{-6}	2.90×10^{-6}	2.90×10^{-6}	2.90×10^{-6}
N_R	5.55	5.62	5.09	4.20
Q_N	0.02	3.08×10^{-9}	1.78×10^{-9}	2×10^{-10}
N_S	0.57	7.64×10^{-8}	3.81×10^{-8}	4.11×10^{-9}
N_E	0.047	0.050	0.057	0.062
N_F	0.08	0.085	0.105	0.118
N_T	0.915	0.915	0.895	0.882
t_D	1.81×10^{-4}	4.7×10^{-8}	2.83×10^{-8}	2.29×10^{-7}

Similarly, table 4.7 reported dominant dimensionless group values of 0.5% wt. additive concentration for four different cases. It is observed that ten-dimensionless numbers and each of them give the same values for four different cases. Based on these ten numbers and considering other dimensionless numbers are constant, the effect of these numbers on oil recovery is determined.

Table 4.7: Dimensional Numbers for 0.5% wt. Additive Concentration Core Experiments and Synthetic Reservoir

Dimensionless Numbers	Case 1	Case 2	Case 3	Case 4
N_{PLo1}	585	585	585	585
N_{PTo1}	2081	2081	2081	2081
M_{ow}	4.9	4.9	4.9	4.9
M_{go}	8.6	8.6	8.6	8.6
Q_L	0.531	0.531	0.531	0.531
N_{LG}	6.79×10^{-3}	261	376	1618
N_{TG}	2.27×10^{-3}	87	126	541
N_{Gwo}	3.13×10^8	3.13×10^8	3.13×10^8	3.13×10^8
N_{Ggo}	4.93×10^7	4.93×10^7	4.93×10^7	4.93×10^7
R_L	2.99	2.99	2.99	2.99
N_C	2.46×10^{-6}	2.46×10^{-6}	2.46×10^{-6}	2.46×10^{-6}
N_R	5.55	5.62	5.09	4.20
Q_N	0.02	3.08×10^{-9}	1.78×10^{-9}	2×10^{-10}
N_S	0.57	7.64×10^{-8}	3.81×10^{-8}	4.11×10^{-9}
N_E	0.047	0.050	0.057	0.062
N_F	0.08	0.085	0.105	0.118
N_T	0.915	0.915	0.895	0.882
t_D	1.54×10^{-4}	3.99×10^{-8}	2.40×10^{-8}	5.35×10^{-7}

Steam flooding scaled model identified the vertical permeability, temperature difference between injected fluid and reservoir fluid, steam quality, total superficial velocity, viscosities of different fluids are the main operational parameters which have a significant effect on steam flood EOR process. Interfacial tension involved in capillary forces, gravity forces and other microscopic property plays an important role in the ultimate recovery of oil. The important dimensionless numbers are derived to investigate the effect of steam flood EOR process concerning oil recovery.

The validation of dimensionless group is unnecessary as the development procedure presented above is evidently complete (Shook et al. 1992). In this section, dimensionless numbers are studied to investigate the effect of those numbers on fractional oil recovery. The response of reservoir on these dimensionless numbers helps to identify the inter-relation between different process control parameters.

The most significant dimensionless numbers obtained after elimination technique from the model equations are presented in table 4.2. The thickness and permeability distribution of the layers are arbitrarily chosen for different cases. Case 1 is considered for small-scale laboratory experiment, and case 2, 3 and 4 are chosen for reservoir scale or field scale. Case 2 is considered for the heterogeneous system where each layer consists of different permeability and thickness. Case 3 is considered for 3 different permeability and 3 different layer thickness, and case 4 is applied for a homogeneous system which consists same permeability and layer thickness.

Figure 4.1 and 4.2 compares oil recovery factor for different cases of core floods and synthetic reservoir models which consists equal dimensionless numbers, but different (0.1% wt. and 0.5% wt.) injected additive concentration.

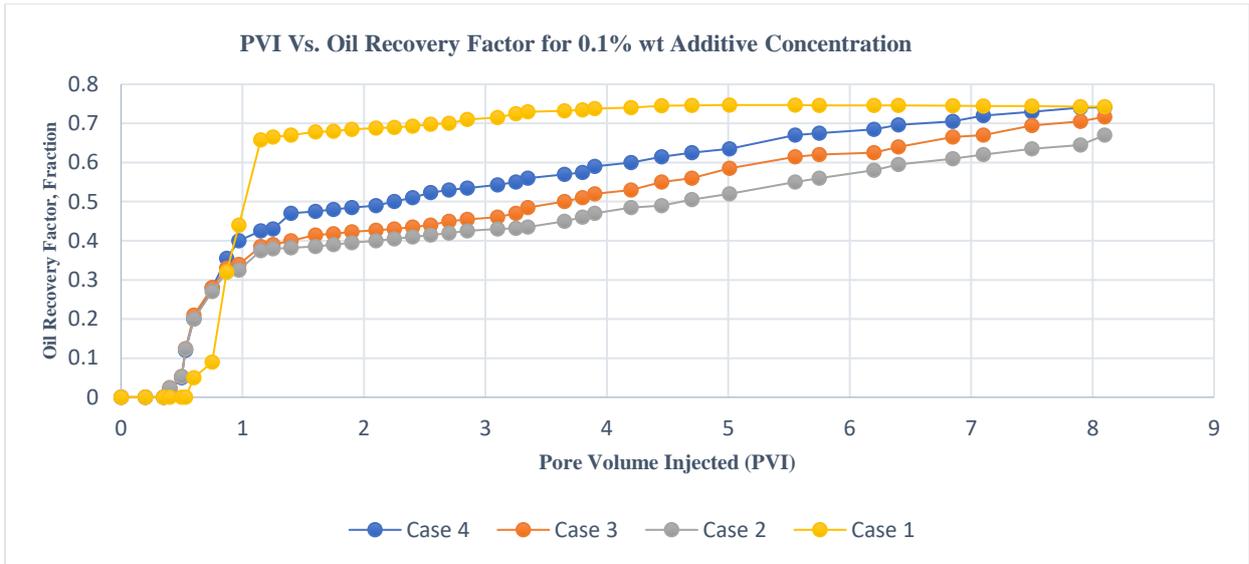


Figure 4.1: Comparison of oil recovery factor for four different cases with 0.1% additive concentration

A higher recovery rate is observed from laboratory experiments compared with synthetic reservoir cases for 0.1% wt. additive concentration. It is also noticed that the rate of recovery and recovery factor is decreasing with increasing heterogeneity, initially due to the larger size of the upper zone. Almost opposite behavior is observed for 0.5% wt. additive concentration injection case. The recovery rate and recovery factor are almost similar to synthetic reservoir models which are slightly higher than the core flood experiments.

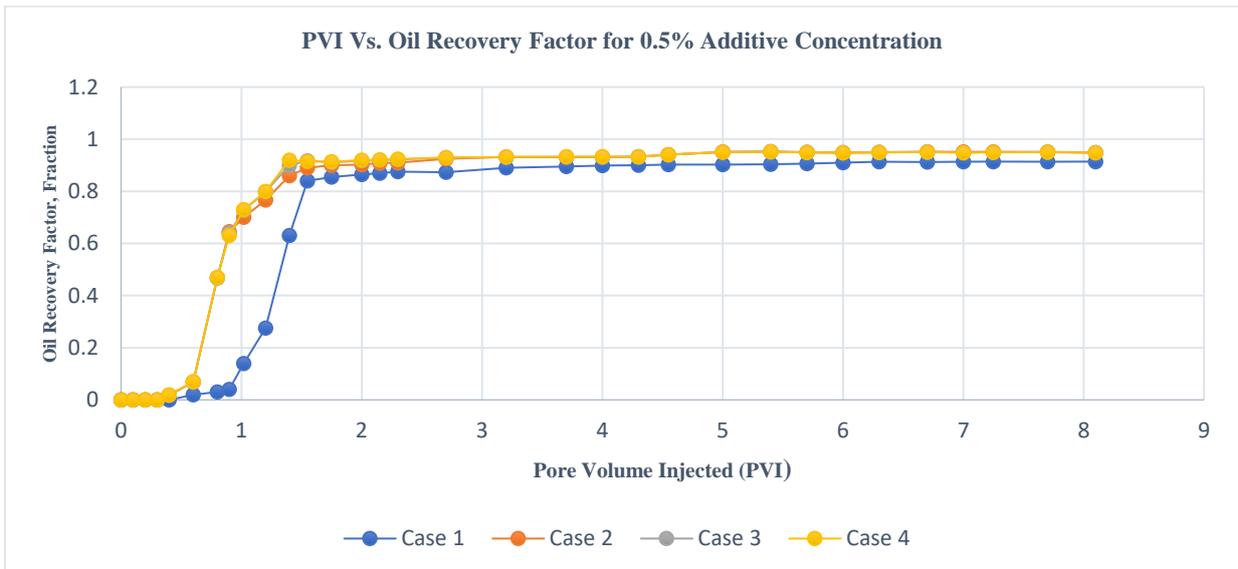


Figure 4.2: Comparison of oil recovery factor for four different cases with 0.5% additive concentration

The dimensionless groups which give same results for four different media, but the geometrically similar porous media is considered for fractional oil recovery. Therefore, the fractional oil recovery can be expressed in the following form of steam flooding process.

$$\text{FOR} = f(t_D, N_{PLo1}, N_{PTo1}, M_{ow}, M_{go}, Q_L, N_{Gwo}, N_{Gog}, R_L, N_C) \quad (15)$$

Fractional Oil Recovery (FOR) is defined as the ratio of cumulative oil produced to original oil in place. FOR is also a function of dimensionless time, which is representing the amount of pore volume injected or PVI. Numerical simulation of steam flooding process with CMG STAR is given in appendix B.

Figure 4.3 and figure 4.4 describes the effect of longitudinal and transverse Peclet number on oil recovery. The Peclet number represents the mixing mechanism of core and field scales. It is the ratio of convective and diffusive transport (Bruining et al., 2012) where the mixing of miscible fluid in the porous media occurs because of diffusion and dispersion. Diffusion can occur when the random movement of molecules of a particular phase that contain a high concentrated solute into a solvent which contain a lower concentration of the same solute. On the other hand, dispersions occur between two fluids where velocity can play a vital role. When mixing occurs in the direction of flow, it is termed as longitudinal dispersion and for the perpendicular direction, it is called transverse dispersion.

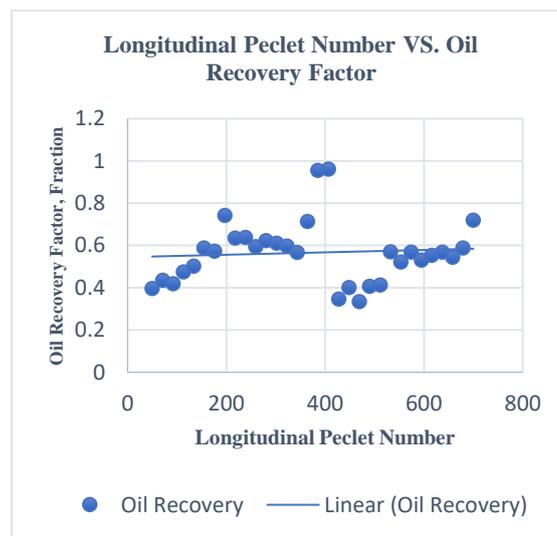


Figure 4.3: Longitudinal Peclet number

The variation of oil recovery with longitudinal and transverse Peclet number is shown in figure 4.3 and 4.4. Figure 4.3 indicates a slight increase in recovery with increasing longitudinal p

Peclet number. But, sometimes oil recovery decreases with increasing longitudinal Peclet number. There is no definitive trend for which is followed by longitudinal Peclet number. Figure 4.4 indicates a slight decrease in increasing transverse Peclet number. Sometimes it does not follow a definitive trend. From the above discussion, it can be concluded that Peclet number has less effect on oil recovery if other properties remain same.

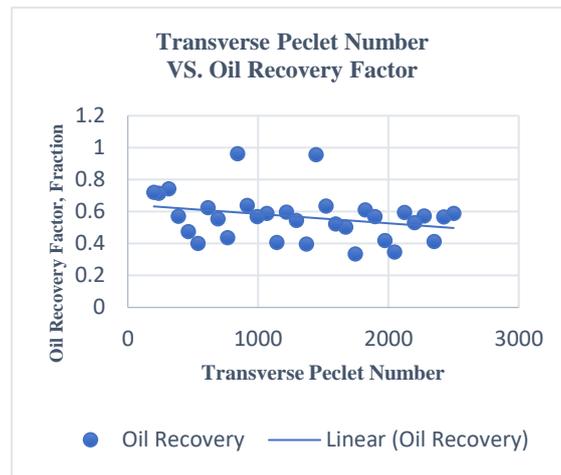


Figure 4.4: Transverse Peclet number

The mobility ratio can describe the ability of a fluid to flow relative to another fluid. It can be termed as the ratio of a displacing fluids to the displaced fluid. In this study, the mobility ratio is not constant due to the change in the viscosities of the displacing and displaced fluids. Figure 4.5, describes the effects of water-oil mobility ratio on oil recovery. As the mobility ratio decreases the oil recovery factor is increasing. It is an obvious reason, as the steam is injected into the reservoir, it can reduce the viscosity of the oil and increase the sweep efficiency and hence increase the oil recovery.

Similarly, figure 4.5, figure 4.6 describes the effects of steam-oil mobility ratio on oil recovery factor. Here, the displacing fluid is steam, and the displaced fluid is oil. For the gaseous and oil phase displacement, the mobility ratio is varying due to the change in effective viscosities of displacing and displaced fluid. From figure 4.6, it is clear that with increasing steam-oil mobility ratio the oil recovery is decreasing.

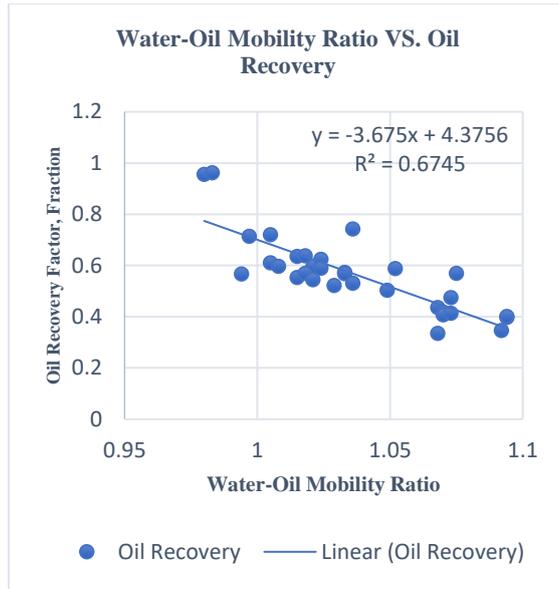


Figure 4.5: Water-oil mobility ratio

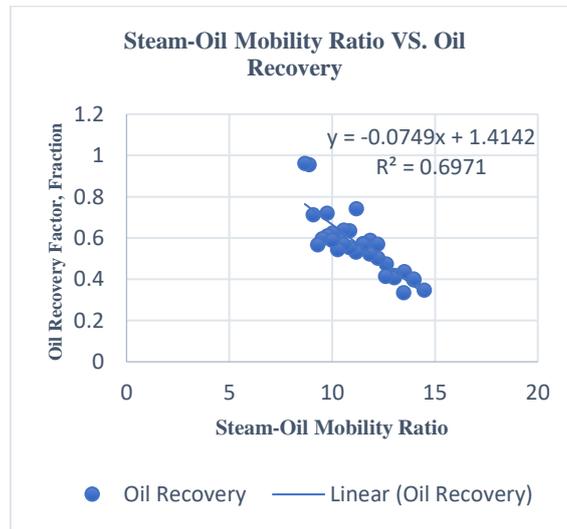


Figure 4.6: Steam-oil mobility ratio

Figure 4.7 describes the effects of dispersion number on oil recovery. It is certainly seen that with increasing dispersion factor the oil recovery is slightly increasing. Sometimes, the recovery is decreasing with increasing dispersion factor, and it does not follow any definitive trend. There is a weak relationship exists between oil recovery and dispersion factor, if other properties remain same.

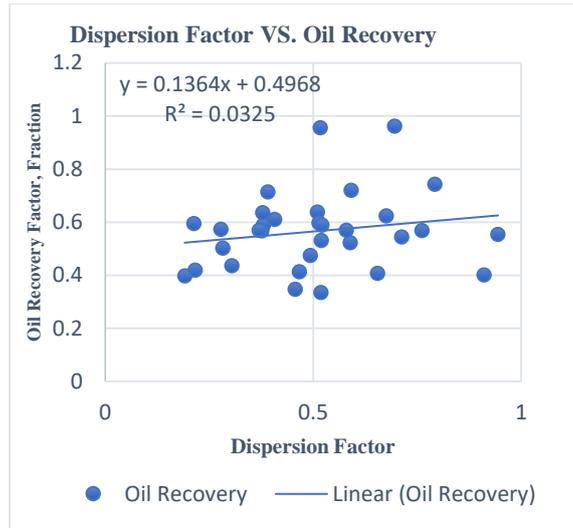


Figure 4.7: Dispersion factor

Figure 4.8 and 4.9 shows the effects of gravity number on oil recovery. Gravity number refers to the ratio of gravity forces to viscous forces. There are two gravity numbers used in this study: oil-water gravity number and steam-oil gravity number. There exists a larger density difference between fluids which indicate a larger value of gravity number. When using an injection fluid such as steam to displace oil, gravity segregation occurs which is more noticeable as the heavy oil moves downhill in the reservoir and steam flows over it. As the gravity number increases for both oil-water (figure 4.8) and steam-oil (figure 4.9), the oil recovery is slight increases. The density difference between fluids is not very large based on the selected conditions, so it is predictable that gravity number will not have a great effect on oil recovery which indicates in figure 4.8 and 4.9.

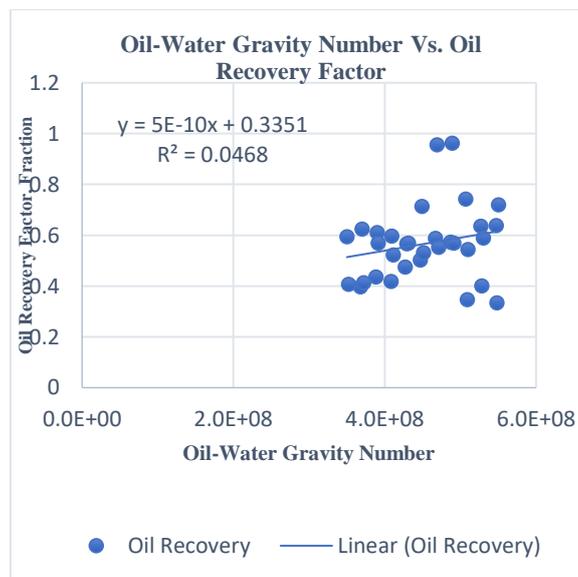


Figure 4.8: Water-oil gravity number

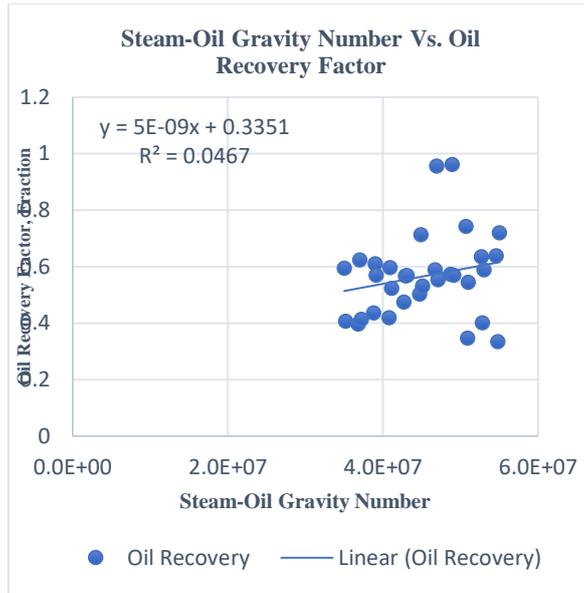


Figure 4.9: Steam-oil gravity number

The effects of effective aspect ratio, R_L on oil recovery is presented in figure 4.10. R_L can describe the cross flow of reservoir fluids in the longitudinal direction to transverse direction. If it becomes zero, then there is no interaction between fluids in the vertical and the horizontal direction. If there exists a large aspect ratio, it indicates a quicker reduction of fluid fluctuations in the vertical direction compared to horizontal direction (Johns and Garmeh, 2010). On the other hand, a smaller ratio can lead to increase the fluid interaction in the horizontal direction to vertical direction (Rai, 2008). There exists a level of cross-flow in the aspect ratio which is a crucial factor that influences the mixing of reservoir fluids. So, the aspect ratio can affect the dispersion and hence the Peclet number. From figure 4.9, the aspect ratio does not follow a definitive trend which is also true for Peclet number.

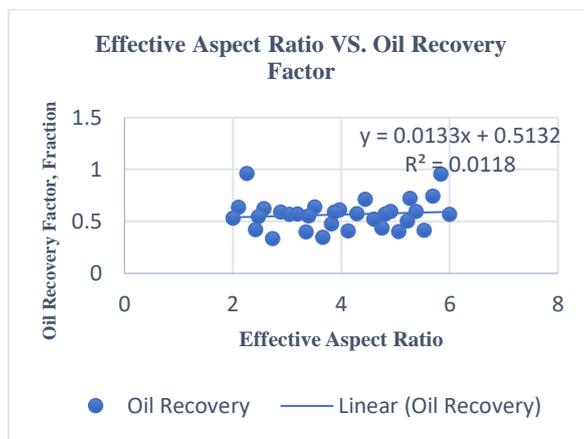


Figure 4.10: Effective aspect ratio

Capillary number is termed as the ratio of viscous to capillary forces. Different forms of the capillary numbers are used in literature (Cense and Berg, 2009). Figure 4.11, describes the effects of capillary number on oil recovery. As the capillary number decreases the oil recovery is increases, and it follows an inverse trend.

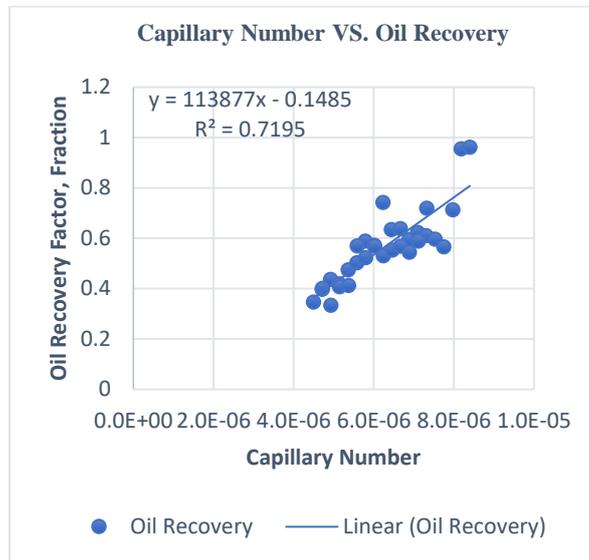


Figure 4.11: Capillary number

The Dykstra-Parsons coefficient is used to account the reservoir heterogeneity. It is an additional input variable in defining the effect of oil recovery. The range of Dykstra-Parsons coefficient lies between 0 to 1. 0 indicates the reservoir is completely homogeneous, and 1 indicates the reservoir is completely heterogeneous. Figure 4.12 shows the effects of Dykstra-Parsons coefficient on oil recovery. There is no definitive trend that it can follow.

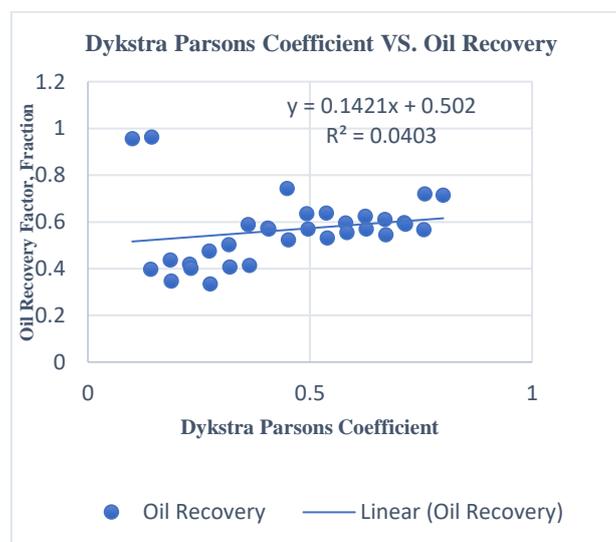


Figure 4.12: Dykstra-Parsons coefficient

The steam additive is a crucial factor which is added to the steam to increase the oil recovery. Figure 4.13 shows the effects of additive concentration on oil recovery. As the additive concentration is increasing from 0.1 to 0.5, the oil recovery is also increasing from 38% to 81%.

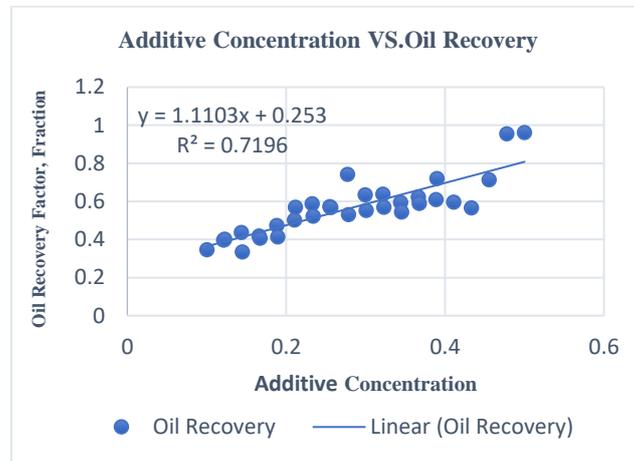


Figure 4.13: Additive concentration

Figure 4.14 describes the effects of steam-oil viscosity ratio on oil recovery factor. As the steam-oil viscosity is increasing the oil recovery is also increasing. This is because steam is injected into the reservoir which will decrease the viscosity of oil phase thus increase the steam-oil viscosity ratio and hence increase the oil recovery.

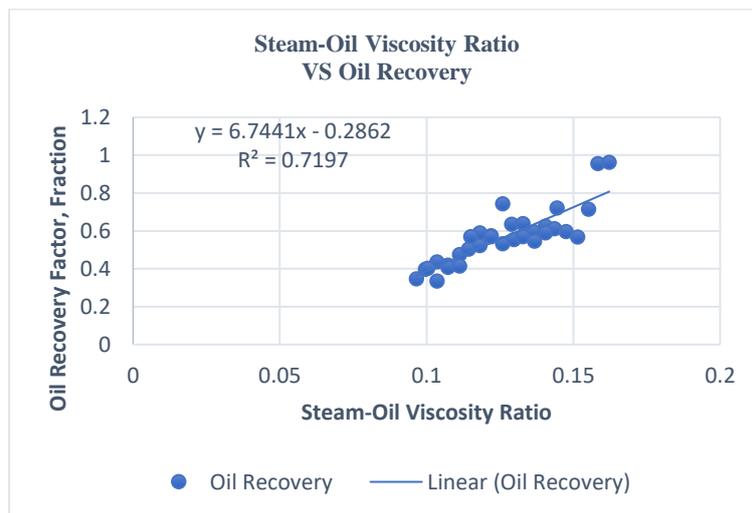


Figure 4.14: Steam-oil viscosity ratio

4.5. New proposed number and its significance

The recovery of oil obtained through the studies of scaling numbers were investigated using gravity and capillary numbers to improve a relationship that captures influential process

controlling parameters. It is found that the oil recovery is directly proportional to gravity numbers and inversely proportional to the capillary number. The results obtained from figure 4.6 and 4.7 suggested that, though the gravity number can provide accurate and closely matched relationship, but few other variables should be studied for the estimation of oil recovery. The pore trapping of oil behind the steam flood front is caused by capillary retention which diminishes the oil recovery performance for steam flooding process. Therefore, capillary force effects must be studied for assessing steam flooding process performance. Moreover, the results show that the mobility ratio and the oil viscosity changes have a profound effect on oil recovery. Figure 4.14 suggests that oil recovery is increased with increasing viscosity ratio (viscosity of steam to oil). Therefore, the mobility ratios and viscosity ratio should be considered for proposing new dimensionless number. A new relationship is proposed in this study from the above findings to characterize and evaluate the performance of steam flooding EOR process. The capillary number, gravity number, mobility ratio and the viscosity ratio are considered to develop this correlation. The proposed new dimensionless number is presented as:

$$N_A = \frac{\left(\frac{\mu_{Steam}}{\mu_o}\right)(N_{Gwo} + N_{Gog})^a}{M_{go}M_{wo}N_C} \quad (16)$$

where, $a = 0.2$

Parameters “a” in the above relationship is considered as the scaling factor. Oil recovery factor obtained in this study for steam flooding EOR process against this proposed number is presented in figure 4.15. Oil recovery displayed in this figure is at the scaling of 0.2. However, the scaling factors would be different for different pore volume steam injected into the formation. There exists an excellent relationship between newly proposed dimensionless number and oil recovery with very low data distortion which is displayed in figure 4.15. The relationship looks more complex in nature but can reasonably capture the significant multiphase flow parameters in both homogeneous and heterogeneous reservoirs. The main importance of this proposed number is that it can be used to predict the performance of a steam flooding EOR field projects. It can also provide the data needed for the estimation of dimensionless group which is provided for the analysis.

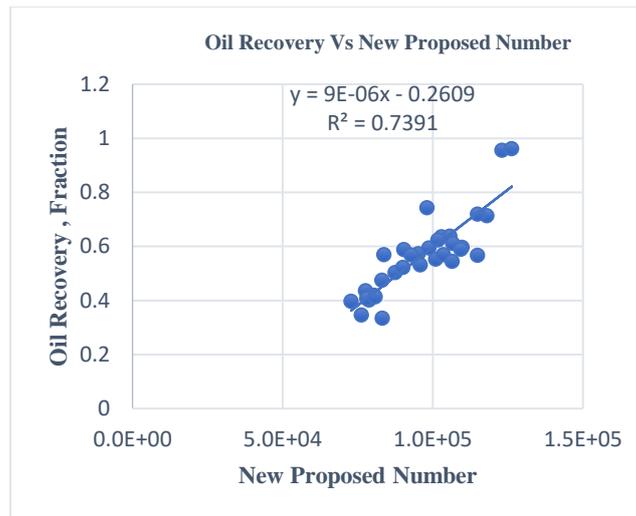


Figure 4.15: New proposed number

4.6. Critical analysis and observations

One laboratory scale and three reservoir scales are studied through the effective combination of developed dimensionless groups. The effect of longitudinal and transverse Peclet number on recovery is negligible. Oil recovery is slightly increasing with increasing longitudinal Peclet number and slightly decreasing with increasing transverse Peclet number which is shown in figure 4.3 and 4.4. On the other hand, mobility ratio has a significant effect on oil recovery shown in figure 4.5 and 4.6. Oil recovery factor is slightly affected by dispersion number. Oil recovery is slightly increased with increasing dispersion number (figure 4.7). Oil recovery factor is increasing with decreasing water-oil and steam-oil mobility ratio. It is an obvious reason because the viscosity of the oil phase is decreasing which is the result of increasing oil recovery. The gravity number had an impact on oil recovery which is shown in figure 4.8 and 4.9. Oil recovery factor has increased with increasing water-oil and steam-oil gravity numbers. The viscosity of the flowing phase is decreasing with time which is ultimately increased the gravity number hence increased the recovery. Effective aspect ratio has a slight effect on oil recovery if other properties are considered constant shown in figure 4.10. If other properties are changing, then it can greatly affect the recovery of oil. Water-oil capillary number influences recovery of oil. As the capillary number is decreasing the recovery of oil is increased shown in figure 4.10. Beside these dimensionless numbers, there are two factors which are considered to build a model to predict oil recovery factor. Dimensionless additive concentration is added as a parameter to analyze the impact of additive concentration on oil recovery. The range of additive concentration is from 0.1% wt. to 0.5% wt. Another additional dimensionless

factor, the Dykstra-Parsons coefficient is added as an input parameter to predict the heterogeneity of the reservoir. It can be defined as:

$$F_{DP} = \frac{k_{0.5} - k_{0.84}}{k_{0.5}} \quad (17)$$

Where $k_{0.5}$ = Median of the permeability

$k_{0.84}$ = One standard deviation from the median permeability

The value of F_{DP} should be lies on 0 to 1. Here 0 representing homogeneous reservoir and 1 represents heterogeneous reservoir. The minimum and maximum value of F_{DP} lies between 0.1 to 0.8 for this study. Oil recovery is increased with increasing additive concentration (figure 13) and increasing Dykstra-Parsons coefficient (figure 4.12).

Conclusions and recommendations

The noteworthy contribution of this study is to develop a novel scaling criteria development approach considering rock and fluid memory concept. Dimensionless numbers are derived using inspectional and dimensional analysis. A rigorous procedure of inspectional analysis is applied using constitutive equations, their initial and boundary conditions to derive the dimensionless groups. Overall, 176 dimensionless groups were initially obtained. The groups which have little or no effect on a specific process were eliminated, and finally, 18 dimensionless groups were found. Three synthetic reservoir models with different physical properties and equal dimensionless numbers are considered with laboratory model to evaluate their effect on oil recovery. Variable results were observed corresponding to the degree of heterogeneity for synthetic reservoirs. The proposed new dimensionless group is specially developed for steam flooding EOR process which can capture important process controlling parameters and work as a useful tool for predicting the performance of a reservoir. It can capture the parameters which can affect the developed methodology as well as the investigated process. It can be further improved by addressing some drawbacks that can be monitored during the conduction of this research. A research to explore the effect of different permeability can be performed in further studies.

Acknowledgements

The authors would like to thank School of Graduate Studies of Memorial University of Newfoundland, Research & Development Corporation of Newfoundland and Labrador (RDC),

funding no. 210992; and Statoil Canada Ltd., funding no. 211162 for providing financial support to accomplish this research.

Nomenclature

A	Area, m^2	V_f	Fluid Volume, m^3
L	Reservoir Length, m	σ_{go}	Interfacial Tension between Gas and Oil Phase, kg/s^2
W	Reservoir Width, m	σ_{ow}	Interfacial Tension between Oil and Gas Phase, kg/s^2
H	Reservoir Thickness, m	ν	Dynamic Viscosity, s/m^2
c	Compressibility, $m s^2/kg$	μ	Viscosity, kg/ms
ϕ	Porosity, Fraction	ρ	Density, kg/m^3
k	Permeability, m^2	r	Pore Throat Radius, m
k_r	Relative Permeability, m^2/m^2	g	Gravitational Acceleration, m/s^2
P	Pressure, kg/ms^2	τ	Tortuosity
q_i	Injection Rate, m^3/s	K	Thermal Conductivity, $W/m.K$
q_{ia}	Injection Rate of Additive, m^3/s	C_p	Specific Heat Capacity, $j/kg.K$
q_{prod}	Production Rate, m^3/s	h	Enthalpy, j/kg
D_{Ta}	Transverse Dispersion of Additive, m^2/s	L_v	Latent Heat, j/kg
D_{La}	Longitudinal Dispersion of Additive, m^2/s	ξ	Dummy variable for time, s
S	Saturation	Subscript	
θ	Contact Angle	f	Fluid
t	Time, s	o	Oil Phase
T	Reservoir Temperature, $^{\circ}C$	w	Water Phase
E	Additive Concentration	g	Gaseous Phase
U	Total Velocity, m/s	i	Initial

u	Velocity, m/s	r	Rock or Reservoir
V_r	Reservoir Volume, m^3	t	Total

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Appendix A

Table 4.1A: Input parameters with dimensions for dimensional analysis

No.	Variables	Definition	Units	Dimensions
1	A	Area	m^2	$[L^2]$
2	L	Reservoir Length	m	$[L]$
3	W	Reservoir Width	m	$[L]$
4	H	Reservoir Thickness	m	$[L]$
5	c_r	Rock Compressibility	$m s^2/kg$	$[Lt^2/M]$
6	c_f	Fluid Compressibility	$m s^2/kg$	$[Lt^2/M]$
7	c_o	Oil Compressibility	$m s^2/kg$	$[Lt^2/M]$
8	c_g	Gas Compressibility	$m s^2/kg$	$[Lt^2/M]$
9	c_w	Water Compressibility	$m s^2/kg$	$[Lt^2/M]$
10	c_t	Total Compressibility	$m s^2/kg$	$[Lt^2/M]$
11	ϕ	Porosity		
12	k	Permeability	m^2	$[L^2]$
13	k_r	Relative Permeability	m^2/m^2	$[L^2/L^2]$
14	P_i	Initial Reservoir Pressure	kg/ms^2	$[M/Lt^2]$
15	P_o	Oil phase Pressure	kg/ms^2	$[M/Lt^2]$
16	P_w	Water phase Pressure	kg/ms^2	$[M/Lt^2]$
17	P_g	Gas phase Pressure	kg/ms^2	$[M/Lt^2]$
18	P_{cgo}	Gas-Oil Capillary Pressure	kg/ms^2	$[M/Lt^2]$
19	P_{cow}	Oil-Water Capillary Pressure	kg/ms^2	$[M/Lt^2]$
20	q_i	Injection Rate	m^3/s	$[L^3/t]$
21	q_{ia}	Injection Rate of Additive	m^3/s	$[L^3/t]$
22	q_{prod}	Production Rate	m^3/s	$[L^3/t]$
23	D_{Ta}	Transverse Dispersion of Additive	m^2/s	$[L^2/t]$

24	D_{La}	Longitudinal Dispersion of Additive	m^2/s	$[L^2/t]$
25	S_g	Gas Saturation		
26	S_o	Oil Saturation		
27	S_w	Water Saturation		
28	θ	Contact Angle		
29	t	time	s	$[t]$
30	T	Reservoir Temperature	$^{\circ}c$	$[T]$
31	U	Total Velocity	m/s	$[L/t]$
32	u_o	Oil Velocity	m/s	$[L/t]$
33	u_w	Water Velocity	m/s	$[L/t]$
34	u_g	Gas Velocity	m/s	$[L/t]$
35	V_r	Reservoir Volume	m^3	$[L^3]$
36	V_f	Fluid Volume	m^3	$[L^3]$
37	σ_{go}	Interfacial Tension between Gas and Oil Phase	kg/s^2	$[M/t^2]$
38	σ_{ow}	Interfacial Tension between Oil and Gas Phase	kg/s^2	$[M/t^2]$
39	ν	Dynamic Viscosity	s/m^2	$[t/L^2]$
40	μ_o	Oil Viscosity	kg/ms	$[M/Lt]$
41	μ_w	Water Viscosity	kg/ms	$[M/Lt]$
42	μ_g	Gas Viscosity	kg/ms	$[M/Lt]$
43	ρ_g	Gas Density	kg/m^3	$[M/L^3]$
44	ρ_o	Oil Density	kg/m^3	$[M/L^3]$
45	ρ_w	Water Density	kg/m^3	$[M/L^3]$
46	$\Delta\rho$	Density Difference between Phases	kg/m^3	$[M/L^3]$
47	r	Pore Throat Radius	m	$[L]$
48	g	Gravitational Acceleration	m/s^2	$[L/t^2]$
49	τ	Tortuosity		

50	K_f	Thermal Conductivity of Reservoir Fluid	$W/m.K$	$[ML/t^3 T]$
51	K_g	Thermal Conductivity of Injected Fluid	$W/m.K$	$[ML/t^3 T]$
52	K_w	Thermal Conductivity of Water	$W/m.K$	$[ML/t^3 T]$
53	K_r	Thermal Conductivity of Reservoir Rock	$W/m.K$	$[ML/t^3 T]$
54	K_o	Thermal Conductivity of Oil	$W/m.K$	$[ML/t^3 T]$
55	C_{pf}	Specific Heat Capacity of reservoir Fluid	$j/kg.K$	$[L^2/t^2 T]$
56	C_{pg}	Specific Heat Capacity of injected Fluid	$j/kg.K$	$[L^2/t^2 T]$
57	C_{pr}	Specific Heat Capacity of Reservoir Rock	$j/kg.K$	$[L^2/t^2 T]$
58	C_{pw}	Specific Heat Capacity of reservoir Water	$j/kg.K$	$[L^2/t^2 T]$
59	h_w	Enthalpy of the Water	j/kg	$[L^2/t^2]$
60	h_o	Enthalpy of the Oil	j/kg	$[L^2/t^2]$
61	h_g	Enthalpy of the Gas	j/kg	$[L^2/t^2]$
62	h_r	Enthalpy of the Reservoir Rock	j/kg	$[L^2/t^2]$
63	L_v	Latent Heat	j/kg	$[L^2/t^2]$
64	ξ	Dummy variable for time	s	$[t]$

1. Number of variables = $n = 64$
2. Fundamental dimensions = $K = 4$ which are: $[L, T, M, t]$
3. $K \rightarrow L, T, \rho_o, C_{pf}$
4. Find dimensionless products (π 's) until $n-K = 60$

Detail derivation of scaling criteria are given below.

The new term U_x and f_x are introduced for the summation of velocity and the fraction of total velocity.

$$U_x = u_{xo} + u_{xw} + u_{xg} \quad (A1)$$

$$U_z = u_{zo} + u_{zw} + u_{zg} \quad (A2)$$

$$f_{xo} = \frac{u_{xo}}{U_x} \quad (A3)$$

$$f_{zo} = \frac{u_{zo}}{U_z} \quad (A4)$$

$$f_{xw} = \frac{u_{xw}}{U_x} = 1 - f_{xo} - f_{xg} \quad (A5)$$

$$f_{zw} = \frac{u_{zw}}{U_z} = 1 - f_{zo} - f_{zg} \quad (A6)$$

$$f_{xg} = \frac{u_{xg}}{U_x} = 1 - f_{xo} - f_{xw} \quad (A7)$$

$$f_{zg} = \frac{u_{zg}}{U_z} = 1 - f_{zo} - f_{zw} \quad (A8)$$

Now putting the values of u_x and u_z into equation (7) to (12) we get,

$$U_x f_{xo} = -\frac{\eta_o}{\Gamma(1-\alpha)} \int_0^t (t-\xi)^{-\alpha} \frac{\partial^2 p_o}{\partial \xi \partial x} d\xi \quad (A9)$$

$$U_z f_{zo} = -\frac{\eta_o}{\Gamma(1-\alpha)} \int_0^t (t-\xi)^{-\alpha} \frac{\partial^2 p_o}{\partial \xi \partial z} d\xi \quad (A10)$$

$$U_x f_{xw} = -\frac{\eta_w}{\Gamma(1-\alpha)} \int_0^t (t-\xi)^{-\alpha} \frac{\partial^2 p_w}{\partial \xi \partial x} d\xi \quad (A11)$$

$$U_z f_{zw} = -\frac{\eta_w}{\Gamma(1-\alpha)} \int_0^t (t-\xi)^{-\alpha} \frac{\partial^2 p_w}{\partial \xi \partial z} d\xi \quad (A12)$$

$$U_x (1 - f_{xo} - f_{xw}) = -\frac{\eta_g}{\Gamma(1-\alpha)} \int_0^t (t-\xi)^{-\alpha} \frac{\partial^2 p_g}{\partial \xi \partial x} d\xi \quad (A13)$$

$$U_z (1 - f_{zo} - f_{zw}) = -\frac{\eta_g}{\Gamma(1-\alpha)} \int_0^t (t-\xi)^{-\alpha} \frac{\partial^2 p_g}{\partial \xi \partial z} d\xi \quad (A14)$$

Capillary pressure of oil-water system can be written as

$$p_{cow} = p_o - p_w \quad (A15)$$

Differentiating equation (A15) with respect to x and ξ we get,

$$\frac{\partial^2 p_{cow}}{\partial \xi \partial x} = \frac{\partial^2 p_o}{\partial \xi \partial x} - \frac{\partial^2 p_w}{\partial \xi \partial x} \quad (A16)$$

$$\frac{\partial^2 p_{cow}}{\partial \xi \partial z} = \frac{\partial^2 p_o}{\partial \xi \partial z} - \frac{\partial^2 p_w}{\partial \xi \partial z} \quad (A17)$$

Capillary pressure for gas-oil system can be written as

$$p_{go} = p_g - p_o \quad (A18)$$

Differentiating equation (A18) with respect to x and ξ we get,

$$\frac{\partial^2 p_{go}}{\partial \xi \partial x} = \frac{\partial^2 p_g}{\partial \xi \partial x} - \frac{\partial^2 p_o}{\partial \xi \partial x} \quad (A19)$$

$$\frac{\partial^2 p_{go}}{\partial \xi \partial z} = \frac{\partial^2 p_g}{\partial \xi \partial z} - \frac{\partial^2 p_o}{\partial \xi \partial z} \quad (A20)$$

Putting the values of equation (A17) and (A20) into equation (A9), (A10), (A13) and (A14) we get,

$$U_x f_{xo} = -\frac{\eta_o}{\Gamma(1-\alpha)} \int_0^t (t-\xi)^{-\alpha} \left[\frac{\partial^2 p_w}{\partial \xi \partial x} + \frac{\partial^2 p_{cow}}{\partial \xi \partial x} \right] d\xi \quad (A21)$$

$$U_z f_{zo} = -\frac{\eta_o}{\Gamma(1-\alpha)} \int_0^t (t-\xi)^{-\alpha} \left[\frac{\partial^2 p_w}{\partial \xi \partial z} + \frac{\partial^2 p_{cow}}{\partial \xi \partial z} \right] d\xi \quad (A22)$$

$$U_x f_{xw} = -\frac{\eta_w}{\Gamma(1-\alpha)} \int_0^t (t-\xi)^{-\alpha} \frac{\partial^2 p_w}{\partial \xi \partial x} d\xi \quad (\text{A23})$$

$$U_z f_{zw} = -\frac{\eta_w}{\Gamma(1-\alpha)} \int_0^t (t-\xi)^{-\alpha} \frac{\partial^2 p_w}{\partial \xi \partial z} d\xi \quad (\text{A24})$$

$$U_x(1-f_{xo}-f_{xw}) = -\frac{\eta_g}{\Gamma(1-\alpha)} \int_0^t (t-\xi)^{-\alpha} \left[\frac{\partial^2 p_w}{\partial \xi \partial x} + \frac{\partial^2 p_{cow}}{\partial \xi \partial x} + \frac{\partial^2 p_{cgo}}{\partial \xi \partial x} \right] d\xi \quad (\text{A25})$$

$$U_z(1-f_{zo}-f_{zw}) = -\frac{\eta_g}{\Gamma(1-\alpha)} \int_0^t (t-\xi)^{-\alpha} \left[\frac{\partial^2 p_w}{\partial \xi \partial z} + \frac{\partial^2 p_{cow}}{\partial \xi \partial z} + \frac{\partial^2 p_{cgo}}{\partial \xi \partial z} \right] d\xi \quad (\text{A26})$$

Adding equation (A21), (A23) and (A25) we get,

$$U_x f_{xo} + U_x f_{xw} + U_x(1-f_{xo}-f_{xw}) = -\frac{(\eta_o+\eta_w+\eta_g)}{\Gamma(1-\alpha)} \int_0^t (t-\xi)^{-\alpha} \left[\frac{\partial^2 p_w}{\partial \xi \partial x} \right] d\xi - \frac{(\eta_o+\eta_g)}{\Gamma(1-\alpha)} \int_0^t (t-\xi)^{-\alpha} \left[\frac{\partial^2 p_{cgo}}{\partial \xi \partial x} \right] d\xi - \frac{\eta_g}{\Gamma(1-\alpha)} \int_0^t (t-\xi)^{-\alpha} \left[\frac{\partial^2 p_{cow}}{\partial \xi \partial x} \right] d\xi \quad (\text{A27})$$

Now, putting the value of u_{xw} into equation (13) we get

$$\frac{\partial}{\partial x}(1-f_{xo}-f_{xw})U_x E_{w1} + \frac{\partial}{\partial x}(1-f_{xo}-f_{xw})U_x E_{w3} + \frac{\partial}{\partial x}(1-f_{xo}-f_{xw})U_x E_{w4} + \phi D_{Lw1} \frac{\partial^2}{\partial x^2} E_{w1} + \phi D_{Lw3} \frac{\partial^2}{\partial x^2} E_{w3} + \phi D_{Lw4} \frac{\partial^2}{\partial x^2} E_{w4} = \phi \frac{\partial}{\partial t} s_w E_{w1} + \phi \frac{\partial}{\partial t} s_w E_{w3} + \phi \frac{\partial}{\partial t} s_w E_{w4} \quad (\text{A28})$$

$$\Rightarrow (1-f_{xo}-f_{xw})E_{w1} \frac{\partial}{\partial x} U_x + (1-f_{xo}-f_{xw})U_x E_{w1} \frac{\partial}{\partial x} (1-f_{xo}-f_{xw}) + (1-f_{xo}-f_{xw})E_{w3} \frac{\partial}{\partial x} U_x + (1-f_{xo}-f_{xw})U_x E_{w3} \frac{\partial}{\partial x} (1-f_{xo}-f_{xw}) + (1-f_{xo}-f_{xw})E_{w4} \frac{\partial}{\partial x} U_x + (1-f_{xo}-f_{xw})U_x E_{w4} \frac{\partial}{\partial x} (1-f_{xo}-f_{xw}) + \phi D_{Lw1} \frac{\partial^2}{\partial x^2} E_{w1} + \phi D_{Lw3} \frac{\partial^2}{\partial x^2} E_{w3} + \phi D_{Lw4} \frac{\partial^2}{\partial x^2} E_{w4} = \phi \frac{\partial}{\partial t} s_w E_{w1} + \phi \frac{\partial}{\partial t} s_w E_{w3} + \phi \frac{\partial}{\partial t} s_w E_{w4} \quad (\text{A29})$$

Since $\frac{\partial}{\partial x}(U_x) = 0$

$$(1-f_{xo}-f_{xw})U_x E_{w1} \frac{\partial}{\partial x} (1-f_{xo}-f_{xw}) + (1-f_{xo}-f_{xw})U_x E_{w3} \frac{\partial}{\partial x} (1-f_{xo}-f_{xw}) + (1-f_{xo}-f_{xw})U_x E_{w4} \frac{\partial}{\partial x} (1-f_{xo}-f_{xw}) + \phi D_{Lw1} \frac{\partial^2}{\partial x^2} E_{w1} + \phi D_{Lw3} \frac{\partial^2}{\partial x^2} E_{w3} + \phi D_{Lw4} \frac{\partial^2}{\partial x^2} E_{w4} = \phi \frac{\partial}{\partial t} s_w E_{w1} + \phi \frac{\partial}{\partial t} s_w E_{w3} + \phi \frac{\partial}{\partial t} s_w E_{w4} \quad (\text{A30})$$

Putting the value of U_x into equation (A30) we get,

$$(1-f_{xo}-f_{xw}) \left[-\frac{(\eta_o+\eta_w+\eta_g)}{\Gamma(1-\alpha)} \int_0^t (t-\xi)^{-\alpha} \left[\frac{\partial^2 p_w}{\partial \xi \partial x} \right] d\xi - \frac{(\eta_o+\eta_g)}{\Gamma(1-\alpha)} \int_0^t (t-\xi)^{-\alpha} \left[\frac{\partial}{\partial \xi} \left(\frac{\partial p_{cow}}{\partial s_w} \frac{\partial s_w}{\partial x} \right) \right] d\xi - \frac{\eta_g}{\Gamma(1-\alpha)} \int_0^t (t-\xi)^{-\alpha} \left[\frac{\partial}{\partial \xi} \left(\frac{\partial p_{cgo}}{\partial s_g} \frac{\partial s_g}{\partial x} \right) \right] d\xi \right] E_{w1} \frac{\partial}{\partial x} (1-f_{xo}-f_{xw}) + (1-f_{xo}-f_{xw}) \left[-\frac{(\eta_o+\eta_w+\eta_g)}{\Gamma(1-\alpha)} \int_0^t (t-\xi)^{-\alpha} \left[\frac{\partial^2 p_w}{\partial \xi \partial x} \right] d\xi - \frac{(\eta_o+\eta_g)}{\Gamma(1-\alpha)} \int_0^t (t-\xi)^{-\alpha} \left[\frac{\partial}{\partial \xi} \left(\frac{\partial p_{cow}}{\partial s_w} \frac{\partial s_w}{\partial x} \right) \right] d\xi - \frac{\eta_g}{\Gamma(1-\alpha)} \int_0^t (t-\xi)^{-\alpha} \left[\frac{\partial}{\partial \xi} \left(\frac{\partial p_{cgo}}{\partial s_g} \frac{\partial s_g}{\partial x} \right) \right] d\xi \right] E_{w3} \frac{\partial}{\partial x} (1-f_{xo}-f_{xw}) + (1-f_{xo}-f_{xw}) \left[-\frac{(\eta_o+\eta_w+\eta_g)}{\Gamma(1-\alpha)} \int_0^t (t-\xi)^{-\alpha} \left[\frac{\partial^2 p_w}{\partial \xi \partial x} \right] d\xi - \frac{(\eta_o+\eta_g)}{\Gamma(1-\alpha)} \int_0^t (t-\xi)^{-\alpha} \left[\frac{\partial}{\partial \xi} \left(\frac{\partial p_{cow}}{\partial s_w} \frac{\partial s_w}{\partial x} \right) \right] d\xi - \frac{\eta_g}{\Gamma(1-\alpha)} \int_0^t (t-\xi)^{-\alpha} \left[\frac{\partial}{\partial \xi} \left(\frac{\partial p_{cgo}}{\partial s_g} \frac{\partial s_g}{\partial x} \right) \right] d\xi \right] E_{w4} \frac{\partial}{\partial x} (1-f_{xo}-f_{xw}) + \phi D_{Lw1} \frac{\partial^2}{\partial x^2} E_{w1} + \phi D_{Lw3} \frac{\partial^2}{\partial x^2} E_{w3} + \phi D_{Lw4} \frac{\partial^2}{\partial x^2} E_{w4} = \phi \frac{\partial}{\partial t} s_w E_{w1} + \phi \frac{\partial}{\partial t} s_w E_{w3} + \phi \frac{\partial}{\partial t} s_w E_{w4} \quad (\text{A31})$$

Constitutive equations

$$u_{xw} = -k_{xw} \lambda_{xw} \left(\frac{\partial p_w}{\partial x} + \rho_w g \sin \theta \right) \quad (\text{A32})$$

$$u_{xo} = -k_{xo} \lambda_{xo} \left(\frac{\partial p_o}{\partial x} + \rho_o g \sin \theta \right) \quad (\text{A33})$$

$$u_{xg} = -k_{xg} \lambda_{xg} \left(\frac{\partial p_g}{\partial x} + \rho_g g \sin \theta \right) \quad (\text{A34})$$

$$p_{cow} = \sigma_{ow} \cos \theta \sqrt{\frac{\phi}{k}} J(s_w) \quad (\text{A35})$$

$$p_{cgo} = \sigma_{go} \cos \theta \sqrt{\frac{\phi}{k}} J(s_o) \quad (\text{A36})$$

Saturation Constraint

$$s_w + s_o + s_g = 1 \quad (\text{A37})$$

$$S_{on} = \frac{s_o - s_{or}}{1 - s_{wi} - s_{or}} \quad (\text{A38})$$

$$S_{wn} = \frac{s_w - s_{wi}}{1 - s_{wi} - s_{or}} \quad (\text{A39})$$

$$S_{gn} = \frac{s_g - s_{gc}}{1 - s_{wi} - s_{or}} \quad (\text{A40})$$

$$t_n = \frac{U_t t}{L\phi(1 - s_{wi} - s_{or})} \quad (\text{A41})$$

Initial and boundary conditions

$$s_w = s_{wi} \text{ at } t = 0, \text{ and } x, z \quad (\text{A42})$$

$$s_g = s_{gi} \text{ at } t = 0, \text{ and } x, z \quad (\text{A43})$$

$$s_o = s_{oi} \text{ at } t = 0, \text{ and } x, z \quad (\text{A44})$$

$$E_{o1} = 0 \text{ at } t = 0, \text{ and } x, z \quad (\text{A45})$$

$$E_{g1} = 0 \text{ at } t = 0, \text{ and } x, z \quad (\text{A46})$$

$$E_{o2} = E_{2i} \text{ at } t = 0, \text{ and } x, z \quad (\text{A47})$$

$$E_{o4} = 0 \text{ at } t = 0, \text{ and } x, z \quad (\text{A48})$$

$$E_{w1} = 0 \text{ at } t = 0, \text{ and } x, z \quad (\text{A49})$$

$$E_{w3} = E_{3i} \text{ at } t = 0, \text{ and } x, z \quad (\text{A50})$$

$$E_{w4} = 0 \text{ at } t = 0, \text{ and } x, z \quad (\text{A51})$$

$$E_{g1} = E_{1j} \text{ at } x = 0, \text{ and } t, z \quad (\text{A52})$$

$$E_{o1} = 0 \text{ at } x = 0, \text{ and } t, z \quad (\text{A53})$$

$$E_{o2} = 0 \text{ at } x = 0, \text{ and } t, z \quad (\text{A54})$$

$$E_{o4} = 0 \text{ at } x = 0, \text{ and } t, z \quad (\text{A55})$$

$$E_{w1} = 0 \text{ at } x = 0, \text{ and } t, z \quad (\text{A56})$$

$$E_{w3} = 0 \text{ at } x = 0, \text{ and } t, z \quad (\text{A57})$$

$$E_{w4} = E_{4j} \text{ at } x = 0, \text{ and } t, z \quad (\text{A58})$$

$$p_g = \Delta p_g + p_o g(H - z) \text{ at } x = L, \text{ and } t, z \quad (\text{A59})$$

$$p_o = \Delta p_o + p_o g(H - z) \text{ at } x = L, \text{ and } t, z \quad (\text{A60})$$

$$p_w = \Delta p_w + p_w g(H - z) \text{ at } x = L, \text{ and } t, z \quad (\text{A61})$$

$$u_{gz} = u_{oz} = u_{wz} = 0 \text{ at } z = 0, \text{ and } x, t \quad (\text{A62})$$

$$u_{gz} = u_{oz} = u_{wz} = 0 \text{ at } z = H, \text{ and } x, t \quad (\text{A63})$$

$$\frac{1}{H} \int_0^H u_{gx} dz = u_r \text{ at } x = 0, \text{ and } z, t \quad (\text{A64})$$

$$P(x, 0) = p_i \text{ in dimensionless form, as } \frac{p_R}{p_i} p_D(i_D, 0) = 1, i = x, z \quad (\text{A65})$$

The external boundary is closed which no flow boundary is considered. The interior boundary is considered as a constant production rate boundary.

According to Darcy's law outer boundary

$$u_{x=L} = -\frac{k}{\mu} \frac{\partial p}{\partial x} = 0, \text{ which can be written in dimensionless form as } \left[\frac{\partial p_D}{\partial x_D} \right]_{x_D=x_i/L} = 0 \quad (\text{A66})$$

$$\text{Similarly, } u_{z=H} = -\frac{k}{\mu} \frac{\partial p}{\partial z} = 0, \text{ which can be written in dimensionless form as } \left[\frac{\partial p_D}{\partial z_D} \right]_{z_D=z_i/H} = 0 \quad (\text{A67})$$

According to Darcy's law inner boundary

$$q_{x=0} = Au_x = \frac{-kA_{yz}}{\mu} \frac{\partial p}{\partial x} \text{ which can be written in dimensionless form as}$$

$$q_{xD} q_{xR} = - \left(\frac{k_R k_D A_{yzR} A_{yzD}}{\mu_R \mu_D} \right) \left(\frac{p_R \partial p_D}{x_R \partial x_D} \right) \quad (\text{A68})$$

$$q_{xD} = - \left(\frac{k_R p_R A_{yzR}}{q_{xR} \mu_R x_R} \right) \left(\frac{k_D A_{yzD} \partial p_D}{\mu_D \partial x_D} \right) \quad (\text{A69})$$

Similarly, we find

$$q_{zD} = - \left(\frac{k_R p_R A_{xyR}}{q_{zR} \mu_R z_R} \right) \left(\frac{k_D A_{xyD} \partial p_D}{\mu_D \partial z_D} \right) \quad (\text{A70})$$

Table 4.2A: Multiplicative Factors

$u_{ox} = u_{oxR} u_{oxD}$	$S_w = S_{wR} S_{wD}$	$\eta_o = \eta_{oR} \eta_{oD}$	$k_{xo} = k_{xoR} k_{xoD}$
$u_{oz} = u_{ozR} u_{ozD}$	$S_o = S_{oR} S_{oD}$	$\eta_w = \eta_{wR} \eta_{wD}$	$k_{zo} = k_{zoR} k_{zoD}$
$u_{wx} = u_{wxR} u_{wxD}$	$S_g = S_{gR} S_{gD}$	$\eta_g = \eta_{gR} \eta_{gD}$	$k_{xw} = k_{xwR} k_{xwD}$
$u_{wz} = u_{wzR} u_{wzD}$	$\rho_o = \rho_{oR} \rho_{oD}$	$E_{o2} = E_{o2R} E_{o2D}$	$k_{zw} = k_{zwR} k_{zwD}$
$u_{gx} = u_{gxR} u_{gxD}$	$\rho_w = \rho_{wR} \rho_{wD}$	$E_{o4} = E_{o4R} E_{o4D}$	$k_{xg} = k_{xgR} k_{xgD}$
$u_{gz} = u_{gzR} u_{gzD}$	$\rho_g = \rho_{gR} \rho_{gD}$	$E_{w3} = E_{w3R} E_{w3D}$	$k_{zg} = k_{zgR} k_{zgD}$
$t = t_R t_D$	$p_o = p_{oR} p_{oD}$	$E_{w4} = E_{w4R} E_{w4D}$	$\mu_o = \mu_{oR} \mu_{oD}$
$x = x_R x_D$	$p_w = p_{wR} p_{wD}$	$E_{g1} = E_{g1R} E_{g1D}$	$\mu_w = \mu_{wR} \mu_{wD}$
$z = z_R z_D$	$p_g = p_{gR} p_{gD}$	$E_{g2} = E_{g2R} E_{g2D}$	$\mu_g = \mu_{gR} \mu_{gD}$

Development of dimensionless group

Multiplicative factors are used here to develop dimensionless groups

Dimensionless groups from aqueous phase

$$\begin{aligned} & \frac{E_{w1R} u_{xwR}}{x_R} \frac{\partial}{\partial x_D} E_{w1D} u_{xwD} + \frac{E_{w1R} u_{zwR}}{z_R} \frac{\partial}{\partial z_D} E_{w1D} u_{zwD} + \frac{E_{w3R} u_{xwR}}{x_R} \frac{\partial}{\partial x_D} E_{w3D} u_{xwD} + \frac{E_{w3R} u_{zwR}}{z_R} \frac{\partial}{\partial z_D} E_{w3D} u_{zwD} + \frac{E_{w4R} u_{xwR}}{x_R} \frac{\partial}{\partial x_D} E_{w4D} u_{xwD} + \\ & \frac{E_{w4R} u_{zwR}}{z_R} \frac{\partial}{\partial z_D} E_{w4D} u_{zwD} + \phi \frac{D_{Lw1R} E_{w1R}}{x_R^2} \frac{\partial^2}{\partial x_D^2} E_{w1D} + \phi \frac{D_{Tw1R} E_{w1R}}{z_R^2} \frac{\partial^2}{\partial z_D^2} E_{w1D} + \phi \frac{D_{Lw3R} E_{w3R}}{x_R^2} \frac{\partial^2}{\partial x_D^2} E_{w3D} + \phi \frac{D_{Tw3R} E_{w3R}}{z_R^2} \frac{\partial^2}{\partial z_D^2} E_{w3D} + \\ & \phi \frac{D_{Lw4R} E_{w4R}}{x_R^2} \frac{\partial^2}{\partial x_D^2} E_{w4D} + \phi \frac{D_{Tw4R} E_{w4R}}{z_R^2} \frac{\partial^2}{\partial z_D^2} E_{w4D} = \phi \frac{S_{wR} E_{w1R}}{t_R} \frac{\partial}{\partial t_D} S_{wD} E_{w1D} + \phi \frac{S_{wR} E_{w3R}}{t_R} \frac{\partial}{\partial t_D} S_{wD} E_{w3D} + \phi \frac{S_{wR} E_{w4R}}{t_R} \frac{\partial}{\partial t_D} S_{wD} \end{aligned} \quad (\text{A71})$$

$$\begin{aligned} &\Rightarrow \frac{t_R u_{xwR}}{\phi_{xR} s_{wR}} \frac{\partial}{\partial x_D} E_{w1D} u_{xwD} + \frac{t_R u_{zwR}}{\phi_{zR} s_{wR}} \frac{\partial}{\partial z_D} E_{w1D} u_{zwD} + \frac{t_R u_{xwR}}{\phi_{xR} s_{wR}} \frac{\partial}{\partial x_D} E_{w3D} u_{xwD} + \frac{t_R u_{zwR}}{\phi_{zR} s_{wR}} \frac{\partial}{\partial z_D} E_{w3D} u_{zwD} + \frac{t_R u_{xwR}}{\phi_{xR} s_{wR}} \frac{\partial}{\partial x_D} E_{w4D} u_{xwD} + \\ &\frac{t_R u_{zwR}}{\phi_{zR} s_{wR}} \frac{\partial}{\partial z_D} E_{w4D} u_{zwD} + \frac{D_{Lw1R} t_R}{x_R^2 s_{wR}} \frac{\partial^2}{\partial x_D^2} E_{w1D} + \frac{D_{Tw1R} t_R}{z_R^2 s_{wR}} \frac{\partial^2}{\partial z_D^2} E_{w1D} + \frac{D_{Lw3R} t_R}{x_R^2 s_{wR}} \frac{\partial^2}{\partial x_D^2} E_{w3D} + \frac{D_{Tw3R} t_R}{z_R^2 s_{wR}} \frac{\partial^2}{\partial z_D^2} E_{w3D} + \frac{D_{Lw4R} t_R}{x_R^2 s_{wR}} \frac{\partial^2}{\partial x_D^2} E_{w4D} + \frac{D_{Tw4R} t_R}{z_R^2 s_{wR}} \frac{\partial^2}{\partial z_D^2} E_{w4D} = \\ &\frac{\partial}{\partial t_D} S_{wD} E_{w1D} + \frac{\partial}{\partial t_D} S_{wD} E_{w3D} + \frac{\partial}{\partial t_D} S_{wD} E_{w4D} \end{aligned} \quad (A72)$$

Dimensionless groups from oleic phase

$$\begin{aligned} &\frac{E_{o1R} u_{xOR}}{x_R} \frac{\partial}{\partial x_D} E_{o1D} u_{xOD} + \frac{E_{o1R} u_{zOR}}{z_R} \frac{\partial}{\partial z_D} E_{o1D} u_{zOD} + \frac{E_{o2R} u_{xOR}}{x_R} \frac{\partial}{\partial x_D} E_{o2D} u_{xOD} + \frac{E_{o2R} u_{zOR}}{z_R} \frac{\partial}{\partial z_D} E_{o2D} u_{zOD} + \frac{E_{o4R} u_{xOR}}{x_R} \frac{\partial}{\partial x_D} E_{o4D} u_{xOD} + \\ &\frac{E_{o4R} u_{zOR}}{z_R} \frac{\partial}{\partial z_D} E_{o4D} u_{zOD} + \phi \frac{D_{Lo1R} E_{o1R}}{x_R^2} \frac{\partial^2}{\partial x_D^2} E_{o1D} + \phi \frac{D_{To1R} E_{o1R}}{z_R^2} \frac{\partial^2}{\partial z_D^2} E_{o1D} + \phi \frac{D_{Lo2R} E_{o2R}}{x_R^2} \frac{\partial^2}{\partial x_D^2} E_{o2D} + \phi \frac{D_{To2R} E_{o2R}}{z_R^2} \frac{\partial^2}{\partial z_D^2} E_{o2D} + \phi \frac{D_{Lo4R} E_{o4R}}{x_R^2} \frac{\partial^2}{\partial x_D^2} E_{o4D} + \\ &\phi \frac{D_{To4R} E_{o4R}}{z_R^2} \frac{\partial^2}{\partial z_D^2} E_{o4D} = \phi \frac{s_{oR} E_{o1R}}{t_R} \frac{\partial}{\partial t_D} S_{oD} E_{o1D} + \phi \frac{s_{oR} E_{o2R}}{t_R} \frac{\partial}{\partial t_D} S_{oD} E_{o2D} + \phi \frac{s_{oR} E_{o4R}}{t_R} \frac{\partial}{\partial t_D} S_{oD} E_{o4D} \end{aligned} \quad (A73)$$

$$\begin{aligned} &\Rightarrow \frac{t_R u_{xOR}}{\phi_{xR} s_{oR}} \frac{\partial}{\partial x_D} E_{o1D} u_{xOD} + \frac{t_R u_{zOR}}{\phi_{zR} s_{oR}} \frac{\partial}{\partial z_D} E_{o1D} u_{zOD} + \frac{t_R u_{xOR}}{\phi_{xR} s_{oR}} \frac{\partial}{\partial x_D} E_{o2D} u_{xOD} + \frac{t_R u_{zOR}}{\phi_{zR} s_{oR}} \frac{\partial}{\partial z_D} E_{o2D} u_{zOD} + \frac{t_R u_{xOR}}{\phi_{xR} s_{oR}} \frac{\partial}{\partial x_D} E_{o4D} u_{xOD} + \frac{t_R u_{zOR}}{\phi_{zR} s_{oR}} \frac{\partial}{\partial z_D} E_{o4D} u_{zOD} + \\ &\frac{D_{Lo1R} t_R}{x_R^2 s_{oR}} \frac{\partial^2}{\partial x_D^2} E_{o1D} + \frac{D_{To1R} t_R}{z_R^2 s_{oR}} \frac{\partial^2}{\partial z_D^2} E_{o1D} + \frac{D_{Lo2R} t_R}{x_R^2 s_{oR}} \frac{\partial^2}{\partial x_D^2} E_{o2D} + \frac{D_{To2R} t_R}{z_R^2 s_{oR}} \frac{\partial^2}{\partial z_D^2} E_{o2D} + \frac{D_{Lo4R} t_R}{x_R^2 s_{oR}} \frac{\partial^2}{\partial x_D^2} E_{o4D} + \frac{D_{To4R} t_R}{z_R^2 s_{oR}} \frac{\partial^2}{\partial z_D^2} E_{o4D} = \frac{\partial}{\partial t_D} S_{oD} E_{o1D} + \frac{\partial}{\partial t_D} S_{oD} E_{o2D} + \\ &\frac{\partial}{\partial t_D} S_{oD} E_{o4D} \end{aligned} \quad (A74)$$

Dimensionless groups from gaseous phase

$$\frac{u_{xgR} E_{g1R}}{x_R} \frac{\partial}{\partial x_D} u_{xgD} E_{g1D} + \frac{u_{zgR} E_{g1R}}{z_R} \frac{\partial}{\partial z_D} u_{zgD} E_{g1D} = \phi \frac{s_{gR} E_{g1R}}{t_R} \frac{\partial}{\partial t_D} S_{gD} E_{g1D} \quad (A75)$$

$$\frac{u_{xgR} t_R}{\phi_{xR} s_{gR}} \frac{\partial}{\partial x_D} u_{xgD} C_{g1D} + \frac{u_{zgR} t_R}{\phi_{zR} s_{gR}} \frac{\partial}{\partial z_D} u_{zgD} C_{g1D} = \frac{\partial}{\partial t_D} S_{gD} C_{g1D} \quad (A76)$$

$$U_{xR} U_{xD} = u_{xOR} u_{xOD} + u_{xwR} u_{xwD} + u_{xgR} u_{xgD} \quad (A77)$$

$$U_{xD} = \frac{u_{xOR}}{U_{xR}} u_{xOD} + \frac{u_{xwR}}{U_{xR}} u_{xwD} + \frac{u_{xgR}}{U_{xR}} u_{xgD} \quad (A78)$$

Similarly

$$U_{zR} U_{zD} = u_{zOR} u_{zOD} + u_{zwR} u_{zwD} + u_{zgR} u_{zgD} \quad (A79)$$

$$U_{zD} = \frac{u_{zOR}}{U_{zR}} u_{zOD} + \frac{u_{zwR}}{U_{zR}} u_{zwD} + \frac{u_{zgR}}{U_{zR}} u_{zgD} \quad (A80)$$

$$f_{xOR} f_{xOD} = \frac{u_{xOR} u_{xOD}}{U_{xR} U_{xD}} \quad (A81)$$

$$f_{xOD} = \left(\frac{u_{xOR}}{f_{xOR} U_{xR}} \right) \frac{u_{xOD}}{U_{xD}} \quad (A82)$$

$$f_{zOR} f_{zOD} = \frac{u_{zOR} u_{zOD}}{U_{zR} U_{zD}} \quad (A83)$$

$$f_{zOD} = \left(\frac{u_{zOR}}{f_{zOR} U_{zR}} \right) \frac{u_{zOD}}{U_{zD}} \quad (A84)$$

$$f_{xwR} f_{xwD} = \frac{u_{xwR} u_{xwD}}{U_{xR} U_{xD}} \quad (A85)$$

$$f_{xwD} = \left(\frac{u_{xwR}}{f_{xwR} U_{xR}} \right) \frac{u_{xwD}}{U_{xD}} \quad (A86)$$

$$f_{zwR} f_{zwD} = \frac{u_{zwR} u_{zwD}}{U_{zR} U_{zD}} \quad (A87)$$

$$f_{zwD} = \left(\frac{u_{zwR}}{f_{zwR} U_{zR}} \right) \frac{u_{zwD}}{U_{zD}} \quad (A88)$$

$$f_{xgR} f_{xgD} = \frac{u_{xgR} u_{xgD}}{U_{xR} U_{xD}} = 1 - f_{xOR} f_{xOD} - f_{xwR} f_{xwD} \quad (A89)$$

$$f_{xgD} = \left(\frac{u_{xgR}}{f_{xgR} U_{xR}} \right) \frac{u_{xgD}}{U_{xD}} = \frac{1}{f_{xgR}} - \left(\frac{f_{xOR}}{f_{xgR}} \right) f_{xOD} - \left(\frac{f_{xwR}}{f_{xgR}} \right) f_{xwD} \quad (A90)$$

$$f_{zgR} f_{zgD} = \frac{u_{zgR} u_{zgD}}{U_{zR} U_{zD}} = 1 - f_{zOR} f_{zOD} - f_{zwR} f_{zwD} \quad (A91)$$

$$\begin{aligned}
& \frac{p_{cOWR} \lambda_{zR}^2}{p_{cgoR} z_R^2} \int_0^{t_D} (t_D - \xi_D)^{-\alpha} \left[\frac{\partial^2 p_{wD}}{\partial \xi_D \partial z_D} + \frac{\partial}{\partial \xi_D} \left(\frac{\partial p_{cOWD}}{\partial s_{wD}} \frac{\partial s_{wD}}{\partial z_D} \right) + \frac{\partial}{\partial \xi_D} \left(\frac{\partial p_{cgoD}}{\partial s_{gD}} \frac{\partial s_{gD}}{\partial z_D} \right) \right] d\xi_D \left\{ \frac{\partial}{\partial z_D} (1 - f_{zOR} f_{zOD} - f_{zWR} f_{zWD}) + (1 - f_{zOR} f_{zOD} - \right. \\
& f_{zWR} f_{zWD}) \left[- \frac{(\eta_{OR} p_{wR} \eta_{OD} + \eta_{WR} p_{wR} \eta_{WD} + \eta_{gR} p_{wR} \eta_{gD})}{\Gamma(1-\alpha) t_R^{\alpha-1} \phi_R s_{wR} z_R^2} \int_0^{t_D} (t_D - \xi_D)^{-\alpha} \left[\frac{\partial^2 p_{wD}}{\partial \xi_D \partial z_D} \right] d\xi_D - \frac{(\eta_{OR} p_{cOWR} \eta_{OD} + \eta_{gR} p_{cOWR} \eta_{gD})}{\Gamma(1-\alpha) t_R^{\alpha-1} \phi_R s_{wR} z_R^2} \int_0^{t_D} (t_D - \right. \\
& \xi_D)^{-\alpha} \left[\frac{\partial}{\partial \xi_D} \left(\frac{\partial p_{cOWD}}{\partial s_{wD}} \frac{\partial s_{wD}}{\partial z_D} \right) \right] d\xi_D - \frac{\eta_{gR} p_{cgoR} \eta_{gD}}{\Gamma(1-\alpha) t_R^{\alpha-1} \phi_R s_{wR} z_R^2} \int_0^{t_D} (t_D - \xi_D)^{-\alpha} \left[\frac{\partial}{\partial \xi_D} \left(\frac{\partial p_{cgoD}}{\partial s_{gD}} \frac{\partial s_{gD}}{\partial z_D} \right) \right] d\xi_D \left\} \frac{\partial}{\partial z_D} (1 - f_{zOR} f_{zOD} - f_{zWR} f_{zWD}) + \right. \\
& \left(\frac{t_R D_{LW1R}}{s_{wR} z_R^2} \right) \phi_D \frac{\partial^2}{\partial x_D^2} D_{LW1D} + \left(\frac{t_R D_{LW3R}}{s_{wR} z_R^2} \right) \phi_D \frac{\partial^2}{\partial x_D^2} D_{LW3D} + \left(\frac{t_R D_{LW4R}}{s_{wR} z_R^2} \right) \phi_D \frac{\partial^2}{\partial x_D^2} D_{LW4D} + \left(\frac{t_R D_{TW1R}}{s_{wR} z_R^2} \right) \phi_D \frac{\partial^2}{\partial z_D^2} D_{LW1D} + \left(\frac{t_R D_{TW3R}}{s_{wR} z_R^2} \right) \phi_D \frac{\partial^2}{\partial z_D^2} D_{LW3D} + \\
& \left. \left(\frac{t_R D_{TW4R}}{s_{wR} z_R^2} \right) \phi_D \frac{\partial^2}{\partial z_D^2} D_{LW4D} = \phi_D \frac{\partial}{\partial t_D} S_{wD} + \phi_D \frac{\partial}{\partial t_D} S_{wD} + \phi_D \frac{\partial}{\partial t_D} S_{wD} \right. \quad (A96)
\end{aligned}$$

Dimensionless group from thermal energy balance equation

$$\begin{aligned}
& \frac{\Delta T V_R M_{1R}}{t_R} \frac{d}{dt_D} \int_{V(t_D)} M_{1D} dV_D + \frac{T_R}{x_R} K_{hCR} \int_{A_{ca}(t_D)} \left(-K_{hCD} \frac{\partial T_D}{\partial x_D} \right) dA + \frac{T_R}{x_R} K_{hR} \int_{A_{sf}(t_D)} \left(-K_{hD} \frac{\partial T_D}{\partial x_D} \right) dA + \\
& \Delta T \left[\sum_{i=w,o} C_{iR} C_{iD} \int_{A_{sf}(t_D)} \rho_{iR} \rho_{iD} (u_{ixR} u_{ixD} - \phi_R S_{iR} v_{xR} \phi_D S_{iD} v_{xD}) dA - (1 - \phi_R \phi_D) C_r \int_{A_{sf}(t_D)} \rho_{rR} v_{xR} \rho_{rD} v_{xD} dA \right] = \\
& m_{sR} m_{sD} [f_{sR} L_{vR} f_{sD} L_{vD} + c_{wR} c_{wD} \Delta T] \quad (A97)
\end{aligned}$$

$$\begin{aligned}
M_D = (1 - \phi_D) \rho_{rD} C_{prD} \left(\frac{(1-\phi) \rho_r C_{pr}}{M_1} \right) + \phi_D C_{pWD} \rho_{wD} S_{wD} \left(\frac{\phi C_{pWD} S_w}{M_1} \right) + \phi_D C_{oD} \rho_{oD} S_{oD} \left(\frac{\phi C_{pOD} S_o}{M_1} \right) + \phi_D C_{pGD} \rho_{gD} S_{gD} \left(\frac{\phi C_{pGD} S_g}{M_1} \right) + \\
\frac{\phi_D L_{vD} \rho_{gD} S_{gD}}{\Delta T_D} \left(\frac{\phi L_{vD} S_g}{M_1 \Delta T} \right) \quad (A98)
\end{aligned}$$

$$K_{hFD} = \frac{K_{hw} S_w}{K_{hf}} K_{hWD} S_{wD} + \frac{K_{ho} S_o}{K_{hf}} + \frac{K_{hg} S_g}{K_{hf}} K_{hGD} S_{gD} \quad (A99)$$

$$K_{heD} = \frac{\phi K_{hf}}{K_{he}} \phi_D K_{hFD} + \frac{(1-\phi) K_{hr}}{K_{he}} (1 - \phi_D) K_{hrD} \quad (A100)$$

$$\begin{aligned}
& \frac{\Delta T M_1 V}{t} \Delta T_D \frac{d}{dt_D} \int_{V(t_D)} M_{1D} dV_D - \frac{K_{hr} T_A}{L} \int_{A_{ca}(t_D)} \left(K_{hrD} \frac{\partial T_D}{\partial x_D} \right) dA_D - \frac{K_{hf} T_A}{L} \int_{A_{sf}(t_D)} \left(K_{hfD} \frac{\partial T_D}{\partial x_D} \right) dA_D + \Delta T C_{pi} \rho_i (u_{ix} - \\
& \phi S_i v_x) A \left[\sum_{i=w,o} C_{iD} \int_{A_{sf}(t_D)} \rho_{iD} (u_{ixD} - \phi_D S_{iD} v_{xD}) dA_D - (1 - \phi) C_r \rho_r v_x A \int_{A_{sf}(t_D)} \rho_{rD} v_{xD} dA_D \right] = \\
& \dot{m}_s [f_s L_v + C_{pw} \Delta T] \dot{m}_{sD} [f_{sD} L_{vD} + C_{pWD} \Delta T_D] \quad (A101)
\end{aligned}$$

$$\begin{aligned}
& \Delta T_D \frac{d}{dt_D} \int_{V(t_D)} M_{1D} dV_D - \left(\frac{K_{hr} T_A t}{L \Delta T M_1 V} \right) \int_{A_{ca}(t_D)} \left(K_{hrD} \frac{\partial T_D}{\partial x_D} \right) dA_D - \left(\frac{K_{hf} T_A t}{L \Delta T M_1 V} \right) \int_{A_{sf}(t_D)} \left(K_{hfD} \frac{\partial T_D}{\partial x_D} \right) dA_D + \left[\sum_{i=w,o} C_{ipD} \int_{A_{sf}(t_D)} \rho_{iD} (u_{ixD} - \right. \\
& \left. \phi_D S_{iD} v_{xD}) dA_D - \left(\frac{(1-\phi) C_{pr} \rho_r v_x A}{\Delta T M_1 V} \right) \int_{A_{sf}(t_D)} \rho_r v_x dA \right] = \left(\frac{m_s f_s L_v t}{\Delta T M_1 V} \right) \dot{m}_{sD} f_{sD} L_{vD} + \left(\frac{m_s C_{pw} t}{M_1 V} \right) \dot{m}_{sD} C_{pWD} \Delta T_D \quad (A102)
\end{aligned}$$

$$\begin{aligned}
& \left(\frac{\Delta T M_1 V}{t \dot{m}_s [f_s L_v + C_w \Delta T]} \right) \Delta T_D \frac{d}{dt_D} \int_{V(t_D)} M_{1D} dV_D - \left(\frac{K_{hr} T_A}{L \dot{m}_s [f_s L_v + C_w \Delta T]} \right) \int_{A_{ca}(t_D)} \left(K_{hrD} \frac{\partial T_D}{\partial x_D} \right) dA_D - \left(\frac{K_{hf} T_A}{L \dot{m}_s [f_s L_v + C_w \Delta T]} \right) \int_{A_{sf}(t_D)} \left(K_{hfD} \frac{\partial T_D}{\partial x_D} \right) dA_D + \\
& \left(\frac{\Delta T C_{pi} \rho_i (u_{ix} - \phi S_i v_x) A}{\dot{m}_s [f_s L_v + C_w \Delta T]} \right) \left[\sum_{i=w,o} C_{iD} \int_{A_{sf}(t_D)} \rho_{iD} (u_{ixD} - \phi_D S_{iD} v_{xD}) dA_D - \left(\frac{(1-\phi) r \rho_r v_x A}{\dot{m}_s [f_s L_v + C_w \Delta T]} \right) \int_{A_{sf}(t_D)} \rho_{rD} v_{xD} dA_D \right] = \dot{m}_{sD} [f_{sD} L_{vD} + C_{wD} \Delta T_D] \quad (A103)
\end{aligned}$$

$$\begin{aligned}
& \left(\frac{\Delta T M_1 V}{t \dot{m}_s [f_s L_v + C_w \Delta T]} \right) \Delta T_D \frac{d}{dt_D} \int_{V(t_D)} M_{1D} dV_D - \left(\frac{K_{hc} T_A}{L \dot{m}_s [f_s L_v + C_w \Delta T]} \right) \int_{A_{ca}(t_D)} \left(K_{hcD} \frac{\partial T_D}{\partial x_D} \right) dA_D - \left(\frac{K_{hD} T_A}{L \dot{m}_s [f_s L_v + C_w \Delta T]} \right) \int_{A_{sf}(t_D)} \left(K_{hD} \frac{\partial T_D}{\partial x_D} \right) dA_D + \\
& \left(\frac{\Delta T C_{pi} \rho_i (u_{ix} - \phi S_i v_x) A}{\dot{m}_s [f_s L_v + C_w \Delta T]} \right) \left[\sum_{i=w,o} C_{iD} \int_{A_{sf}(t_D)} \rho_{iD} (u_{ixD} - \phi_D S_{iD} v_{xD}) dA_D - \left(\frac{(1-\phi) C_r \rho_r v_x A}{\dot{m}_s [f_s L_v + C_w \Delta T]} \right) \int_{A_{sf}(t_D)} \rho_{rD} v_{xD} dA_D \right] = \dot{m}_{sD} [f_{sD} L_{vD} + C_{wD} \Delta T_D] \quad (A104)
\end{aligned}$$

Dimensionless group from constitutive equations

$$u_{xWR} u_{xWD} = - \frac{k_{xWR} k_{xWD} p_{wR} \lambda_{xWR} \lambda_{xWD}}{x_R} \frac{\partial p_{wD}}{\partial x_D} + \frac{k_{xWR} k_{xWD} \lambda_{xw} \lambda_{xWR} \lambda_{xWD}}{x_R} \rho_{oR} g_R z_R \sin \theta_R \rho_{oD} g_D z_D \sin \theta_D \quad (A105)$$

$$u_{xWD} = \left(\frac{k_{xWR} \lambda_{xWR} p_{wR}}{x_R u_{xWR}} \right) k_{xWD} \lambda_{xWD} + \left(\frac{k_{xWR} \lambda_{xWR} p_{wR} g_R z_R \sin \theta_R}{x_R u_{xWR}} \right) k_{xWD} \lambda_{xWD} \rho_{wD} g_D z_D \sin \theta_D \quad (A106)$$

Similarly,

$$u_{xOD} = \left(\frac{k_{xOR} \lambda_{xOR} p_{oR}}{x_R u_{xOR}} \right) k_{xOD} \lambda_{xOD} + \left(\frac{k_{xOR} \lambda_{xOR} \rho_{oR} g_R z_R \sin \theta_R}{x_R u_{xOR}} \right) k_{xOD} \lambda_{xOD} \rho_{oD} g_D z_D \sin \theta_D \quad (A107)$$

$$u_{xGD} = \left(\frac{k_{xGR} \lambda_{xGR} p_{gR}}{x_R u_{xGR}} \right) k_{xGD} \lambda_{xGD} + \left(\frac{k_{xGR} \lambda_{xGR} p_{gR} g_R z_R \sin \theta_R}{x_R u_{xGR}} \right) k_{xGD} \lambda_{xGD} \rho_{gD} g_D z_D \sin \theta_D \quad (A108)$$

$$u_{zWD} = \left(\frac{k_{zWR} \lambda_{zWR} p_{wR}}{z_R u_{zWR}} \right) k_{zWD} \lambda_{zWD} + \left(\frac{k_{zWR} \lambda_{zWR} \rho_{wR} g_R z_R \sin \theta_R}{z_R u_{zWR}} \right) k_{zWD} \lambda_{zWD} \rho_{wD} g_D z_D \sin \theta_D \quad (A109)$$

$$u_{z0D} = \left(\frac{k_{z0R} \lambda_{z0R} \rho_{0R}}{z_R u_{z0R}} \right) k_{z0D} \lambda_{z0D} + \left(\frac{k_{z0R} \lambda_{z0R} \rho_{0R} g_R z_R \sin \theta_R}{z_R u_{z0R}} \right) k_{z0D} \lambda_{z0D} \rho_{0D} g_D z_D \sin \theta_D \quad (\text{A110})$$

$$u_{zgD} = \left(\frac{k_{zgR} \lambda_{zgR} \rho_{wR}}{z_R u_{zgR}} \right) k_{zgD} \lambda_{zgD} + \left(\frac{k_{zgR} \lambda_{zgR} \rho_{gR} z_R \sin \theta_R}{z_R u_{zgR}} \right) k_{zgD} \lambda_{zgD} \rho_{gD} g_D z_D \sin \theta_D \quad (\text{A111})$$

Dimensionless group from capillary pressure

$$p_{c0w} = \sigma_{0w} \cos \theta \sqrt{\frac{\phi}{k}} J(s_w) \quad (\text{A112})$$

Differentiate with respect to s_w

$$\frac{\partial p_{c0w}}{\partial s_w} = \sigma_{0w} \cos \theta \sqrt{\frac{\phi}{k}} \frac{\partial J(s_w)}{\partial s_w} \quad (\text{A113})$$

$$\frac{\partial p_{c0wD}}{\partial s_w D} = \frac{\sigma_{0wR} J_R(s_w) \cos \theta_R \sqrt{\frac{\phi_R}{k_R}}}{p_{c0wR}} \sigma_{0wD} J_D(s_w) \cos \theta_D \sqrt{\frac{\phi_D}{k_D}} \frac{\partial J_D(s_w)}{\partial s_w D} \quad (\text{A114})$$

and

$$p_{cgo} = \sigma_{go} \cos \theta \sqrt{\frac{\phi}{k}} J(s_g) \quad (\text{A115})$$

$$\frac{\partial p_{cgoD}}{\partial s_g D} = \frac{\sigma_{goR} J_R(s_g) \cos \theta_R \sqrt{\frac{\phi_R}{k_R}}}{p_{cgoR}} \sigma_{goD} J_D(s_g) \cos \theta_D \sqrt{\frac{\phi_D}{k_D}} \quad (\text{A116})$$

Dimensionless group from saturation constraint

$$s_w + s_o + s_g = 1 \quad (\text{A117})$$

$$s_{wR} s_{wD} = 1 - s_{oR} s_{oD} - s_{gR} s_{gD} \quad (\text{A118})$$

$$s_{wD} = \left(\frac{1}{s_{wR}} \right) - \left(\frac{s_{oR}}{s_{wR}} \right) s_{oD} - \left(\frac{s_{gR}}{s_{wR}} \right) s_{gD} \quad (\text{A119})$$

$$s_{oD} = \frac{s_o - s_{or}}{1 - s_{wi} - s_{or}} \quad (\text{A120})$$

$$s_{wD} = \frac{s_w - s_{wi}}{1 - s_{wi} - s_{or}} \quad (\text{A121})$$

$$s_{gD} = \frac{s_g - s_{gc}}{1 - s_{wi} - s_{or}} \quad (\text{A122})$$

$$t_D = \frac{U t}{L \phi (1 - s_{wi} - s_{or})} \quad (\text{A123})$$

Dimensionless group from initial and boundary conditions

$$s_{wD} = \frac{s_{wi}}{s_{wD}} \text{ at } t_D = 0, \text{ and } x_D, z_D \quad (\text{A124})$$

$$s_{gD} = \frac{s_{gi}}{s_{gR}} \text{ at } t_D = 0, \text{ and } x_D, z_D \quad (\text{A125})$$

$$s_{oD} = \frac{s_{oi}}{s_{or}} \text{ at } t_D = 0, \text{ and } x_D, z_D \quad (\text{A126})$$

$$E_{o1D} = 0 \text{ at } t_D = 0, \text{ and } x_D, z_D \quad (\text{A127})$$

$$E_{g1D} = 0 \text{ at } t_D = 0, \text{ and } x_D, z_D \quad (\text{A128})$$

$$E_{o2D} = \frac{E_{zi}}{E_{o2R}} \text{ at } t_D = 0, \text{ and } x_D, z_D \quad (\text{A129})$$

$$E_{o4D} = 0 \text{ at } t_D = 0, \text{ and } x_D, z_D \quad (\text{A130})$$

$$E_{w1D} = 0 \text{ at } t_D = 0, \text{ and } x_D, z_D \quad (\text{A131})$$

$$E_{w3D} = \frac{E_{3i}}{E_{w3R}} \text{ at } t_D = 0, \text{ and } x_D, z_D \quad (\text{A132})$$

$$E_{w4D} = 0 \text{ at } t_D = 0, \text{ and } x_D, z_D \quad (\text{A133})$$

$$E_{g1D} = \frac{E_{1j}}{E_{g1R}} \text{ at } x_D = 0, \text{ and } t_D, z_D \quad (\text{A134})$$

$$E_{o1D} = 0 \text{ at } x_D = 0, \text{ and } t_D, z_D \quad (\text{A135})$$

$$E_{o2D} = 0 \text{ at } x_D = 0, \text{ and } t_D, z_D \quad (\text{A136})$$

$$E_{o4D} = 0 \text{ at } x_D = 0, \text{ and } t_D, z_D \quad (\text{A137})$$

$$E_{w1D} = 0 \text{ at } x_D = 0, \text{ and } t_D, z_D \quad (\text{A138})$$

$$E_{w3D} = 0 \text{ at } x_D = 0, \text{ and } t_D, z_D \quad (\text{A139})$$

$$E_{w4D} = \frac{E_{4j}}{E_{w4R}} \text{ at } x_D = 0, \text{ and } t_D, z_D \quad (\text{A140})$$

$$p_{gD} = \left(\frac{\Delta p_{gR}}{p_{gR}} \right) + \left(\frac{\rho_{gR} g_{RzR}}{p_{gR}} \right) \left(\frac{H}{z_R} - z_D \right) \text{ at } x_D = \frac{L}{x_R}, \text{ and } t_D, z_D \quad (\text{A141})$$

$$p_{oD} = \left(\frac{\Delta p_{oR}}{p_{oR}} \right) + \left(\frac{\rho_{oR} g_{RzR}}{p_{oR}} \right) \left(\frac{H}{z_R} - z_D \right) \text{ at } x_D = \frac{L}{x_R}, \text{ and } t_D, z_D \quad (\text{A142})$$

$$p_{wD} = \left(\frac{\Delta p_{wR}}{p_{wR}} \right) + \left(\frac{\rho_{wR} g_{RzR}}{p_{wR}} \right) \left(\frac{H}{z_R} - z_D \right) \text{ at } x_D = \frac{L}{x_R}, \text{ and } t_D, z_D \quad (\text{A143})$$

$$u_{gzD} = u_{ozD} = u_{wzD} = 0 \text{ at } z_D = 0, \text{ and } x_D, t_D \quad (\text{A144})$$

$$u_{gzD} = u_{ozD} = u_{wzD} = 0 \text{ at } z_D = \frac{H}{z_R}, \text{ and } x_D, t_D \quad (\text{A145})$$

$$\int_0^{\frac{H}{z_R}} u_{gzD} dz_D = \frac{HU_L}{u_{gxRzR}} \text{ at } x_D = 0, \text{ and } z_D, t_D \quad (\text{A146})$$

Table 4.3A: Initial dimensionless groups from inspectional analysis

$\pi_1 = \frac{t_R u_{xwR}}{\phi x_R S_{wR}}$	$\pi_{45} = \frac{\eta_{gR} p_{cowR}}{\Gamma(1-\alpha) t_R^{\alpha-1} \phi_R S_{wR} x_R^2}$	$\pi_{89} = \frac{\eta_{wR} p_{wR}}{\Gamma(1-\alpha) t_R^{\alpha-1} \phi_R S_{wR} z_R^2}$	$\pi_{133} = \frac{S_{gl}}{S_{gR}}$
$\pi_2 = \frac{t_R u_{zwR}}{\phi z_R S_{wR}}$	$\pi_{46} = \frac{f_{xOR} \eta_{oR} p_{cowR}}{\Gamma(1-\alpha) t_R^{\alpha-1} \phi_R S_{wR} x_R^2}$	$\pi_{90} = \frac{\eta_{gR} p_{wR}}{\Gamma(1-\alpha) t_R^{\alpha-1} \phi_R S_{wR} z_R^2}$	$\pi_{134} = \frac{S_{ol}}{S_{oR}}$
$\pi_3 = \frac{D_{Lw1R} t_R}{x_R^2 S_{wR}}$	$\pi_{47} = \frac{f_{xOR} \eta_{gR} p_{cowR}}{\Gamma(1-\alpha) t_R^{\alpha-1} \phi_R S_{wR} x_R^2}$	$\pi_{91} = \frac{f_{xOR} \eta_{oR} p_{wR}}{\Gamma(1-\alpha) t_R^{\alpha-1} \phi_R S_{wR} z_R^2}$	$\pi_{135} = \frac{E_{2i}}{E_{o2R}}$
$\pi_4 = \frac{D_{Tw1R} t_R}{z_R^2 S_{wR}}$	$\pi_{48} = \frac{f_{xwR} \eta_{oR} p_{cowR}}{\Gamma(1-\alpha) t_R^{\alpha-1} \phi_R S_{wR} x_R^2}$	$\pi_{92} = \frac{f_{xOR} \eta_{wR} p_{wR}}{\Gamma(1-\alpha) t_R^{\alpha-1} \phi_R S_{wR} z_R^2}$	$\pi_{136} = \frac{E_{3i}}{E_{w3R}}$
$\pi_5 = \frac{D_{Lw3R} t_R}{x_R^2 S_{wR}}$	$\pi_{49} = \frac{f_{xwR} \eta_{gR} p_{cowR}}{\Gamma(1-\alpha) t_R^{\alpha-1} \phi_R S_{wR} x_R^2}$	$\pi_{93} = \frac{f_{xOR} \eta_{gR} p_{wR}}{\Gamma(1-\alpha) t_R^{\alpha-1} \phi_R S_{wR} z_R^2}$	$\pi_{137} = \frac{E_{1j}}{E_{g1R}}$
$\pi_6 = \frac{D_{Tw3R} t_R}{z_R^2 S_{wR}}$	$\pi_{50} = \frac{\eta_{gR} p_{cgoR}}{\Gamma(1-\alpha) t_R^{\alpha-1} \phi_R S_{wR} x_R^2}$	$\pi_{94} = \frac{f_{xwR} \eta_{oR} p_{wR}}{\Gamma(1-\alpha) t_R^{\alpha-1} \phi_R S_{wR} z_R^2}$	$\pi_{138} = \frac{E_{4j}}{E_{w4R}}$
$\pi_7 = \frac{D_{Lw4R} t_R}{x_R^2 S_{wR}}$	$\pi_{51} = \frac{f_{xOR} \eta_{gR} p_{cgoR}}{\Gamma(1-\alpha) t_R^{\alpha-1} \phi_R S_{wR} x_R^2}$	$\pi_{95} = \frac{f_{xwR} \eta_{wR} p_{wR}}{\Gamma(1-\alpha) t_R^{\alpha-1} \phi_R S_{wR} z_R^2}$	$\pi_{139} = \frac{\Delta p_{gR}}{p_{gR}}$
$\pi_8 = \frac{D_{Tw4R} t_R}{z_R^2 S_{wR}}$	$\pi_{52} = \frac{f_{xwR} \eta_{gR} p_{cgoR}}{\Gamma(1-\alpha) t_R^{\alpha-1} \phi_R S_{wR} x_R^2}$	$\pi_{96} = \frac{f_{xwR} \eta_{gR} p_{wR}}{\Gamma(1-\alpha) t_R^{\alpha-1} \phi_R S_{wR} z_R^2}$	$\pi_{140} = \frac{\rho_{gR} g_{RzR}}{p_{gR}}$
$\pi_9 = \frac{t_R u_{xOR}}{\phi x_R S_{oR}}$	$\pi_{53} = \frac{p_{wR}}{p_{cowR}}$	$\pi_{97} = \frac{\eta_{oR} p_{cowR}}{\Gamma(1-\alpha) t_R^{\alpha-1} \phi_R S_{wR} z_R^2}$	$\pi_{141} = \frac{\rho_{gR} g_{RzR}}{p_{gR}}$

$\pi_{10} = \frac{t_R u_{zOR}}{\phi z_R s_{OR}}$	$\pi_{54} = \frac{x_R^2}{z_R^2}$	$\pi_{98} = \frac{\eta_{gR} p_{cOWR}}{\Gamma(1-\alpha) t_R^{\alpha-1} \phi_R s_{WR} z_R^2}$	$\pi_{142} = \frac{\Delta p_{OR}}{p_{OR}}$
$\pi_{11} = \frac{D_{Lo1R} t_R}{x_R^2 s_{OR}}$	$\pi_{55} = \frac{p_{WR} x_R^2}{p_{cOWR} z_R^2}$	$\pi_{99} = \frac{f_{xOR} \eta_{OR} p_{cOWR}}{\Gamma(1-\alpha) t_R^{\alpha-1} \phi_R s_{WR} z_R^2}$	$\pi_{143} = \frac{\rho_{OR} g_R H_R}{p_{OR}}$
$\pi_{12} = \frac{D_{To1R} t_R}{z_R^2 s_{OR}}$	$\pi_{56} = \frac{p_{WR}}{p_{cGOR}}$	$\pi_{100} = \frac{f_{xOR} \eta_{gR} p_{cOWR}}{\Gamma(1-\alpha) t_R^{\alpha-1} \phi_R s_{WR} z_R^2}$	$\pi_{144} = \frac{\rho_{OR} g_R z_R}{p_{OR}}$
$\pi_{13} = \frac{D_{Lo2R} t_R}{x_R^2 s_{OR}}$	$\pi_{57} = \frac{p_{WR} x_R^2}{p_{cGOR} z_R^2}$	$\pi_{101} = \frac{f_{xWR} \eta_{OR} p_{cOWR}}{\Gamma(1-\alpha) t_R^{\alpha-1} \phi_R s_{WR} z_R^2}$	$\pi_{145} = \frac{\Delta p_{WR}}{p_{WR}}$
$\pi_{14} = \frac{D_{To2R} t_R}{z_R^2 s_{OR}}$	$\pi_{58} = \frac{p_{cOWR}}{p_{cGOR}}$	$\pi_{102} = \frac{f_{xWR} \eta_{OR} p_{cOWR}}{\Gamma(1-\alpha) t_R^{\alpha-1} \phi_R s_{WR} z_R^2}$	$\pi_{146} = \frac{\rho_{WR} g_R H_R}{p_{WR}}$
$\pi_{15} = \frac{D_{Lo4R} t_R}{x_R^2 s_{OR}}$	$\pi_{59} = \frac{p_{cOWR} x_R^2}{p_{cGOR} z_R^2}$	$\pi_{103} = \frac{\eta_{gR} p_{cGOR}}{\Gamma(1-\alpha) t_R^{\alpha-1} \phi_R s_{WR} z_R^2}$	$\pi_{147} = \frac{\rho_{WR} g_R z_R}{p_{WR}}$
$\pi_{16} = \frac{D_{To4R} t_R}{z_R^2 s_{OR}}$	$\pi_{60} = \frac{f_{xOR} p_{WR}}{p_{cOWR}}$	$\pi_{104} = \frac{f_{xOR} \eta_{gR} p_{cGOR}}{\Gamma(1-\alpha) t_R^{\alpha-1} \phi_R s_{WR} z_R^2}$	$\pi_{148} = \frac{H U_t}{z_R u_{gXR} z_R}$
$\pi_{17} = \frac{u_{xgR} t_R}{\phi x_R s_{gR}}$	$\pi_{61} = \frac{f_{xOR} x_R^2}{z_R^2}$	$\pi_{105} = \frac{f_{xWR} \eta_{gR} p_{cGOR}}{\Gamma(1-\alpha) t_R^{\alpha-1} \phi_R s_{WR} z_R^2}$	$\pi_{149} = \frac{z_R^2 D_{Lo1R}}{x_R^2 D_{To1R}}$
$\pi_{18} = \frac{u_{zgR} t_R}{\phi z_R s_{gR}}$	$\pi_{62} = \frac{f_{xOR} p_{WR} x_R^2}{p_{cOWR} z_R^2}$	$\pi_{106} = \frac{t_R D_{LW1R}}{s_{WR} x_R^2}$	$\pi_{150} = \frac{z_R^2 D_{Lo2R}}{x_R^2 D_{To2R}}$
$\pi_{19} = \frac{u_{xOR}}{U_{xR}}$	$\pi_{63} = \frac{f_{xOR} p_{WR}}{p_{cGOR}}$	$\pi_{107} = \frac{t_R D_{LW3R}}{s_{WR} x_R^2}$	$\pi_{151} = \frac{z_R^2 D_{Lo4R}}{x_R^2 D_{To4R}}$
$\pi_{20} = \frac{u_{xWR}}{U_{xR}}$	$\pi_{64} = \frac{f_{xOR} p_{WR} x_R^2}{p_{cGOR} z_R^2}$	$\pi_{108} = \frac{t_R D_{LW4R}}{s_{WR} x_R^2}$	$\pi_{152} = \frac{z_R^2 D_{LW1R}}{x_R^2 D_{TW1R}}$
$\pi_{21} = \frac{u_{xgR}}{U_{xR}}$	$\pi_{65} = \frac{f_{xOR} p_{cOWR}}{p_{cGOR}}$	$\pi_{109} = \frac{t_R D_{TW1R}}{s_{WR} z_R^2}$	$\pi_{153} = \frac{z_R^2 D_{LW2R}}{x_R^2 D_{TW2R}}$
$\pi_{22} = \frac{u_{zOR}}{U_{zR}}$	$\pi_{66} = \frac{f_{xOR} p_{cOWR} x_R^2}{p_{cGOR} z_R^2}$	$\pi_{110} = \frac{t_R D_{TW3R}}{s_{WR} z_R^2}$	$\pi_{154} = \frac{z_R^2 D_{LW4R}}{x_R^2 D_{TW4R}}$
$\pi_{23} = \frac{u_{zWR}}{U_{zR}}$	$\pi_{67} = \frac{f_{xWR} p_{WR}}{p_{cOWR}}$	$\pi_{111} = \frac{t_R D_{TW4R}}{s_{WR} z_R^2}$	$\pi_{155} = \frac{H}{z_R}$
$\pi_{24} = \frac{u_{zgR}}{U_{zR}}$	$\pi_{68} = \frac{f_{xWR} x_R^2}{z_R^2}$	$\pi_{112} = \frac{k_{xWR} \lambda_{xWR} p_{WR}}{x_R u_{xWR}}$	$\pi_{156} = \frac{L}{x_R}$
$\pi_{25} = \frac{u_{xOR}}{f_{xOR} U_{xR}}$	$\pi_{69} = \frac{f_{xWR} p_{WR} x_R^2}{f_{xWR} p_{cOWR} z_R^2}$	$\pi_{113} = \frac{k_{xWR} \lambda_{xWR} \rho_{WR} g_R z_R \sin \theta_R}{x_R u_{xWR}}$	$\pi_{157} = \frac{H U_t}{u_{gXR} z_R}$
$\pi_{26} = \frac{u_{zOR}}{f_{zOR} U_{zR}}$	$\pi_{70} = \frac{f_{xWR} p_{WR}}{p_{cGOR}}$	$\pi_{114} = \frac{k_{xOR} \lambda_{xOR} p_{OR}}{x_R u_{xOR}}$	$\pi_{158} = \frac{K_{hr} T A t}{\Delta T M_1 V}$
$\pi_{27} = \frac{u_{xWR}}{f_{xWR} U_{xR}}$	$\pi_{71} = \frac{f_{xWR} p_{WR} x_R^2}{p_{cGOR} z_R^2}$	$\pi_{115} = \frac{k_{xOR} \lambda_{xOR} \rho_{OR} g_R z_R \sin \theta_R}{x_R u_{xOR}}$	$\pi_{159} = \frac{K_{hf} T A t}{\Delta T M_1 V}$
$\pi_{28} = \frac{u_{zWR}}{f_{zWR} U_{zR}}$	$\pi_{72} = \frac{f_{xWR} p_{cOWR}}{p_{cGOR}}$	$\pi_{116} = \frac{k_{xgR} \lambda_{xgR} p_{gR}}{x_R u_{xgR}}$	$\pi_{160} = \frac{t C_{po} \rho_o u_{ox} A}{M_1 V}$
$\pi_{29} = \frac{u_{xgR}}{f_{xgR} U_{xR}}$	$\pi_{73} = \frac{f_{xWR} p_{cOWR} x_R^2}{p_{cGOR} z_R^2}$	$\pi_{117} = \frac{k_{xgR} \lambda_{xgR} \rho_{gR} g_R z_R \sin \theta_R}{x_R u_{xgR}}$	$\pi_{161} = \frac{t C_{pw} \rho_w u_{wx} A}{M_1 V}$
$\pi_{30} = \frac{f_{xOR}}{f_{xgR}}$	$\pi_{74} = \frac{f_{zOR} p_{WR} x_R^2}{p_{cOWR} z_R^2}$	$\pi_{118} = \frac{k_{zWR} \lambda_{zWR} p_{WR}}{z_R u_{zWR}}$	$\pi_{162} = \frac{t C_{po} \rho_o \phi S_o v_x A}{M_1 V}$

$\pi_{31} = \frac{f_{xwR}}{f_{xgR}}$	$\pi_{75} = \frac{f_{zOR}P_{wR}}{p_{cgoR}}$	$\pi_{119} = \frac{k_{zWR}\lambda_{zWR}\rho_{wR}g_R z_R \sin\theta_R}{Z_R u_{xwR}}$	$\pi_{163} = \frac{t C_{pw} \rho_w \phi S_w v_x A}{M_1 V}$
$\pi_{32} = \frac{u_{zgR}}{f_{zgR} U_{zR}}$	$\pi_{76} = \frac{f_{zOR} P_{wR} X_R^2}{p_{cgoR} Z_R^2}$	$\pi_{120} = \frac{k_{zOR} \lambda_{zOR} \rho_{oR}}{Z_R u_{zOR}}$	$\pi_{164} = \frac{(1-\phi) C_{pr} t \rho_r v_x A}{\Delta T M_1 V}$
$\pi_{33} = \frac{f_{zOR}}{f_{zgR}}$	$\pi_{77} = \frac{f_{zOR} P_{wR}}{p_{cgoR}}$	$\pi_{121} = \frac{k_{zOR} \lambda_{zOR} \rho_{oR} g_R z_R \sin\theta_R}{Z_R u_{zOR}}$	$\pi_{165} = \frac{m_s f_s L_v t}{\Delta T M_1 V}$
$\pi_{34} = \frac{f_{zWR}}{f_{zgR}}$	$\pi_{78} = \frac{f_{zOR} P_{wR} X_R^2}{p_{cgoR} Z_R^2}$	$\pi_{122} = \frac{k_{zGR} \lambda_{zGR} \rho_{wR}}{Z_R u_{zGR}}$	$\pi_{166} = \frac{m_s C_{pw} t}{M_1 V}$
$\pi_{35} = \frac{\eta_{oR} P_{wR}}{\Gamma(1-\alpha) t_R^{\alpha-1} \phi_R S_{wR} X_R^2}$	$\pi_{79} = \frac{f_{zOR} P_{cowR}}{p_{cgoR}}$	$\pi_{123} = \frac{k_{zGR} \lambda_{zGR} \rho_{gR} g_R z_R \sin\theta_R}{Z_R u_{zGR}}$	$\pi_{167} = \frac{(1-\phi) \rho_r C_{pr}}{M_1}$
$\pi_{36} = \frac{\eta_{wR} P_{wR}}{\Gamma(1-\alpha) t_R^{\alpha-1} \phi_R S_{wR} X_R^2}$	$\pi_{80} = \frac{f_{xOR} P_{cowR} X_R^2}{p_{cgoR} Z_R^2}$	$\pi_{124} = \frac{\sigma_{owR} J_R(S_w) \cos\theta_R \sqrt{\frac{\phi_R}{k_R}}}{p_{cowR}}$	$\pi_{168} = \frac{\phi C_{pw} \rho_w S_w}{M_1}$
$\pi_{37} = \frac{\eta_{gR} P_{wR}}{\Gamma(1-\alpha) t_R^{\alpha-1} \phi_R S_{wR} X_R^2}$	$\pi_{81} = \frac{f_{xWR} P_{wR}}{p_{cowR}}$	$\pi_{125} = \frac{\sigma_{goR} J_R(S_g) \cos\theta_R \sqrt{\frac{\phi_R}{k_R}}}{p_{cgoR}}$	$\pi_{169} = \frac{\phi C_{po} \rho_o S_o}{M_1}$
$\pi_{38} = \frac{f_{xOR} \eta_{oR} P_{wR}}{\Gamma(1-\alpha) t_R^{\alpha-1} \phi_R S_{wR} X_R^2}$	$\pi_{82} = \frac{f_{xWR} X_R^2}{Z_R^2}$	$\pi_{126} = \frac{S_{oR}}{S_{wR}}$	$\pi_{170} = \frac{\phi C_{pg} \rho_g S_g}{M_1}$
$\pi_{39} = \frac{f_{xOR} \eta_{gR} P_{wR}}{\Gamma(1-\alpha) t_R^{\alpha-1} \phi_R S_{wR} X_R^2}$	$\pi_{83} = \frac{f_{xWR} P_{wR} X_R^2}{f_{xWR} P_{cowR} Z_R^2}$	$\pi_{127} = \frac{S_{gR}}{S_{wR}}$	$\pi_{171} = \frac{\phi L_v \rho_g S_g}{M_1 \Delta T}$
$\pi_{40} = \frac{f_{xOR} \eta_{gR} P_{wR}}{\Gamma(1-\alpha) t_R^{\alpha-1} \phi_R S_{wR} X_R^2}$	$\pi_{84} = \frac{f_{xWR} P_{wR}}{p_{cgoR}}$	$\pi_{128} = \frac{s_o - s_{or}}{1 - s_{wi} - s_{or}}$	$\pi_{172} = \frac{K_{hw} S_w}{K_{hf}}$
$\pi_{41} = \frac{f_{xWR} \eta_{oR} P_{wR}}{\Gamma(1-\alpha) t_R^{\alpha-1} \phi_R S_{wR} X_R^2}$	$\pi_{85} = \frac{f_{xWR} P_{wR} X_R^2}{p_{cgoR} Z_R^2}$	$\pi_{129} = \frac{s_w - s_{wi}}{1 - s_{wi} - s_{or}}$	$\pi_{173} = \frac{K_{ho} S_o}{K_{hf}}$
$\pi_{42} = \frac{f_{xWR} \eta_{wR} P_{wR}}{\Gamma(1-\alpha) t_R^{\alpha-1} \phi_R S_{wR} X_R^2}$	$\pi_{86} = \frac{f_{xWR} P_{cowR}}{p_{cgoR}}$	$\pi_{130} = \frac{s_g - s_{gc}}{1 - s_{wi} - s_{or}}$	$\pi_{174} = \frac{K_{hg} S_g}{K_{hf}}$
$\pi_{43} = \frac{f_{xWR} \eta_{gR} P_{wR}}{\Gamma(1-\alpha) t_R^{\alpha-1} \phi_R S_{wR} X_R^2}$	$\pi_{87} = \frac{f_{xWR} P_{cowR} X_R^2}{p_{cgoR} Z_R^2}$	$\pi_{131} = \frac{U_i t}{L \phi (1 - s_{wi} - s_{or})}$	$\pi_{175} = \frac{\phi K_{hf}}{K_{he}}$
$\pi_{44} = \frac{\eta_{oR} P_{cowR}}{\Gamma(1-\alpha) t_R^{\alpha-1} \phi_R S_{wR} X_R^2}$	$\pi_{88} = \frac{\eta_{oR} P_{wR}}{\Gamma(1-\alpha) t_R^{\alpha-1} \phi_R S_{wR} Z_R^2}$	$\pi_{132} = \frac{S_{wi}}{S_{wD}}$	$\pi_{176} = \frac{(1-\phi) K_{hr}}{K_{he}}$

Steam flooding process involves heat and mass transfer of a complex multiphase flow system. Other physicochemical phenomena are also involved which are difficult and impracticable to be scaled simultaneously. So, it is important to evaluate each group in terms of their effect on oil recovery.

The reference variables are arbitrarily chosen so that the dimensionless equations should be simplified. The dimensionless groups which do not affect the process should be eliminated. Some of the groups should be 0, 1 or equal to another group leads to the elimination of some groups. The reference velocity of all phases was made equal with respect to the direction of flow. The reference phase saturations are also made equal.

$$u_{xoR} = u_{xwR} = u_{xgR} = u_{xR}$$

$$u_{zoR} = u_{zwR} = u_{zgR} = u_{zR}$$

$$s_{oR} = s_{wR} = s_{gR} = S_R = 1 - s_{gr} - s_{wc} - s_{or}$$

This relationship leads group 19, 20 and 21 equals to 1.

The pseudopermeability of different phases are made equal.

Setting group 155 and 156 into 1 can leads:

$$x_R = L$$

$$z_R = H$$

The result of setting group 155 and 156 equal to 1 and equating group 157 into 1 leads to:

$$u_{xgR} = U_t \text{ and } u_{xgR} = u_{xR}$$

Therefore, $u_{xoR} = u_{xwR} = U_t$

The resulting relationships has an impact on group 1, 9 and 17 by making them equal.

Moreover, a relationship can be built by equating these groups into 1.

$$t_R = \frac{\phi x_R s_{wR}}{u_{xwR}} = \frac{\phi L S_R}{U_t}$$

Equating group 2, 10 and 18 to 1 and substituting for t_R leads to

$$u_{zoR} = u_{zwR} = u_{zgR} = u_{zR} = \frac{H}{L} U_t$$

$$\eta_{gR} = \eta_{oR} = \eta_{wR} = \eta_R \text{ and } f_{xgR} = f_{xoR} = f_{xwR} = f_R; f_{zgR} = f_{zoR} = f_{zwR} = \frac{H}{L} f_R$$

Then group 30, 31, 33 and 34 equals to 1.

Setting group 112, 114 and 116 to 1, and solving for pressure

$$p_{wR} = \frac{L U_t}{k_{xwR} \lambda_{xwR}}$$

$$p_{oR} = \frac{L U_t}{k_{xoR} \lambda_{xoR}}$$

$$p_{gR} = \frac{L U_t}{k_{xgR} \lambda_{xgR}}$$

Group 139, 142, and 145 set to zero, bearing the following relationships:

$$\Delta p_{gR} = p_{gi} - p_{wf}$$

$$\Delta p_{oR} = p_{oi} - p_{wf}$$

$$\Delta p_{wR} = p_{wi} - p_{wf}$$

Therefore, $p_{gi} = p_{oi} = p_{wi} = p_{wf}$

For the case of concentration scale factors, injected additive concentration E_{4j} , is selected as the major variable in scaling different fluid concentrations. Thus, group 138 should be equal to 1.

$$E_{Aj} = E_{w4R}$$

Other component fluid concentrations should be made equal and set to equal of injected additive concentration.

$$E_{g1R} = E_{o2R} = E_{w3R} = E_{Aj}$$

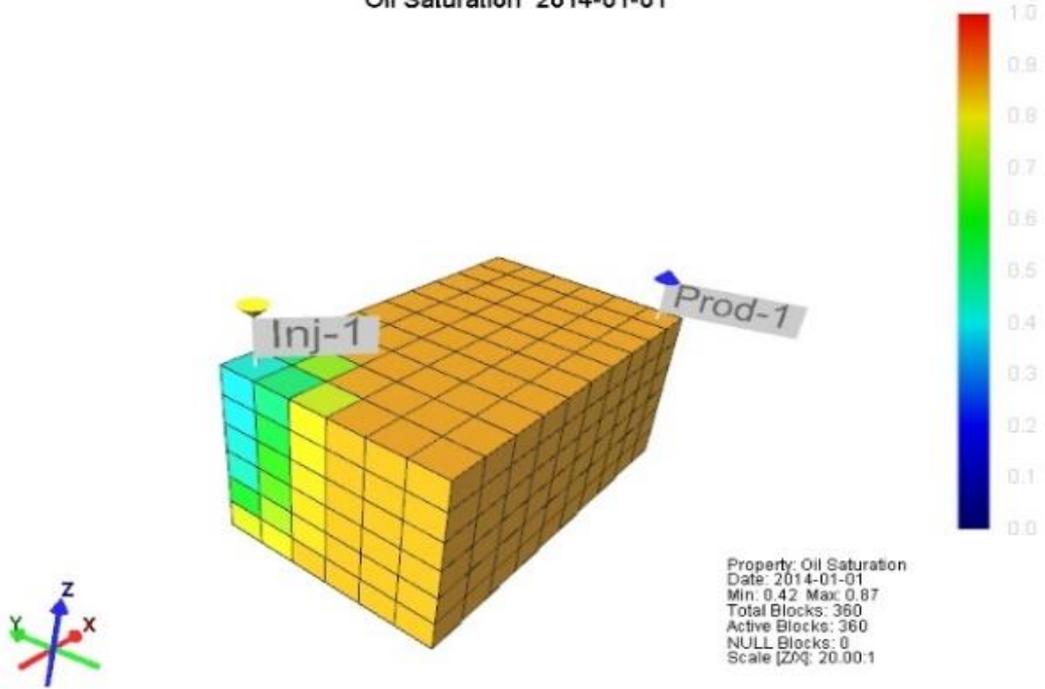
The longitudinal and transverse dispersion groups (3 to 8 and 11 to 16) can be simplified as:

$$\frac{\phi D_{Lw1R}}{LU_t}, \frac{\phi D_{Tw1R}L}{H^2U_t}, \frac{\phi D_{Lw2R}}{LU_t}, \frac{\phi D_{Tw2R}L}{H^2U_t}, \frac{\phi D_{Lw3R}}{LU_t}, \frac{\phi D_{Tw3R}L}{H^2U_t}, \frac{\phi D_{Lo1R}}{LU_t}, \frac{\phi D_{To1R}L}{H^2U_t}, \frac{\phi D_{Lo2R}}{LU_t}, \frac{\phi D_{To2R}L}{H^2U_t}, \frac{\phi D_{Lo3R}}{LU_t} \text{ and } \frac{\phi D_{To3R}L}{H^2U_t}.$$

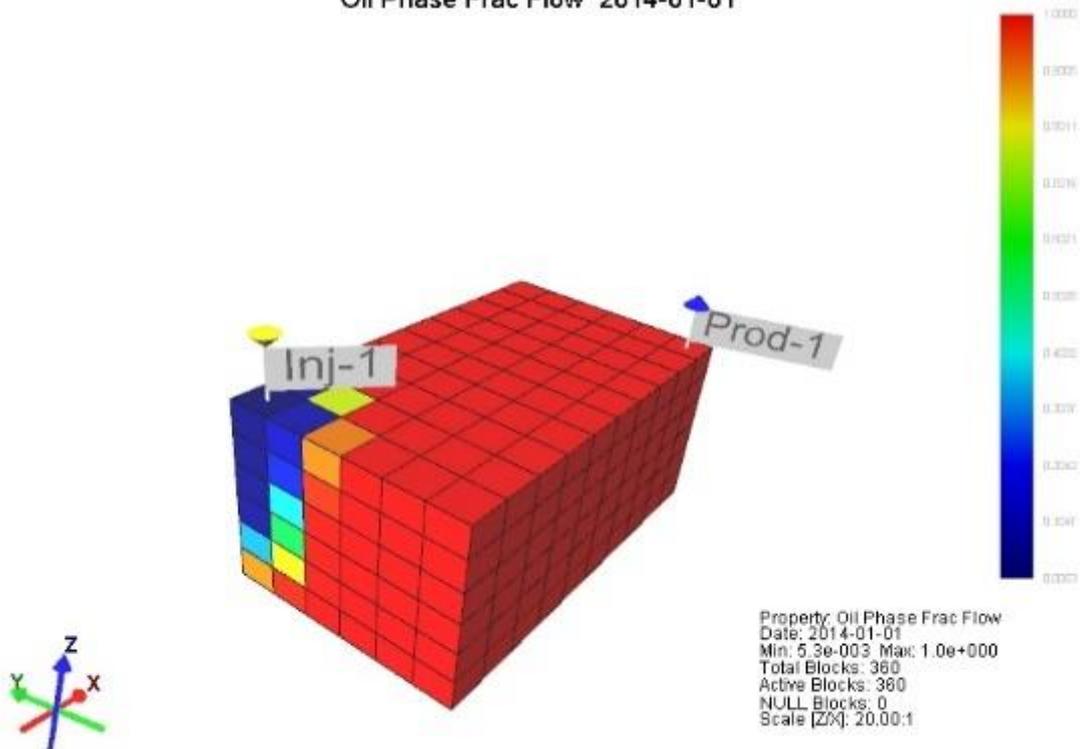
Further reduction of some groups can be attained by considering a specific component has no dispersion effect inside its own phase. For example, if dispersion coefficient D_{Lw3R} , D_{Tw3R} of brine are considered within aqueous phase, an assumption can be made since brine is a major component of the aqueous phase. The velocity of brine is same as the weighted velocity of aqueous phase (Panday and Corapcioglu, 1989). The same concept can be applied to dispersion coefficient of other phases. The dispersion coefficient of oleic phase is also eliminated as the additive is not reactive with oil. Steam is only presented in oleic and gaseous phases. Therefore, dispersion coefficient D_{Lw1R} , D_{Tw1R} of steam in the aqueous phase are eliminated. The gas-oil capillary number can be eliminated as the miscible steam-oil system, the interfacial tension $\sigma_{gOR} = 0$ (Kulkarni, 2005). The dimensionless groups obtained through inspectional analysis recur and rest of the groups are not independent make it possible for further reduction of groups. All the dimensionless groups are multiplicative. If the logarithmic scale is taken, then it is possible to form a system of linear equations. Coefficient matrix is used to further reduces the dimensionless groups. The final form of dimensionless groups is summarized in Table 2.

Appendix B

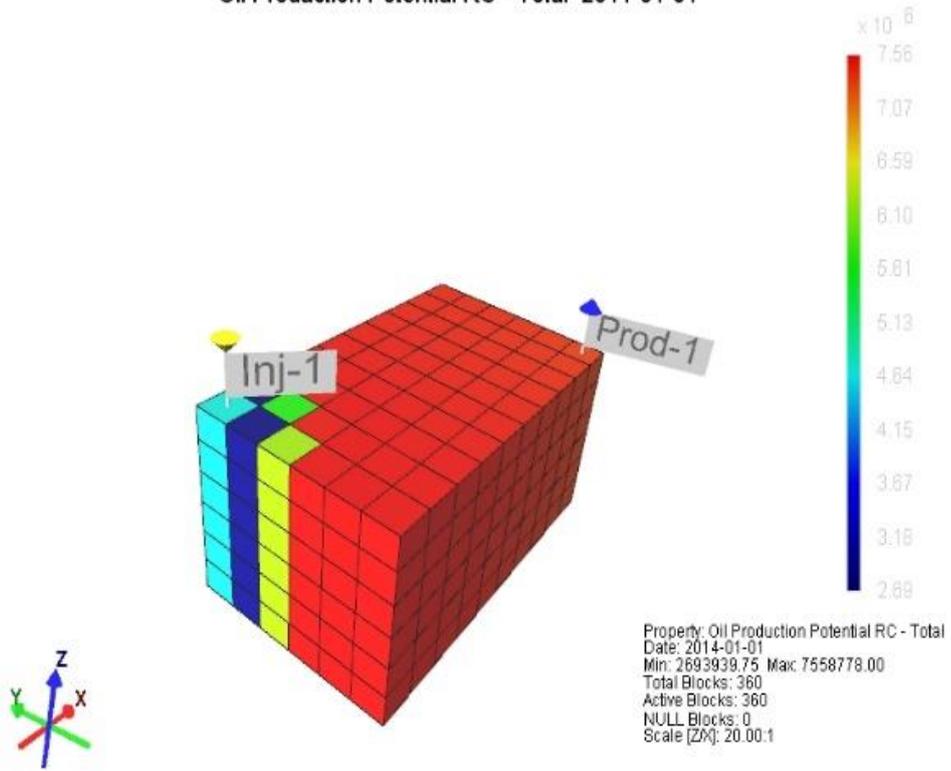
Oil Saturation 2014-01-01



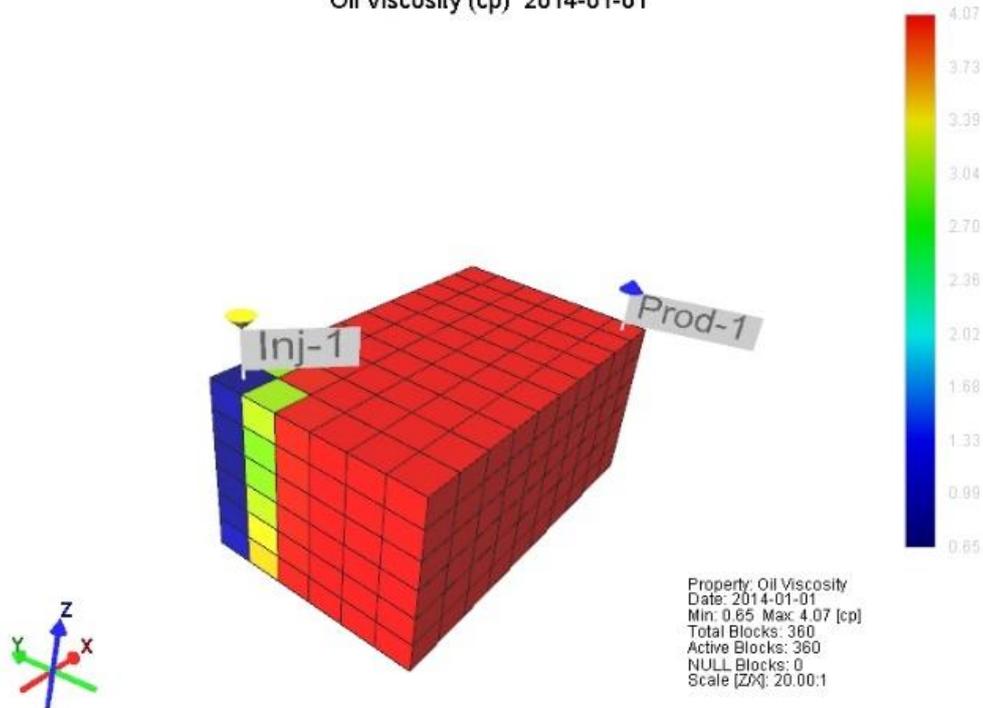
Oil Phase Frac Flow 2014-01-01



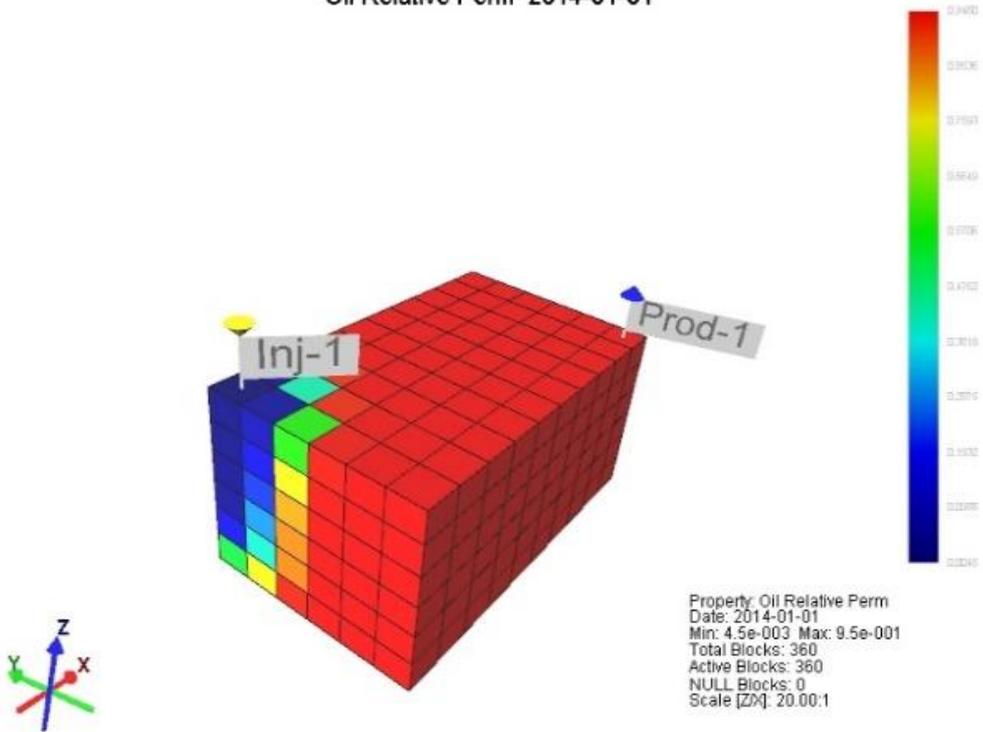
Oil Production Potential RC - Total 2014-01-01



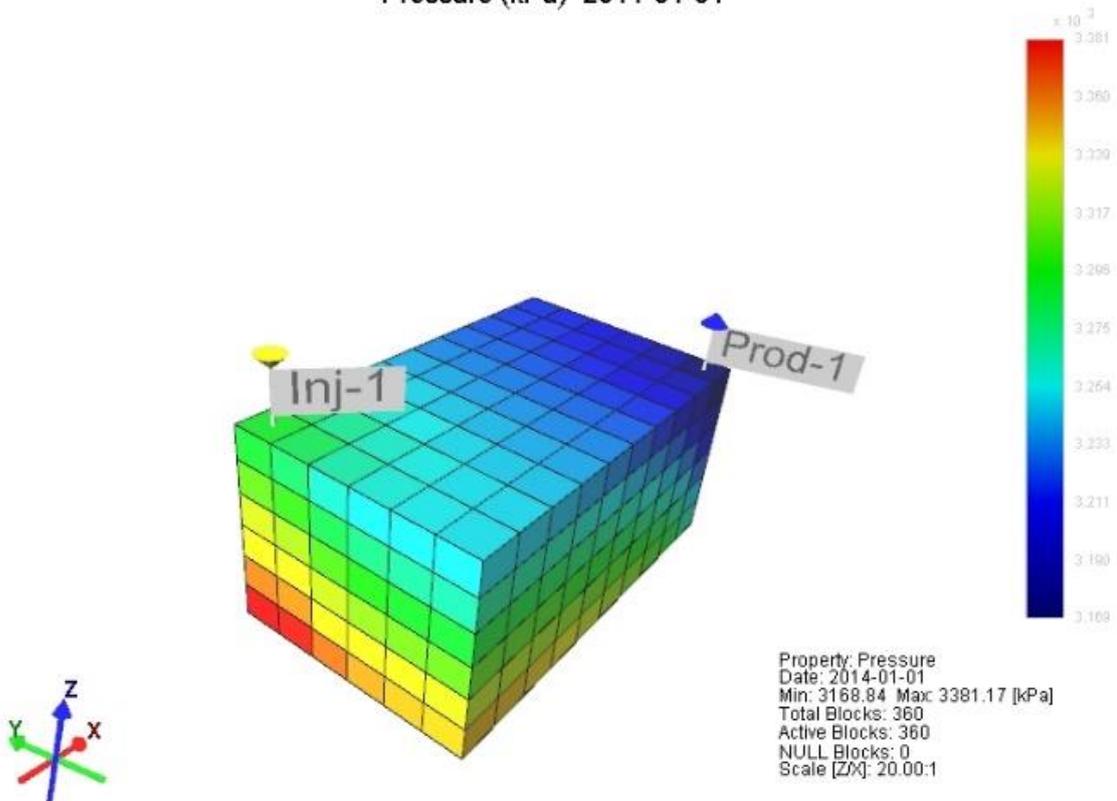
Oil Viscosity (cp) 2014-01-01



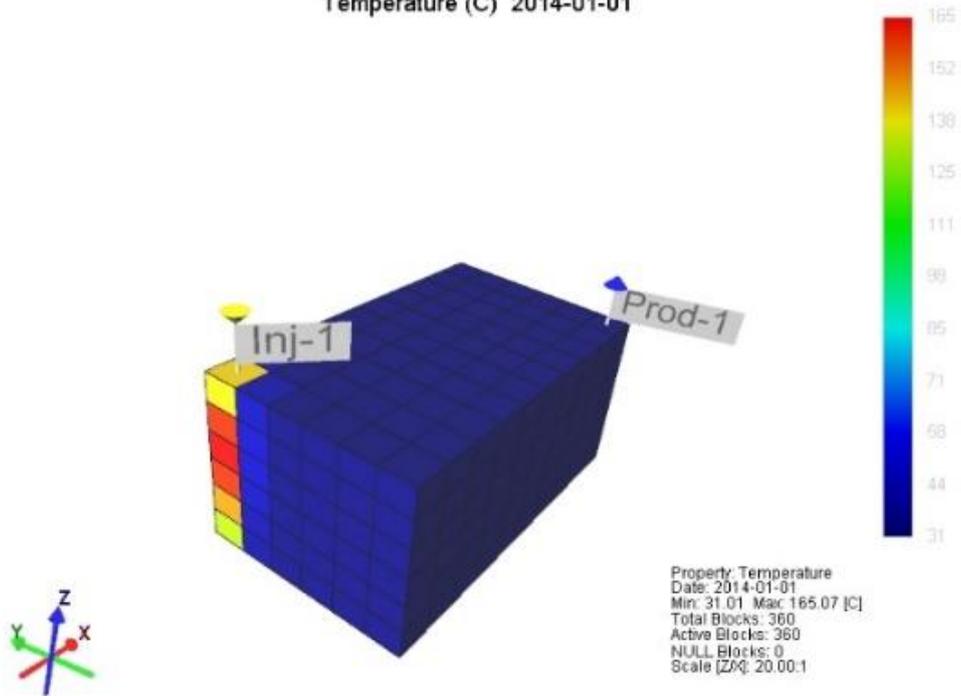
Oil Relative Perm 2014-01-01



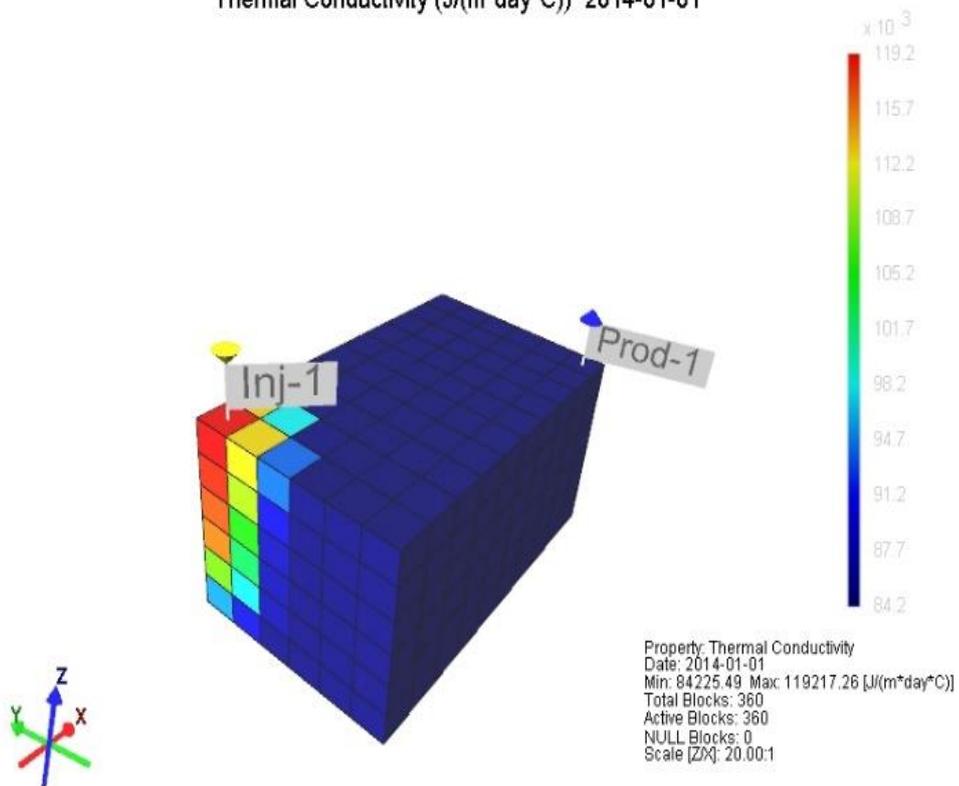
Pressure (kPa) 2014-01-01

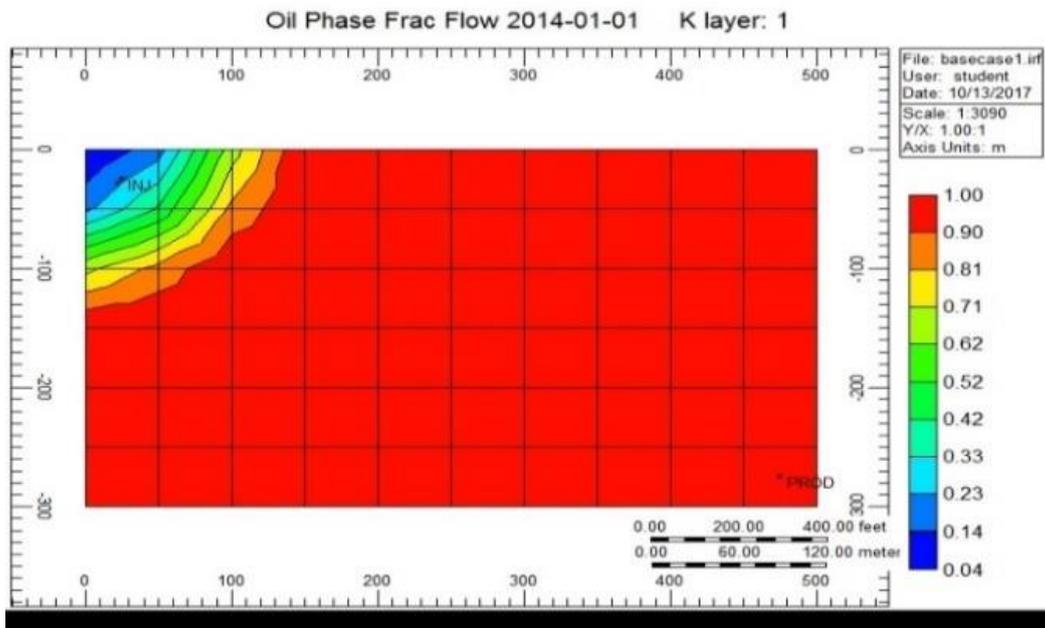


Temperature (C) 2014-01-01

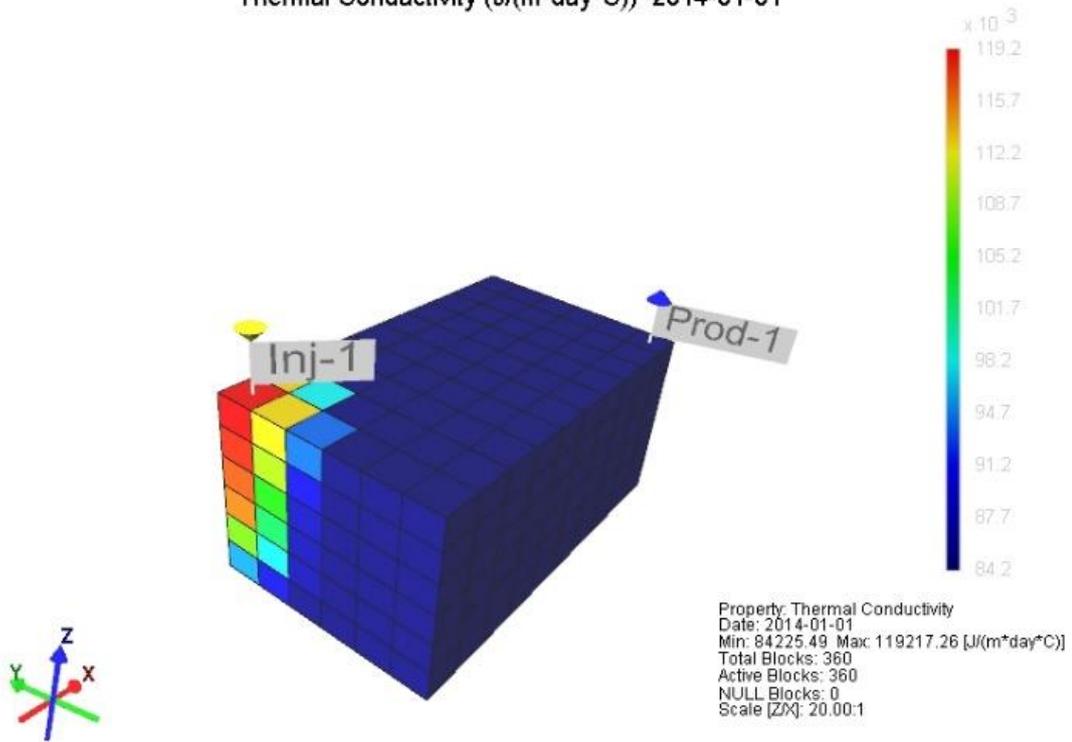


Thermal Conductivity (J/(m*day*C)) 2014-01-01

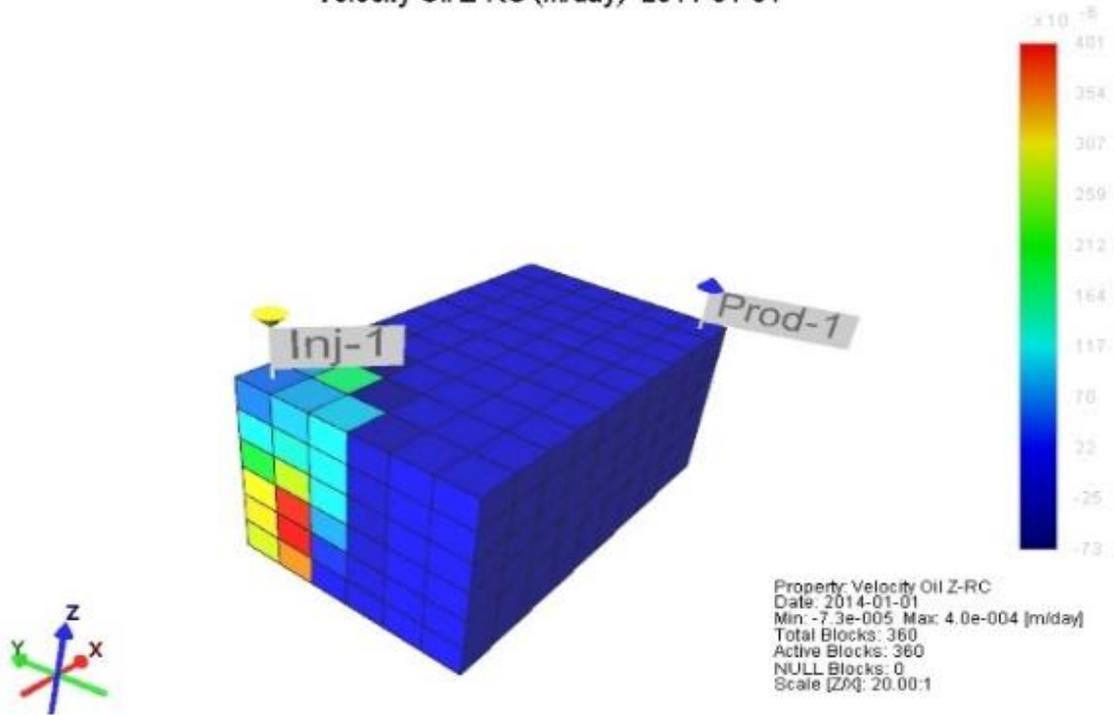




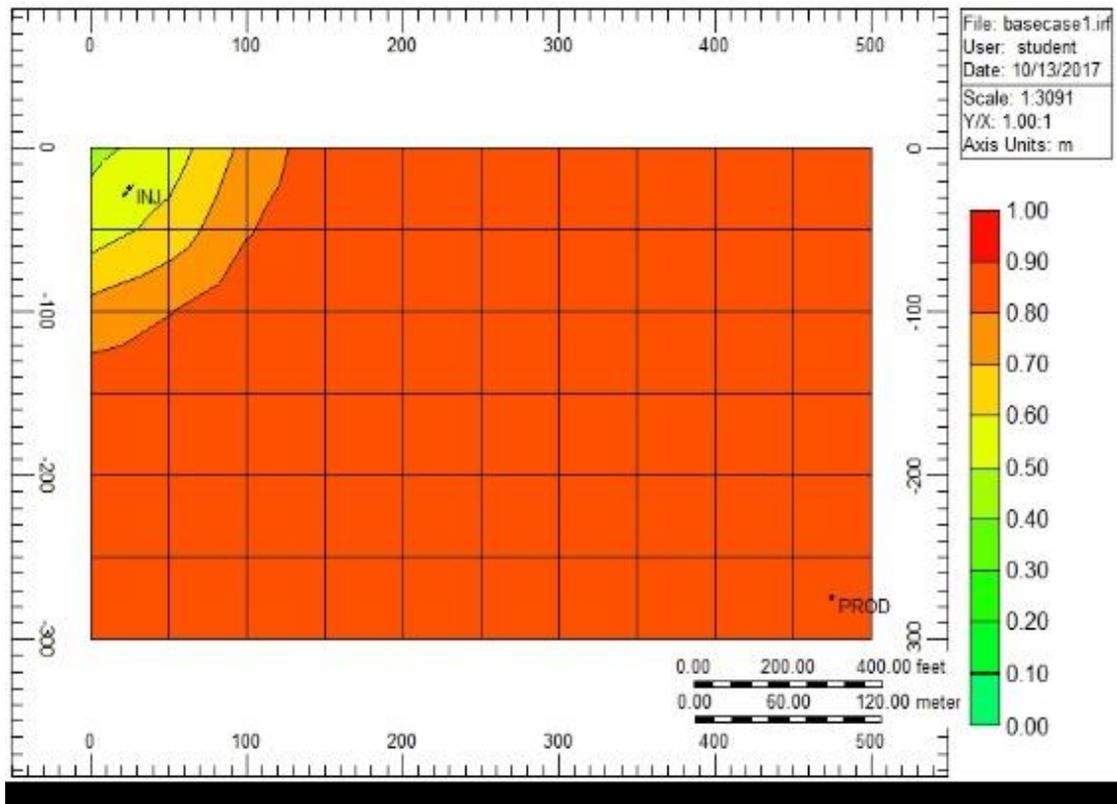
Thermal Conductivity (J/(m*day*C)) 2014-01-01



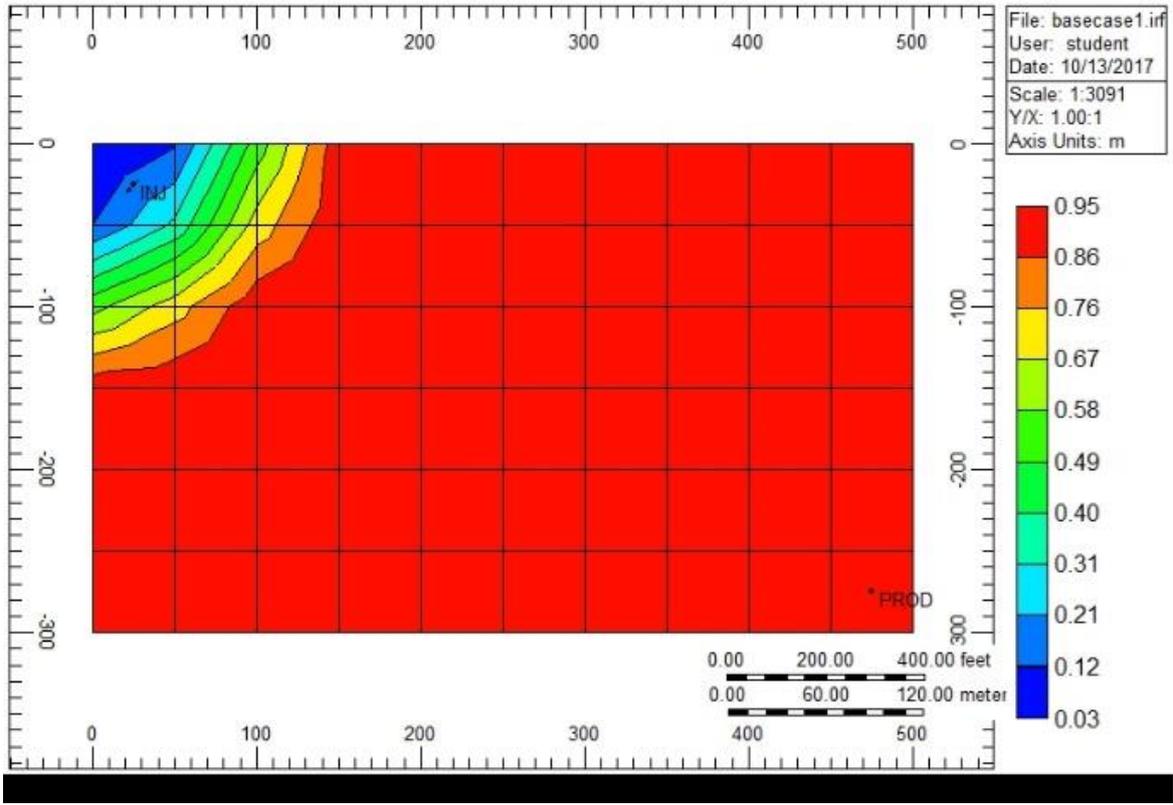
Velocity Oil Z-RC (m/day) 2014-01-01



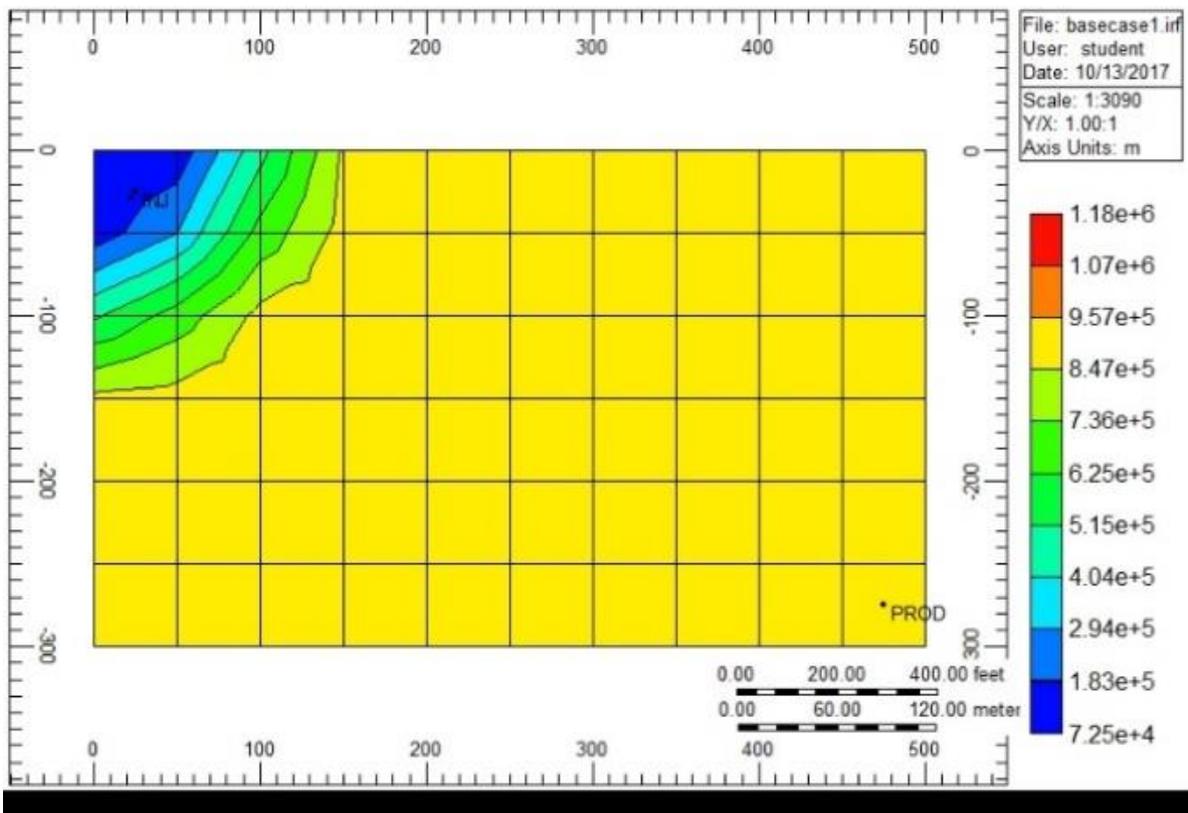
Oil Saturation 2014-01-01 K layer: 1



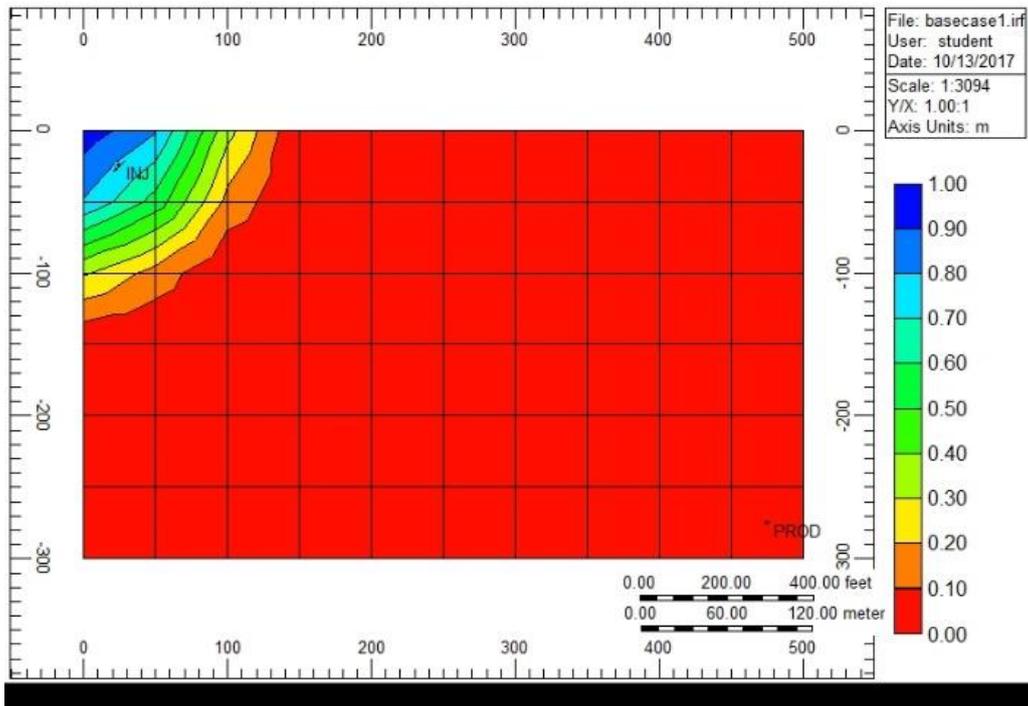
Oil Relative Perm 2014-01-01 K layer: 1



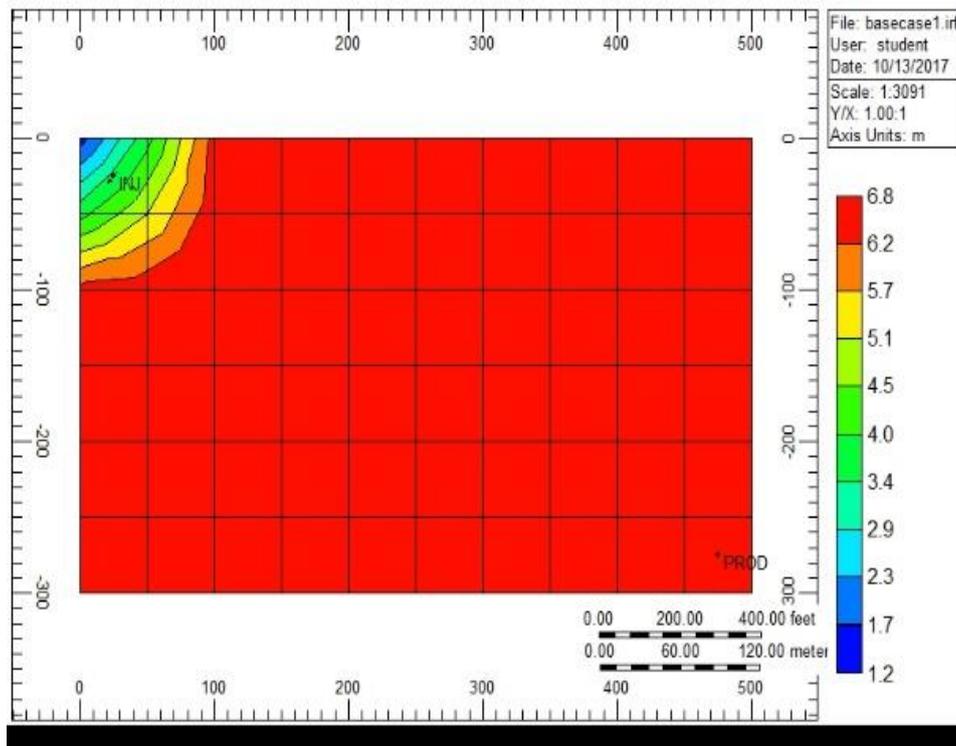
Oil Production Potential RC 2014-01-01 K layer: 1



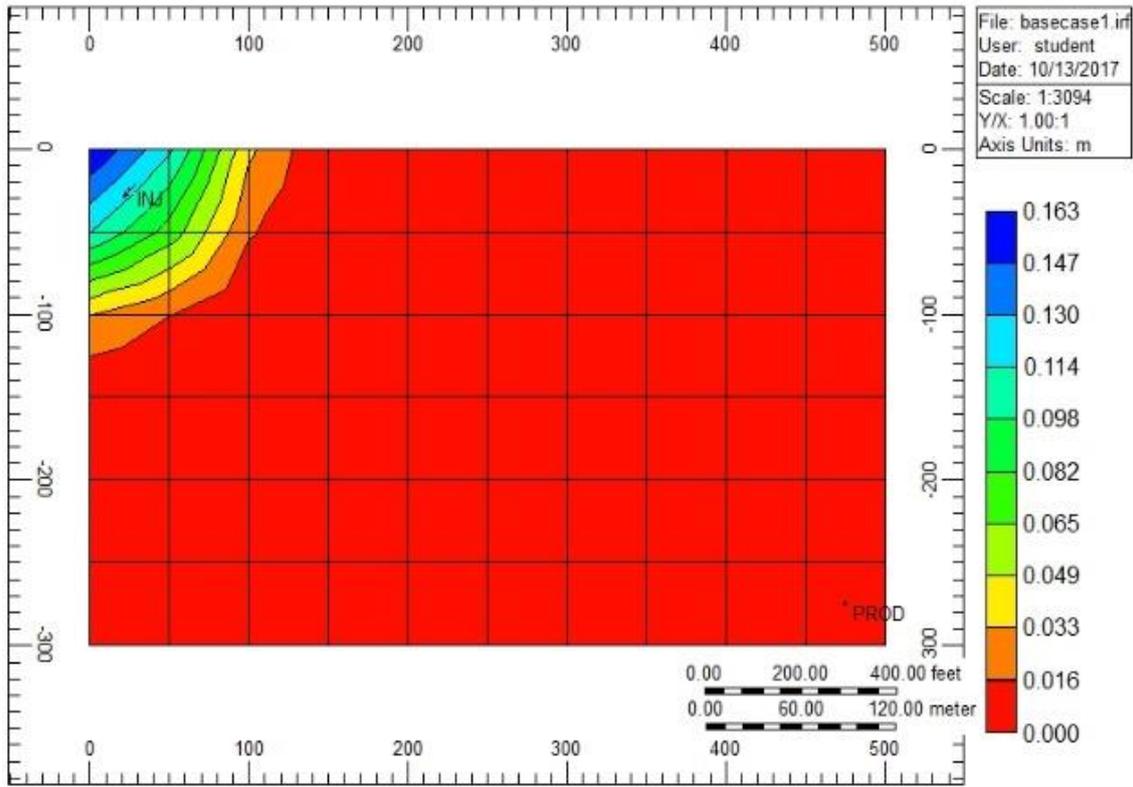
Water Phase Frac Flow 2014-01-01 K layer: 1



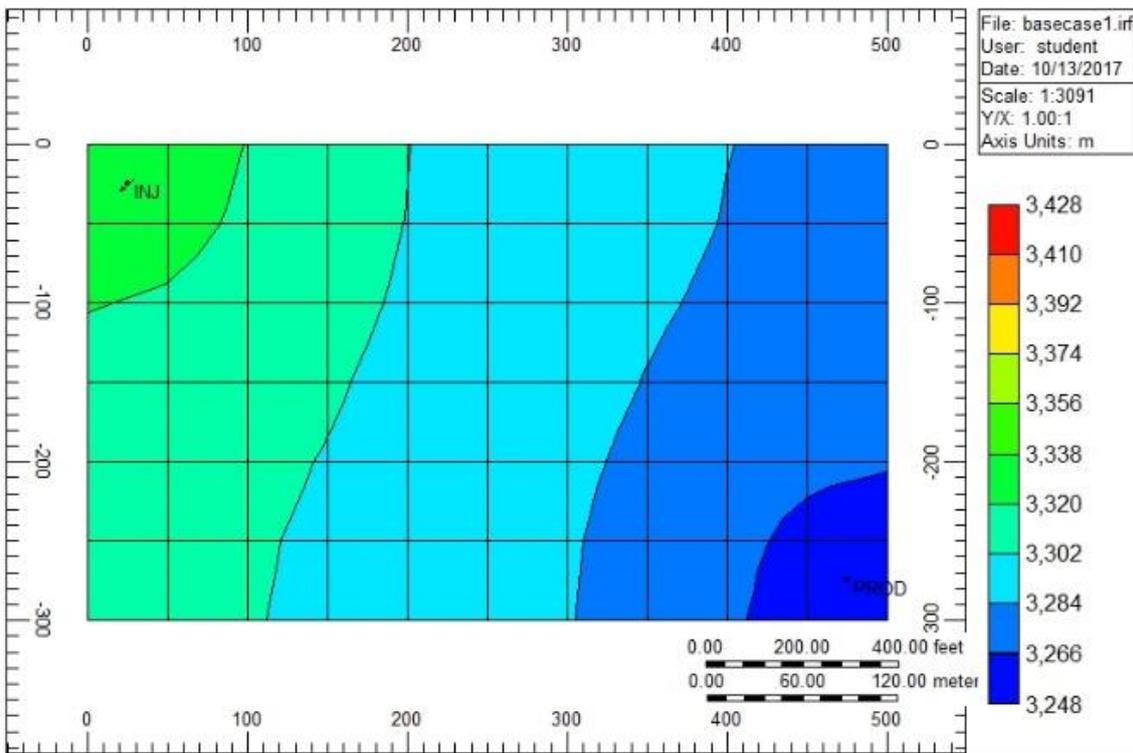
Oil Viscosity (cp) 2014-01-01 K layer: 1



Water Relative Perm 2014-01-01 K layer: 1



Pressure (kPa) 2014-01-01 K layer: 1



Chapter Five

Sensitivity Analysis of Scaled Model and Numerical Simulation Study of Steam Flooding Process

Abstract

Steam flooding is a tertiary oil recovery method where steam is injected into the reservoir to decrease the oil viscosity and hence increase the oil recovery. A set of scaling criteria of a steam flooding process is derived from governing equations with their initial and boundary conditions, constitutive relationships, constraints. Eighteen dimensionless groups governing the process of steam flooding for enhanced oil recovery were investigated using inspectional analysis, and a numerical study was performed to quantify their effects on oil recovery. The derived numbers involved capillary and gravity forces, diffusion, dispersion, heat conduction, mobility ratio, etc. A new dimensionless number is proposed which can better describe the steam flooding process and evaluate the dominant parameters affecting the process. The sensitivity analysis of dimensionless parameters is performed to determine the dominant scaling numbers for steam flooding process. A numerical simulation study is performed to quantify the effects of permeability variations, the steam quality on oil recovery.

Keywords: Dimensionless numbers; Sensitivity analysis; Proposed new number; Inspectional analysis; Numerical simulation etc.

5.1. Introduction

Steam flooding process is an important thermal flooding technique which can apply in many parts of the world in commercial scale. Continuous steam injection and their main elements as a part of displacement technique, were analyzed thoroughly by different experimental studies both in field and laboratory scale (Willman et al., 1961; Johnson et al., 1971; Baker, 1973; Wu, 1977; Blevins et al., 1969; Blevins and Billingsley, 1975). Steam flooding process involves more than 80% of the enhanced oil recovery technique. Thus, it is the most important technique for the petroleum industry to predict the performance of a reservoir. Many researchers (Marx and Langenheim, 1959; Willman et al., 1961; Wilson and Root, 1966; Baker, 1969; Shutler, 1969; Mandl and Volek, 1969; Coats et al., 1974; Weinstein et al., 1977; Myhill and Stegemeier, 1978) give emphasis on improving the efficiency of steam flooding process. Mathematical models are used as an aid in understanding and designing the steam flooding process along with laboratory and field tests (Marx and Langenheim, 1959; Mandl and Volek,

1969; Shutler and Boberg 1972; Neuman, 1975; Van Lookeren, 1983; Shutler, 1969; Abdalla and Coats, 1971; Coats et al.,1974; Coats, 1976; Weinstein et al., 1977). Numerous laboratory studies have been performed as an attempt to achieve this objective. Several experiments were planned which involve numerical simulator to analysis the numerous mechanism of a given process to expand the results for field predictions. Other experiments refer to as scaled experiments were performed to permit the comparative performance of numerous mechanism observed in different experiments to predict the performance expected in the field scale. It can also permit the interpretation of results to implement in the field scale.

Scaling criteria development for the steam flooding process have been evolved from isothermal process to hot-water injection into the reservoir. Several scaling studies have been performed to analyze the isothermal reservoir or process (Leverett et al., 1942; Rapoport and Leas, 1953; Rapoport, 1955; Croes and Schwarz,1955; Geertsma et al., 1956; Perkins and Collins, 1960; Carpenter et al., 1962; Nielsen and Tek, 1963; Baker, 1967; Dietz, 1967). The scaling for the hot-water drive has been investigated in the study of Geertsma et al., 1956; Baker, 1967; and Dietz, 1967. Development of scaling criteria by dimensional and inspectional analysis has been investigated by Ruark, 1935; Richardson,1961; Loomis and Crowell, 1964; and Rahman et al., 2017. Scaling of steam flooding process and the development of experimental study has been studied for years. Some of the early work has been reported by Niko and Troost (1971) and Harmsen (1971). Ali and Redford (1977) presented a review of previous works on scaling the steam flooding process. Depending on the different degree of complexity of scaling criteria, it is divided into two broad categories: high-pressure model (operating at field pressure) and low-pressure model (operating at vacuum). The same fluid found in the prototype is employed in the model for high-pressure model. The criteria used extensively for the high-pressure model is introduced by Pujol and Boberg (1972). On the other hand, the low-pressure model requires fluid which has different properties from those found in the prototype to satisfy all the criteria. Stegemeier et al., (1980) developed the criteria widely used in the low-pressure model. Huygen (1976) developed a high pressure scaled model where only heat flow is considered for crushed sandstone. Pursley (1974) studied the effects of heterogeneity, steam quality, bottom water, gas cap on reservoir response by applying Pujol and Boberg's high-pressure scaling model. Prats (1977) applied the low-pressure model and found it suitable for simulating vaporization phenomena in the pressure cycling process.

Reservoir simulation is the best tool developed for characterizing and optimizing the performance of a reservoir. Numerical reservoir simulators use the mathematical equations

which can describe the behavior of a specific process under investigation. Numerical reservoir simulation of thermal flooding EOR process has been largely accepted in the oil and gas industry because it can solve problems that cannot be solved in any other way (Staggs and Herbeck, 1971; Coats, 1980 and 1982; Rubin and Buchanan, 1983; Ali, 1984; Mattax and Dalton 1990). A numerical simulation study of steam flooding process is executed to investigate the effect of reservoir heterogeneity on oil recovery using CMG STARS software. CMG STARS files are provided in appendix C. In addition, it can quantify the effect of injection rate and steam quality on oil recovery. Finally, scaled model study and reservoir simulation study is used to develop an effective production strategy for steam flooding process.

In this study, 18 dimensionless groups are derived from the comprehensive inspectional analysis. The sensitivity analysis of these groups and their effect on oil recovery is investigated. Dominant scaling groups for steam flooding process has determined through the sensitivity analysis. The effect of reservoir heterogeneity or permeability variation is investigated by Dykstra-Parsons coefficient. A new combined dimensionless group is proposed using combined process controlling parameters for suitable prediction of oil recovery. Finally, numerical reservoir simulation is done to predict the performance of scaled steam flooding process.

5.2. The Governing Equations

The governing equations using modified Darcy's law, constitutive relationships, constraints are used for steam flooding process. Memory concept (Rahman et al., 2017; Hosain and Islam 2011; Caputo, 1997) is incorporated to derive those dimensionless numbers.

The flow equation can be written as

$$u_x = -\eta \left[\frac{\partial^\alpha}{\partial t^\alpha} \left(\frac{\partial p}{\partial x} \right) \right] \quad (1)$$

where $\frac{\partial^\alpha}{\partial t^\alpha} [p(x, t)] = \frac{1}{\Gamma(1-\alpha)} \int_0^t (t-\xi)^{-\alpha} \frac{\partial}{\partial \xi} [p(x, t)] d\xi$, with $0 \leq \alpha < 1$

Equation (1) can be written as

$$u_x = -\frac{\eta}{\Gamma(1-\alpha)} \int_0^t (t-\xi)^{-\alpha} \frac{\partial^2 p}{\partial \xi \partial x} d\xi \quad (2)$$

Equation (2) can be written for oil, water and gas phase in the direction of x and z-axes.

$$u_{x_o} = -\frac{\eta_o}{\Gamma(1-\alpha)} \int_0^t (t-\xi)^{-\alpha} \frac{\partial^2 p_o}{\partial \xi \partial x} d\xi \quad (3)$$

$$u_{zo} = -\frac{\eta_o}{\Gamma(1-\alpha)} \int_0^t (t-\xi)^{-\alpha} \frac{\partial^2 p_o}{\partial \xi \partial z} d\xi \quad (4)$$

$$u_{xw} = -\frac{\eta_w}{\Gamma(1-\alpha)} \int_0^t (t-\xi)^{-\alpha} \frac{\partial^2 p_w}{\partial \xi \partial x} d\xi \quad (5)$$

$$u_{zw} = -\frac{\eta_w}{\Gamma(1-\alpha)} \int_0^t (t-\xi)^{-\alpha} \frac{\partial^2 p_w}{\partial \xi \partial z} d\xi \quad (6)$$

$$u_{xg} = -\frac{\eta_g}{\Gamma(1-\alpha)} \int_0^t (t-\xi)^{-\alpha} \frac{\partial^2 p_g}{\partial \xi \partial x} d\xi \quad (7)$$

$$u_{zg} = -\frac{\eta_g}{\Gamma(1-\alpha)} \int_0^t (t-\xi)^{-\alpha} \frac{\partial^2 p_g}{\partial \xi \partial z} d\xi \quad (8)$$

Now the mass balance equation for distinct phases are written as

Mass balance of aqueous phase

$$\begin{aligned} \frac{\partial}{\partial x} u_{xw} E_{w1} + \frac{\partial}{\partial z} u_{zw} E_{w1} + \frac{\partial}{\partial x} u_{xw} E_{w3} + \frac{\partial}{\partial z} u_{zw} E_{w3} + \frac{\partial}{\partial x} u_{xw} E_{w4} + \frac{\partial}{\partial z} u_{zw} E_{w4} + \phi E_{Lw1} \frac{\partial^2}{\partial x^2} E_{w1} + \phi E_{Tw1} \frac{\partial^2}{\partial z^2} E_{w1} + \\ \phi D_{Lw3} \frac{\partial^2}{\partial x^2} E_{w3} + \phi D_{Tw3} \frac{\partial^2}{\partial z^2} E_{w3} + \phi D_{Lw4} \frac{\partial^2}{\partial x^2} E_{w4} + \phi D_{Tw4} \frac{\partial^2}{\partial z^2} E_{w4} = \phi \frac{\partial}{\partial t} s_w E_{w1} + \phi \frac{\partial}{\partial t} s_w E_{w3} + \phi \frac{\partial}{\partial t} s_w E_{w4} \end{aligned} \quad (9)$$

Mass balance of oleic phase

$$\begin{aligned} \frac{\partial}{\partial x} u_{ox} E_{o1} + \frac{\partial}{\partial z} u_{oz} E_{o1} + \frac{\partial}{\partial x} u_{ox} E_{o2} + \frac{\partial}{\partial z} u_{oz} E_{o2} + \frac{\partial}{\partial x} u_{ox} E_{o4} + \frac{\partial}{\partial z} u_{oz} E_{o4} + \phi E_{Lo1} \frac{\partial^2}{\partial x^2} E_{o1} + \phi E_{To1} \frac{\partial^2}{\partial z^2} E_{o1} + \\ \phi E_{Lo2} \frac{\partial^2}{\partial x^2} E_{o2} + \phi D_{To2} \frac{\partial^2}{\partial z^2} E_{o2} + \phi D_{Lo4} \frac{\partial^2}{\partial x^2} E_{o4} + \phi D_{To4} \frac{\partial^2}{\partial z^2} E_{o4} = \phi \frac{\partial}{\partial t} s_o E_{o1} + \phi \frac{\partial}{\partial t} s_o E_{o2} + \phi \frac{\partial}{\partial t} s_o E_{o4} \end{aligned} \quad (10)$$

Mass balance of gaseous phase

$$\frac{\partial}{\partial x} u_{xg} E_{g1} + \frac{\partial}{\partial z} u_{zg} E_{g1} = \phi \frac{\partial}{\partial t} s_g E_{g1} \quad (11)$$

Thermal energy balance equation can be written in integral form over the steam zone modified from Yortsos (1979)

$$\begin{aligned} \Delta T \frac{d}{dt} \int_{v(t)} M_1 dv + \int_{A_{ca(t)}} \left(-K_{nc} \frac{\partial T}{\partial x} \right) dA + \int_{A_{sf(t)}} \left(-K_n \frac{\partial T}{\partial x} \right) dA + \Delta T \left[\sum_{i=w,o} C_i \int_{A_{sf(t)}} \rho_i (u_{ix} - \phi s_i v_x) dA - \right. \\ \left. (1-\phi) C_r \int_{A_{sf(t)}} \rho_r v_x dA \right] = m_s [f_s L_v + C_w \Delta T] \end{aligned} \quad (12)$$

After applying a general procedure of inspectional analysis along with some initial and boundary conditions and some modifications, the dimensionless groups are reported in table 5.1.

5.3. Dimensionless Groups

Dimensionless groups from the inspectional analysis are reported in table 5.1. Major scaling groups are listed in table 5.1. Different elimination techniques are used to select those numbers from primary dimensionless numbers. Capillary, gravity, Peclet, geometric aspect ratio, thermal conductivity ratio, mobility ratio, heat capacity ratio, etc. are listed in table 5.1.

Table 5.1: Dimensionless Groups from Inspectional Analysis.

Longitudinal Peclet Number	$\frac{1}{G_1} = N_{PLo1} = \frac{LU_t}{\phi E_{Lo1R}}$
Transverse Peclet Number	$\frac{1}{G_2} = N_{PTo1} = \frac{H^2 U_t}{\phi E_{To1R} L}$
Water-Oil Mobility Ratio	$G_3 = M_{ow} = \frac{\mu_o k_{rw}}{\mu_w k_{ro}}$
Gas-oil Mobility Ratio	$G_4 = M_{go} = \frac{\mu_o k_{rg}}{\mu_g k_{ro}}$
Gravity to Longitudinal Fluid Movement Ratio	$\frac{1}{G_5} = N_{LG} = \frac{\Gamma(1 - \alpha) t_R^{\alpha-1} \phi_R S_R L^2}{f_R \eta_R \rho_{WR}}$
Gravity to Transverse Fluid Movement Ratio	$\frac{1}{G_6} = N_{TG} = \frac{\Gamma(1 - \alpha) t_R^{\alpha-1} \phi_R S_R L H}{f_R \eta_R \rho_{WR}}$
Dispersion Factor	$\sqrt{G_7} = Q_L = \frac{L}{H} \sqrt{\frac{D_{To1R}}{D_{Lo1R}}}$
Water-Oil Gravity Number	$G_8 = N_{Gwo} = \frac{k_{xwR} \lambda_{xwR} \rho_{woR} g_R H \sin \theta_R}{LU_t}$
Gas-Oil Gravity Number	$G_9 = N_{Gog} = \frac{k_{xoR} \lambda_{xoR} \rho_{ogR} g_R H \sin \theta_R}{LU_t}$
Effective Aspect Ratio	$\sqrt{G_{10}} = R_L = \frac{L}{H} \sqrt{\frac{k_z}{k_x}}$
Oil-Water Capillary Number	$\frac{1}{G_{11}} = N_C = \frac{LU_t \mu_w}{\sigma_{owR} k_{rw} \cos \theta_R \sqrt{\phi_R k_{xw}}}$
Volumetric heat capacity ratio	$G_{12} = N_R = \frac{(1 - \phi) \rho_r C_{pr}}{\phi C_{pw} \rho_w S_w}$
Heat Injected to Heat Stored Ratio	$G_{13} = Q_N = \frac{m_s f_s L_v t}{\Delta T M_1 L^3}$
Mass Flux of Steam to Water	$G_{14} = N_S = \frac{m_s t}{\phi \rho_w S_w L^3}$
Heat Enthalpy to Heat Stored Ratio	$G_{15} = N_E = \frac{\phi L_v \rho_g S_g}{M_1 \Delta T}$
Fluid Thermal Conductivity to Effective Thermal Conductivity Ratio	$G_{16} = N_F = \frac{\phi K_{hf}}{K_{he}}$

Rock Thermal Conductivity to Effective Thermal Conductivity Ratio	$G_{17} = N_T = \frac{(1 - \phi)K_{hr}}{K_{he}}$
Dimensionless Time	$G_{18} = t_D = \frac{U_t t}{L\phi(1 - s_{wi} - s_{or})}$

Different rock and fluid properties are employed to find out the value of each dimensionless groups which is reported in table 5.2 and 5.3. Four different cases are studied where the reservoir has four different dimensions and different rock and fluid properties depending on temperature and pressure conditions (Table 5.3) Only ten dimensionless numbers give the same value for each case. These ten dimensionless numbers are evaluated, and their relative effect on oil recovery are estimated. The common parameters which are used in dimensionless number evaluation for all four cases are noted in table 5.2.

Table 5.2: Common parameters required in scaling groups

Parameters	Values	Parameters	values	Parameters	Values
k_z (mD)	800	K_w =(Kj/h-m-k)	3.7758	C_{pw} (Kj/kg-k)	4.1868
k_x (mD)	800	K_g =(Kj/h-m-k)	0.0143	f_R	0.2
k_{rg}	0.150	K_{hf} =(Kj/h-m-k)	1.7288	m_s (ft ² /s)	17.20
k_{ro}	0.085	K_{he} =(Kj/h-m-k)	6.7936	L_v (Btu/lb)	837.3
k_{rw}	0.400	h_L (Kj/h-m ² k)	280.87	M_1 (Btu/ft ³ °F)	3.69
g (cm/s ²)	980.7	p_i (pa)	1.7×10^7	η_R	0.35
σ_{ow} (dyne/cm)	49.0	C_{pg} (Kj/kg-k)	29.7263	α	0.2
K_r =(Kj/h-m-k)	9.346	C_{pr} (Kj/kg-k)	0.8792	f_s	0.8
K_o =(Kj/h-m-k)	1.3962	C_{po} (Kj/kg-k)	2.0934	C_{pw} (Kj/kg-k)	4.1868

Four different dimensions of reservoir is considered with their corresponding rock and fluid properties are reported in table 5.3. Depending on temperature and pressure conditions the properties should be different from each other. Reservoir length, width, total fluid velocity, longitudinal and transvers dispersion, porosity, viscosity and density of each phases are noted in table 5.3.

Table 5.3: Parameters required in scaling groups for four different cases

Parameters	Case 1	Case 2	Case 3	Case 4
L, cm (ft)	7.65	1500 (49.2)	1800 (59.0)	3735 (122.5)
H, cm (ft)	2.56	502 (16.5)	602.4 (19.8)	1250 (41.0)
U_T , ft/s	3.36×10^{-4}	1.71×10^{-5}	1.43×10^{-5}	2.50×10^{-6}
D_{Lo1R} , ft ² /s	1.12×10^{-4}	1.12×10^{-3}	9.67×10^{-4}	3.38×10^{-4}
D_{To1R} , ft ² /s	3.53×10^{-6}	3.53×10^{-5}	3.05×10^{-5}	1.067×10^{-5}
ϕ	0.332	0.332	0.385	0.400
μ_w at 2500 psi, cP	0.99	0.99	0.99	0.99
μ_o at 2500 psi, cP	1.03	1.03	1.03	1.03
μ_g at 2500 psi, cP	0.125	0.125	0.125	0.125
ρ_w at 2500 psi, g/cm ³	1.020	1.005	1.005	1.005
ρ_o at 2500 psi, g/cm ³	0.683	0.988	0.991	0.998
ρ_g at 2500 psi, g/cm ³	0.942	1.001	1.002	1.003
ρ_r at 2500 psi, g/cm ³	2.680	2.681	2.682	2.683

5.4. Scaling group for reservoir heterogeneity

Reservoir heterogeneity is a key factor in determining the oil recovery from petroleum reservoirs. Most of the Canadian heavy oil reservoirs sands comprises a considerable amount of heterogeneity (Akram, 2012) which must be counted when proposing parameters for field development using steam flooding process. The Dykstra-Parsons coefficient is comprised as an additional dimensionless number to account for reservoir heterogeneity. It can be defined as:

$$F_{DP} = \frac{k_{0.5} - k_{0.84}}{k_{0.5}} \quad (13)$$

Where, $k_{0.5}$ = Median of the permeability

$k_{0.84}$ = One standard deviation from the median permeability

The value of F_{DP} should be lies on 0 to 1. Here 0 representing homogeneous reservoir and 1 represents heterogeneous reservoir. The minimum and maximum value of F_{DP} lies between 0.1 to 0.8 for this study.

5.5. Steam-oil viscosity ratio

Steam-oil viscosity ratio is an important dimensionless group which can characterize the steam flooding process. Steam is injected into the reservoir through the injection well which will reduce the viscosity of the oil and increase the flow efficiency and hence increase the oil recovery. It also largely depends on the contact time. Steam-oil viscosity ratio can be expressed as:

$$R_{ST} = \frac{\mu_g}{\mu_o} \quad (14)$$

Where μ_g and μ_o is the viscosity of steam and oil respectively.

5.6. Proposed new group

The estimation of oil recovery is obtained through reservoir simulation and scaled model studies of steam flooding process. The new dimensionless number is developed that can capture important process controlling parameters. Steam-oil viscosity ratio, gravity number, capillary number, mobility ratio is used to develop this number. Oil recovery is proportional to gravity number and steam-oil viscosity ratio and inversely proportional to mobility ratios and capillary number. The main objective of proposing this number is it can capture physical process more effectively as more parameters are involved in this number than any other dimensionless numbers.

The recovery of oil obtained through the studies of scaling numbers were investigated using gravity and capillary numbers to improve a relationship that captures influential process controlling parameters. It is found that the oil recovery is directly proportional to gravity numbers and inversely proportional to the capillary number. The obtained results suggested that, though the gravity number can provide accurate and closely matched relationship, but few other variables should be studied for the estimation of oil recovery. The pore trapping of oil behind the steam flood front is caused by capillary retention which diminishes the oil recovery performance for steam flooding process. Thus, capillary force effects must be counted for assessing steam flooding process performance. Moreover, the results show that the mobility ratio and the oil viscosity changes have a profound effect on oil recovery. Figure 11 suggests

that oil recovery is increased with increasing viscosity ratio (viscosity of steam to oil). Therefore, the mobility ratios and viscosity ratio should be considered for proposing new dimensionless number. A novel relationship is obtained in this study from the above findings to characterize and evaluate the performance of steam flooding EOR process. The capillary number, gravity number, mobility ratio and the viscosity ratio are considered to develop this correlation. The proposed new dimensionless number is presented as:

$$N_A = \frac{\left(\frac{\mu_{Steam}}{\mu_o}\right)(N_{Gwo}+N_{Gog})^a}{M_{go}M_{wo}N_C} \quad (15)$$

where $a = 0.2$ is a scaling factor which shows the effect of gravity number is less than any other numbers in the proposed new dimensionless group.

Table 5.4 describes different dimensionless numbers with maximum, minimum and mean value. It can also show the recovery factor coefficients along with standard error of each dimensionless group.

Table 5.4: Values of each group corresponding to minimum and maximum level

Groups	Minimum	Maximum	Mean	Regression Coefficient
N_{PLo1}	50	700	375	1.09×10^{-4}
N_{PTo1}	200	2500	1332.32	-4.09×10^{-5}
M_{ow}	0.98	1.09	1.04	-0.09
M_{go}	8.67	14.48	11.32	-0.11
Q_L	0.349	0.863	0.546	0.0007
N_{Gwo}	2.00×10^8	3.49×10^8	2.69×10^8	2.92×10^{-10}
N_{Gog}	3.5×10^7	5.5×10^7	4.52×10^7	1.22×10^{-9}
R_L	2.00	5.84	3.97	1.02×10^{-2}
N_C	4.5×10^{-6}	8.4×10^{-6}	6.27×10^{-6}	-0.03711
V_{Dp}	0.1	0.8	0.45	0.00457
C_{AD}	0.1	0.5	0.282	0.133
R_{ST}	0.0965	0.1622	0.1356	0.150
C_A	7.28×10^4	12.62×10^4	9.82×10^4	0.0345

5.7. Sensitivity analysis of dimensionless numbers

It should be unrealistic to assess the effect of individually all scaling groups on oil recovery because of the extreme workload and large demand for resources. Only thirteen groups are evaluated to analyze their relative effect on oil recovery. A standardized effect is estimated by dividing every regression coefficient with its standard error. Figure 1 shows the value of standardized effect of each scaling group on oil recovery in a normal plot. The positive value indicates a proportional relationship and a negative value indicate the inversely proportional relationship. It also shows the relative importance and magnitude of each group on oil recovery. From figure 1 it should be noted that the most dominant groups are new proposed dimensionless group, steam-oil viscosity ratio, capillary number, mobility ratios and additive concentration groups that can largely affect a steam flooding process. On the other hand, there are some groups which have a minor or insignificant effect on oil recovery that can be termed as secondary scaling groups for steam flooding process.

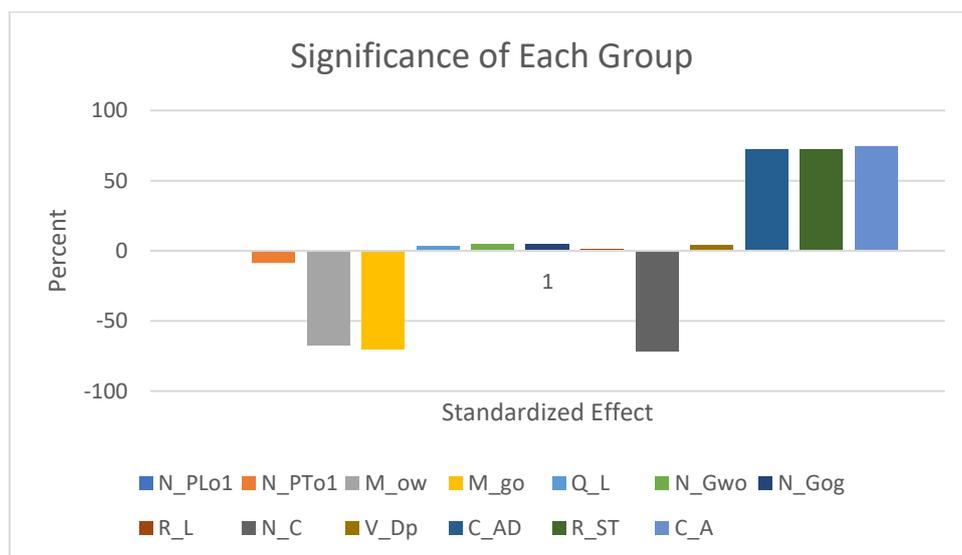


Figure 5.1: Absolute value of standardized effect

5.8. Dominant scaling groups

Dominant dimensionless groups are summarized below:

5.8.1. New proposed number

Newly proposed number has the significant effect on enhanced oil recovery by steam flooding. It is the combination of five dimensionless numbers which is employed to predict the performance of a steam flooding process. The capillary number, gravity number, steam-oil viscosity ratio, mobility ratios are used to develop a relationship that can capture vital steam

flooding process operative physical properties. As the steam-oil viscosity ratio increases with the injection of steam into the reservoir, it will result in increasing oil recovery. Therefore, the change in viscosity is considered in developing the new dimensionless number. From the sensitivity analysis study, it is concluded that the new combination number has the significant effect on oil recovery.

5.8.2 Steam-oil viscosity ratio

Steam-oil viscosity ratio has a noteworthy effect on oil recovery. As steam is injected into the reservoir, it will decrease the viscosity of the oil phase and increase the sweep efficiency. As the viscosity of the oil phase is decreased, which will increase steam-oil viscosity ratio and hence increase the oil recovery.

5.8.3. Steam additive concentration

Another important dimensionless number is the concentration of steam additive which has a significant effect on oil recovery. The concentration of additive is increased the displacement efficiency of steam flooding process. It has the capability of increasing the mobility during the displacement process. In the homogeneous reservoir, heavier oil component flowed to the bottom layer, while the steam flows predominantly to the top layer of the reservoir. As the additive is injected along with the steam, it will help to displace the oil from top layers to the bottom layers. Steam with the additive is acting as a main displacing fluid to displace oil from the lower layers. As the additive concentration is increased from 0.1% wt. to 0.5% wt. It significantly increased the oil recovery.

5.8.4. Capillary number

The capillary number also greatly affect the oil recovery. It is a dimensionless number which characterizes the ratio of viscous force to capillary force to analyze the fluid flow through porous media (Hilfer et al., 2015; Melrose, 1974; Abrams, 1975; Morrow, 1979; Chatzis and Morrow, 1984; Fulcher et al., 1985). When $N_C \gg 1$ then the viscous force dominates over capillary force and when $N_C \ll 1$, then the viscous force is insignificant compared with capillary force. It is a key factor in determining the remaining oil saturation. It has increased the sweep efficiency of the reservoir fluid. The capillary number also has a profound effect on the relative permeability of wetting phase and non-wetting phase (oil) relative permeability behaves as a function of interfacial tension and viscosity variables. As the capillary number is

the ratio of viscous to capillary force, so as the viscosity decreases capillary number will also decrease from 4.5×10^{-6} to 8.4×10^{-6} , as a result oil recovery factor is increased.

5.8.5. Mobility ratios

Steam-oil and water-oil mobility ratio have greatly affected the oil recovery for steam flooding process. In oil reservoirs, the end-point mobility ratio of gaseous phase to oleic phase and the aqueous phase to oleic phase is the main reason to bypassing the oil and residual oil saturation at the end of the displacement process. As the steam is injected into the reservoir, it will reduce the viscosity of the oil and hence increase the sweep efficiency. The mobility ratio can be decreased either by increasing water viscosity, or by decreasing oil viscosity. Additives are added to increase the water viscosity and steam can decrease the oil viscosity and hence increase the oil recovery.

5.9. Secondary scaling groups

Secondary scaling groups are summarized below.

5.9.1. Longitudinal and transverse Peclet number

The proportion of convective and diffusive transport is used to compare the mixing mechanism of field and core scale which is represented by Peclet number. In porous media, the mixing of two different miscible fluid can occur through diffusion and dispersion. Diffusion can occur when a higher concentration of solvent of a specific phase can mix with a lower concentration of a solute through the random movement of the molecules. As the steam is injected into the reservoir, it can penetrate the oleic phase by molecular diffusion. Diffusion coefficients are largely depending on the composition of the mixture (Sahimi et al., 2006). On the other hand, the dispersion can occur when velocity can play an important role in the case of mixing two fluids. The longitudinal dispersion can occur when the mixing occurs in the direction of flow and while the direction of flow is perpendicular it is known as transverse dispersion number. As the Peclet number is the ratio of this two number, it can affect recovery factor to a small extend. Another important fact in utilizing Peclet number for scale comparisons, the dispersion is largely scaled dependent. The values of dispersion measured in the field scale are larger than those observed in the corefloods (Blackwell, 1959; Chen, 1991; John et al., 2008).

5.9.2. Oil and gas gravity number

Oil and gas gravity number denotes the proportion of gravitational force to viscous force. It has an insignificant effect on oil recovery for steam flooding process. As the gravity force is typically very small in comparison with viscous force because of the high viscosity of the heavy oil. Therefore, the effect of gravity number on oil recovery for steam flooding is insignificant.

5.9.3. Dykstra-Parsons coefficient

Dykstra-Parsons coefficient estimates the variability of permeability distribution in the reservoir. As Dykstra-Parsons coefficient rises, injected steam and additive be likely to flow through the high permeable zones which will result in a large amount of oil bypassed in the low permeable zones.

5.9.4. Dispersion number

Dispersion occurs between two fluids where velocity can play a significant role. When additional mixing of uneven fluids or concentration can occur in the reservoir, then there is a dispersion effect exists between fluids. In steam flooding process, the dispersion can occur when steam is in contact with the oil phase. The longitudinal and transverse dispersion numbers can be estimated using Perkins and Johnston equations (Perkins and Johnston, 1963). In this study, dispersion number has a slight effect on oil recovery. As the dispersion number is increasing, the oil recovery is also slightly increased.

5.9.5. Effective aspect ratio

The aspect ratio has a moderate effect on oil recovery for steam flooding process. When the aspect ratio is small, then injected steam can rapidly break across the production well which will result in poor sweep efficiency for the high permeable reservoir. On the other hand, when the aspect ratio is large the injected fluid can cross flow through the low permeable zones through capillary imbibition and hence improve the sweep efficiency.

5.10. Numerical reservoir simulation model

Numerical simulation for steam flooding process has been conducted using a commercial fully implicit thermal reservoir simulator, Computer Modelling Group (CMG) STARS. A simplified model with single injection and production 3D well was created for this study. A homogeneous

reservoir with cartesian grid block of $10 \times 6 \times 6$ in the $i \times j \times k$ direction. Figure 5.2 shows a 3D view of the reservoir model.

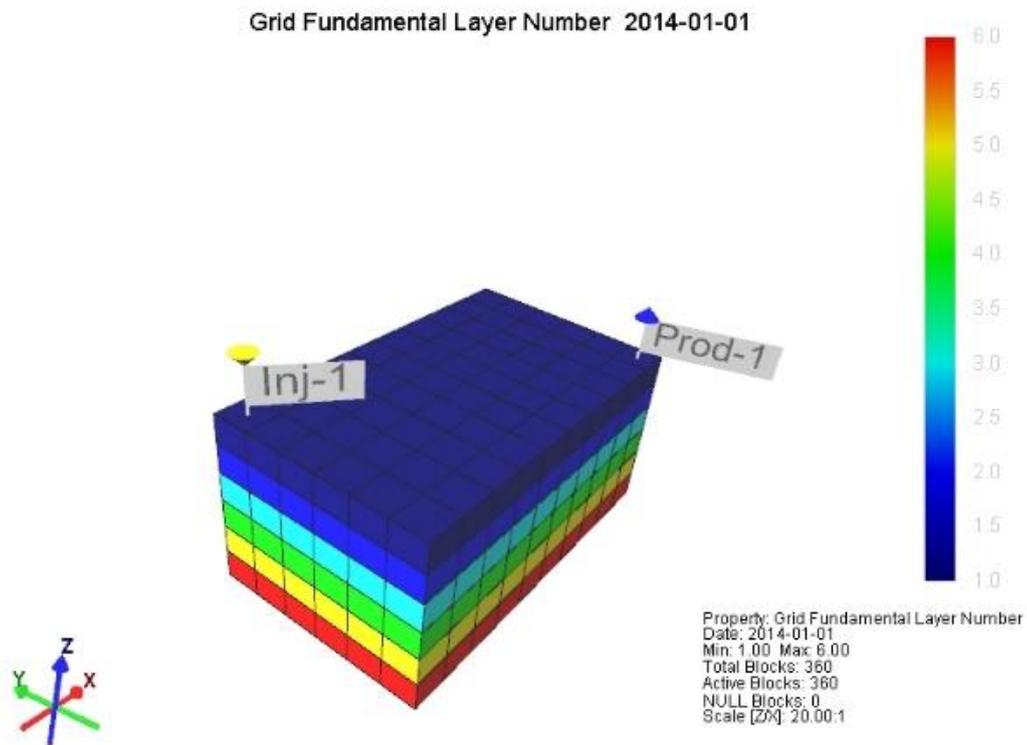


Figure 5.2: 3D view of reservoir model

The permeability and porosity of the reservoir is 1200 mD and 0.332 respectively, and the vertical and horizontal permeability ratio is 1 for all grid blocks. The thermal properties and selected reservoir and fluid properties are tabulated in table 5.5. The thermal properties of rock and fluid are taken from the published literature. The initial pressure and temperature are assumed to be 3200 kpa and 12 °c respectively. The initial oil saturation is assumed to be 87%, and no gas cap is present in the reservoir. Capillary pressure is assumed to be zero at reservoir conditions as the heavy oil seems to be immobile because of high viscosity and the interfacial tension between oil and water phase becomes very small. The default value for aqueous and gaseous phase properties was considered for CMG STARS.

Table 5.5: Reservoir and fluid properties

Parameters	Value	Parameters	Value
Model Grid	10×6×6	Initial Gas Saturation	0.0
Porosity	0.332	Initial Pressure (kpa)	3200
Permeability (mD)	1200	Formation Compressibility (1/kpa)	1×E ⁻⁶
Initial Temperature (°c)	12	Volumetric Heat Capacity of Overburden and Underburden (j/m ³ °c)	2.3×E ⁺⁶
Initial Oil Saturation	0.87	Thermal Conductivity of Reservoir Rock (j/m*day* °c)	2.3×E ⁺⁵
Injected Steam quality	0.8	Thermal Conductivity of Oil Phase (j/m*day* °c)	1.2×E ⁺⁴
Injected Steam Pressure (kpa)	4000	Thermal Conductivity of Water Phase (j/m*day* °c)	5.4×E ⁺⁴
Bottomhole Flowing Pressure (kpa)	3200	Thermal Conductivity of Gas Phase (j/m*day* °c)	4000
Injected Steam Temperature (°c)	250	Thermal Conductivity of Overburden and Underburden (j/m*day* °c)	1.5×E ⁺⁵
Initial Water Saturation	0.13		

The temperature dependency of viscosity is shown in figure 5.3 where it shows that with increasing temperature the oil viscosity is decreasing. The viscosity correlation of Mehrotra and Svercek is used to evaluate the full range of viscosity and temperature relationship (Mehrotra and Svercek, 1986).

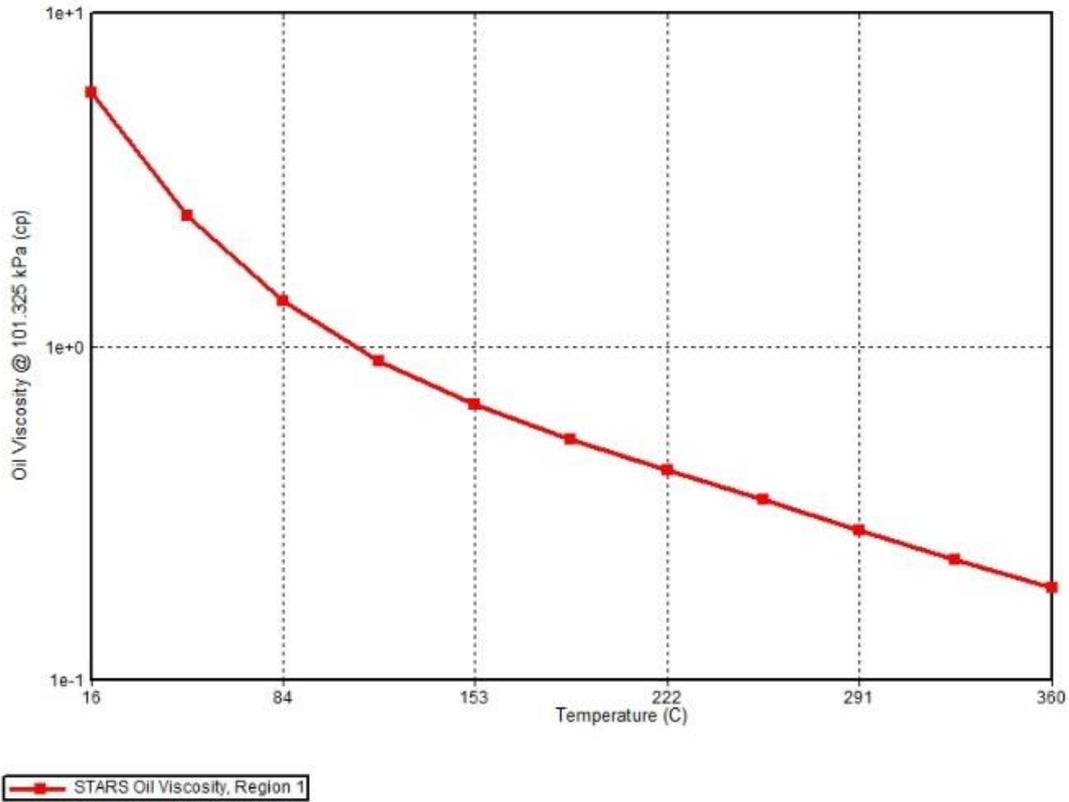


Figure 5.3: Viscosity variation with temperature

5.10.1. Relative Permeability

No experimental data are available for rock and fluid properties, so Stone’s model (Figure 5.4) was used to develop three-phase relative permeability curves. Rock was considered to be water-wet, and water-oil and gas-oil relative permeability curves are showed in figure 5.5 and figure 5.6. Table 5.6 depicts different endpoint saturation of water-oil and gas-liquid saturation table. Quadratic smoothing methods are used to smooth the oil-water and gas-liquid table.

Table 5.6: Input parameters for relative permeability curve generation

SWCON - Endpoint Saturation: Connate Water	0.13
SWCRIT - Endpoint Saturation: Critical Water	0.13
SOIRW - Endpoint Saturation: Irreducible Oil for Water-Oil Table	0
SORW - Endpoint Saturation: Residual Oil for Water-Oil Table	0.39
SOIRG - Endpoint Saturation: Irreducible Oil for Gas-Liquid Table	0
SORG - Endpoint Saturation: Residual Oil for Gas-Liquid Table	0.2

SGCON - Endpoint Saturation: Connate Gas	0
SGCRIT - Endpoint Saturation: Critical Gas	0.05
KROCW - Kro at Connate Water	0.948
KRWIRO - Krw at Irreducible Oil	0.79
KRGCL - Krg at Connate Liquid	0.2
KROGCG - Krog at Connate Gas	
Exponent for calculating Krw from KRWIRO	2
Exponent for calculating Krow from KROCW	2
Exponent for calculating Krog from KROGCG	2
Exponent for calculating Krg from KRGCL	2

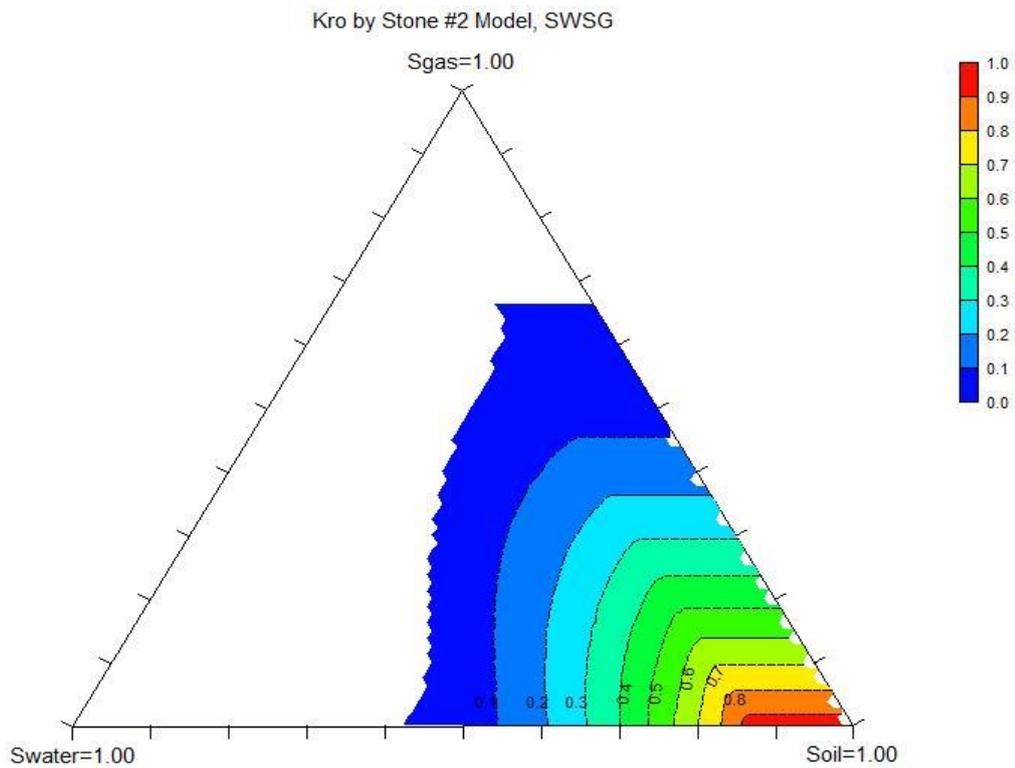


Figure 5.4: Stone's model

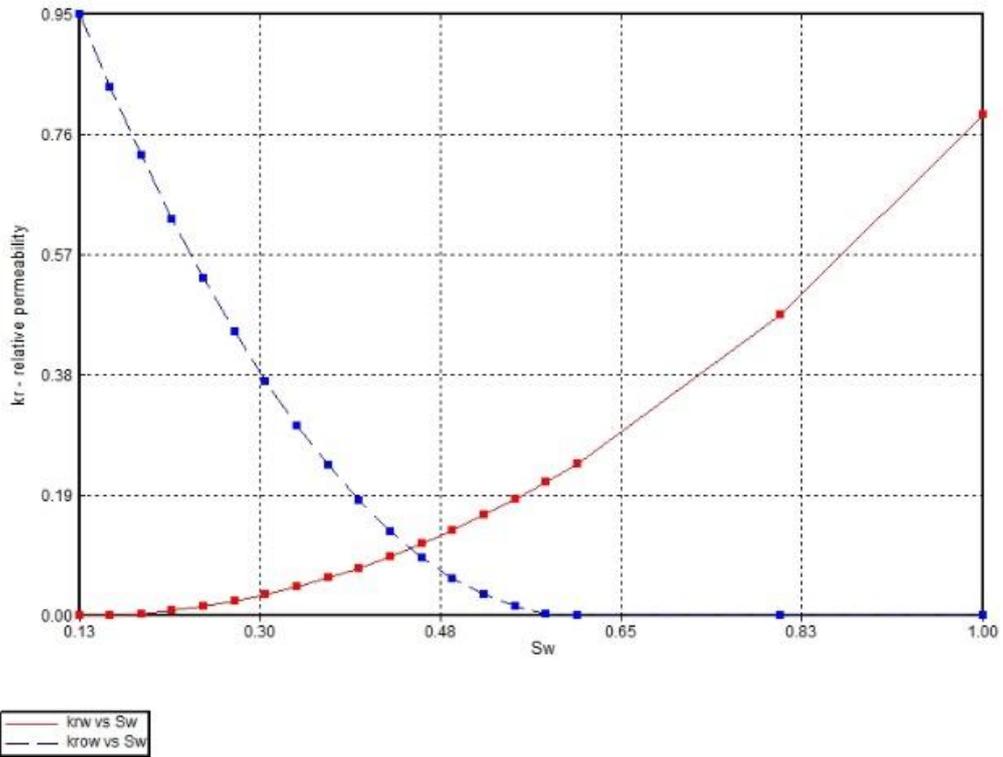


Figure 5.5: Relative permeability of water and oil with water saturation

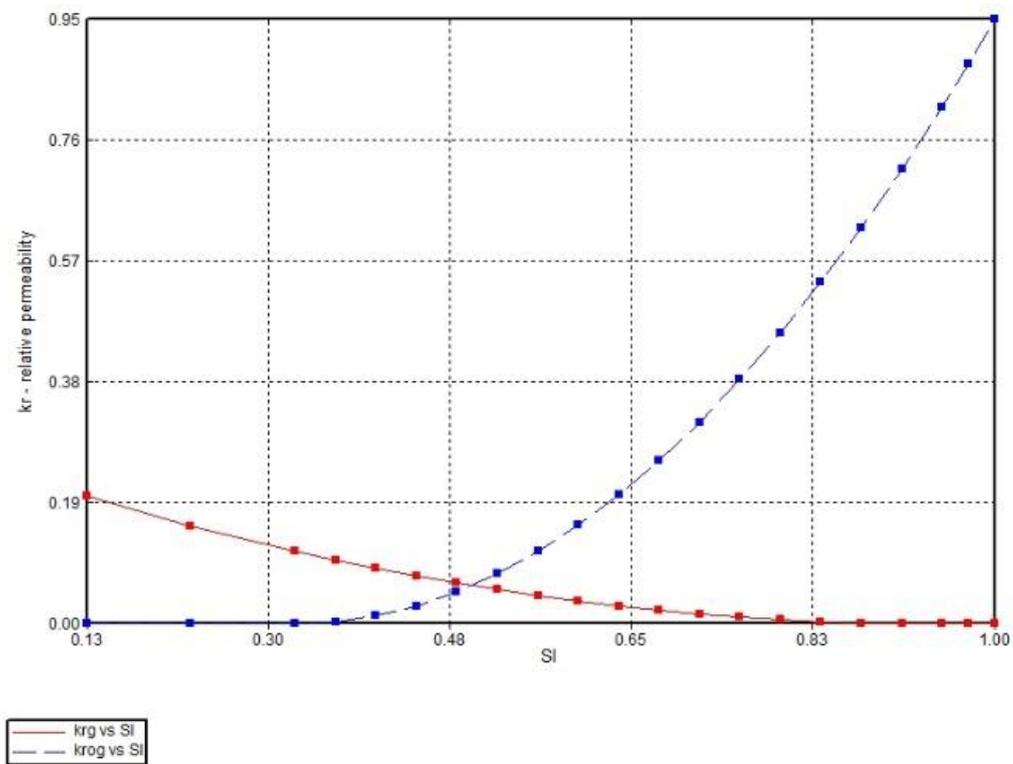


Figure 5.6: Relative permeability of gas and oil with liquid saturation

5.10.2. Initial conditions

The initial pressure and temperature is 3200 kpa and 12 °c respectively, and the reservoir model top layer is located at a depth of 1000 m. The initial water saturation is 13%, and initial injection rate is 300 m³/day and the injected steam quality is 0.8.

5.10.3. Wellbore constraint

There are two main well constraints for injection well which are minimum bottomhole flowing pressure of 4000 kpa and injected fluid rate of 300 m³/day. It can operate above 800 kpa above the reservoir pressure. The corresponding temperature at the bottom hole pressure is 250 °c and the steam quality for injected steam is 0.8 at the sand face. The production well constraints should be minimum bottom hole flowing pressure of 3200 kpa and liquid production rate is 600 m³/day.

5.10.4. Basecase study

One injection and one production well with the homogeneous reservoir is considered for Basecase. The porosity is considered 0.332 and permeability is 1200 mD. The ratio of vertical to horizontal permeability is 1. The different rock and fluid properties and their effect on oil production are determined. Numerous simulations were conducted for this reservoir model. The base case was compared with other cases where permeability variations, change of injection rate and steam quality variations are considered.

As the steam is injected into the reservoir the pressure and temperature should be increased in the reservoir, which are shown in figure 5.7. The viscosity is decreasing with increasing time. The injected heat can flow through inject well to the production well and there is some heat lost in the formation. As the reservoir is considered homogeneous and there is no change in porous space, so the viscosity is gradually decreasing as the relative permeability of the oil is increased.

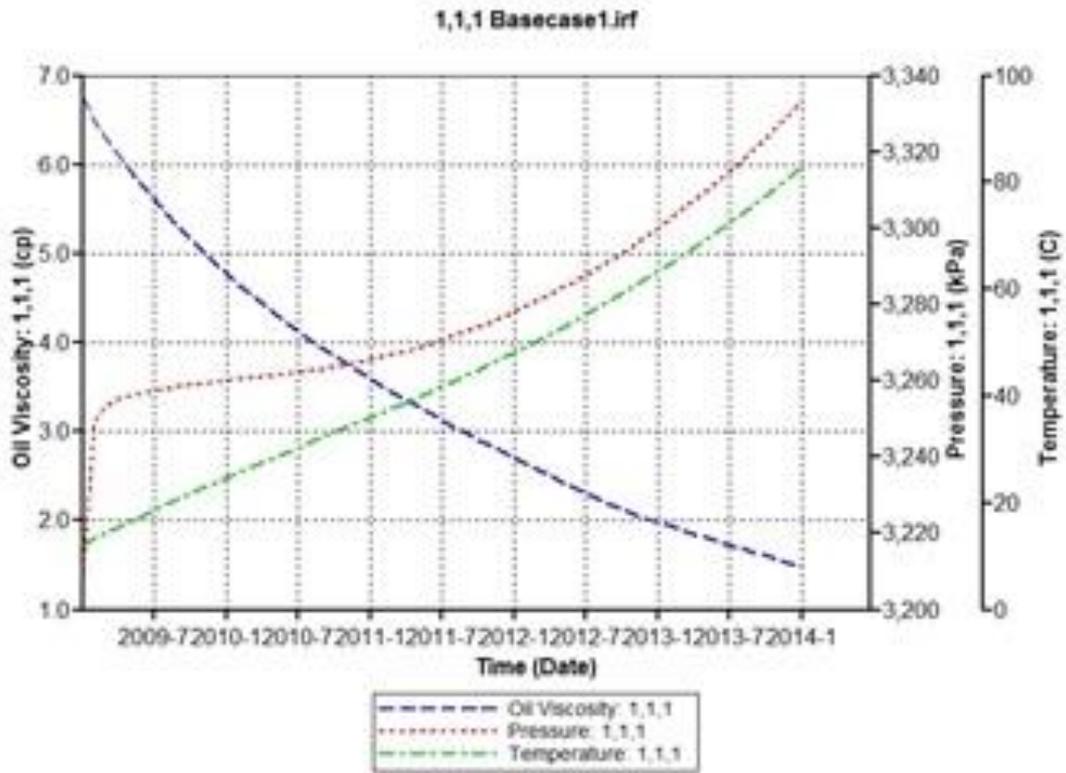


Figure 5.7: Viscosity, pressure, temperature variation with time

5.10.5. Effects of heterogeneity

The effect of heterogeneity or permeability variations is studied through 3 simulations run. Table 5.7 shows permeability variations for 3 different cases for 6 layers of the reservoir. The change of different properties with permeability variations is studied through this simulation run.

Table 5.7: Permeability variation for three different cases with six different layers

Layer	Permeability		
	Basecase 1	Basecase 2	Basecase 3
Layer 1	1200	800	1000
Layer 2	1200	700	1000
Layer 3	1200	900	1100
Layer 4	1200	850	1100
Layer 5	1200	950	1150
Layer 6	1200	1000	1150

Figure 5.8 shows the oil and water recovery factor with time. Oil recovery factor is increasing, and water recovery factor is decreasing with time. As the steam is injected into the reservoir, it can reduce the viscosity of the oil and hence increase the oil recovery. The steam additive can increase the water viscosity and hence decrease the water recovery factor.

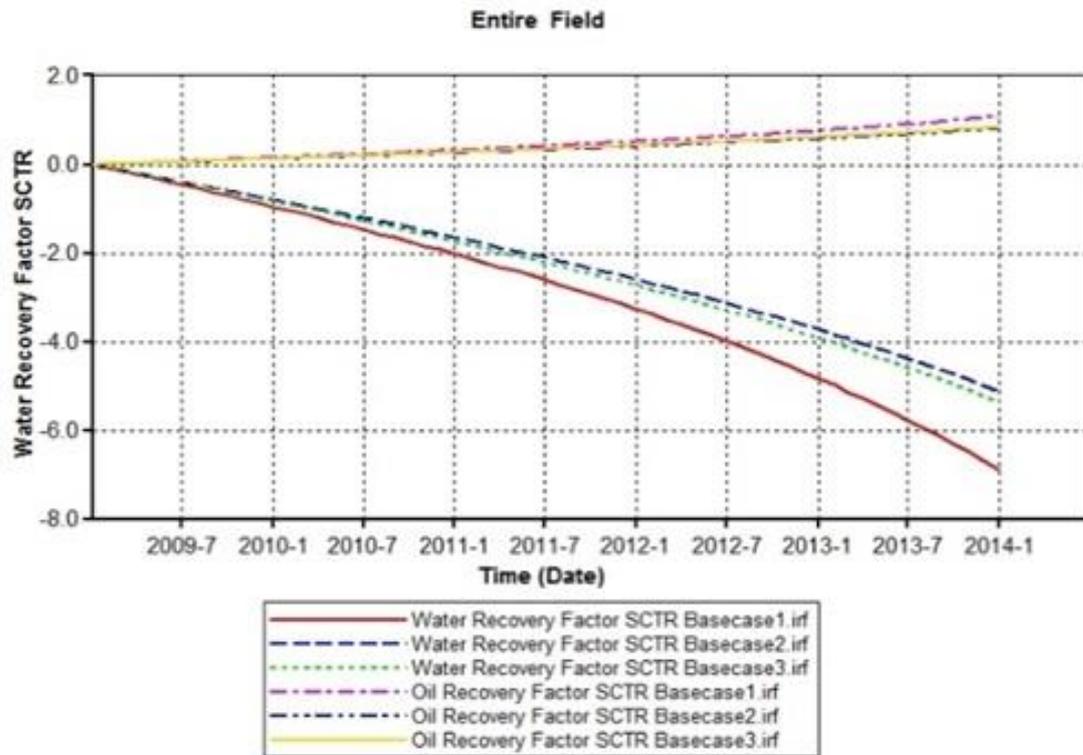


Figure 5.8: Oil and water recovery factor

Figure 5.9 describes the change in average oil saturation and oil production rate with time. As the reservoir heterogeneity is increasing from Basecase 1 < Basecase 3 < Basecase 2, the oil recovery factor is also decreasing with increasing heterogeneity. As the oil recovery factor is decreasing with increasing heterogeneity, the oil production rate is increasing with decreasing heterogeneity. The average oil saturation is also decreased with decreasing heterogeneity and increasing time.

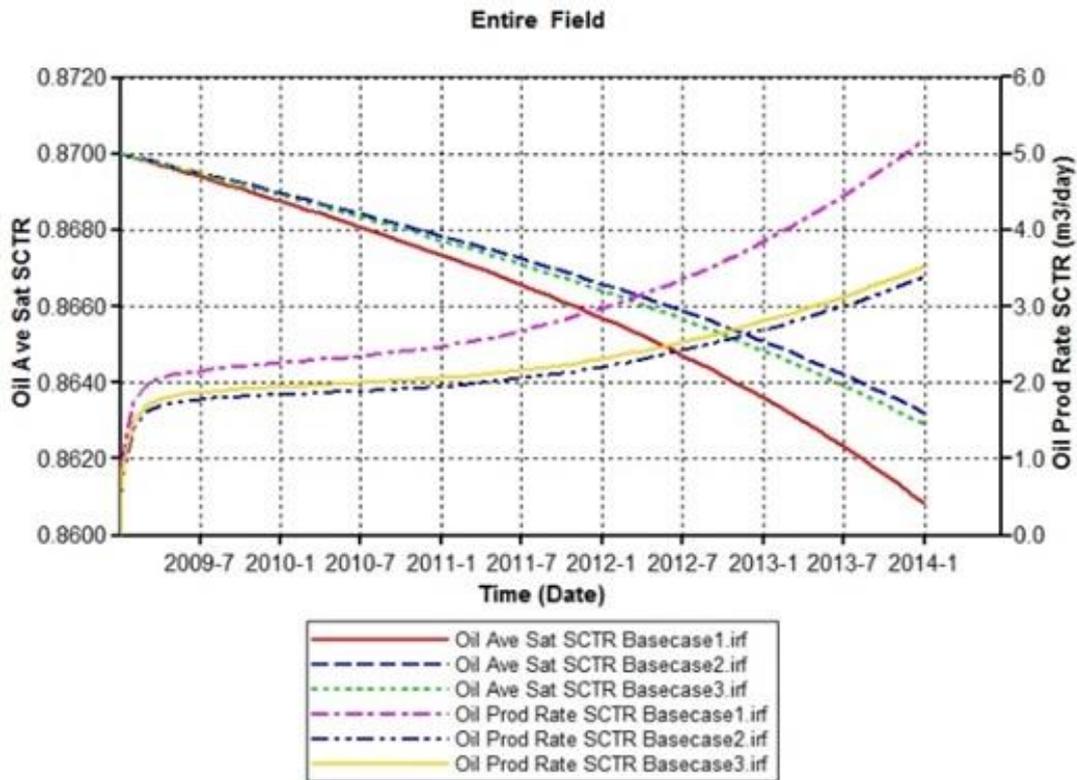


Figure 5.9: Oil average saturation and oil production rate

Figure 5.10, shows that average temperature is decreased with increasing heterogeneity and time. In a homogeneous reservoir heat loss should be less than a heterogeneous reservoir which results in a low average temperature for the heterogeneous reservoir.

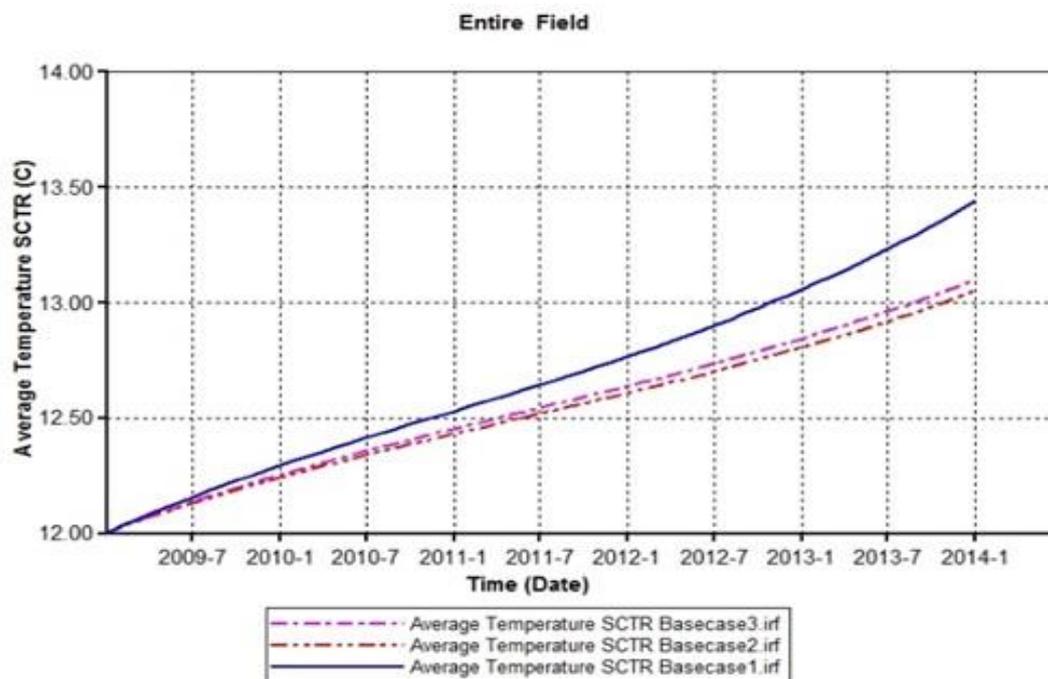


Figure 5.10: Average temperature

Figure 5.11 depicts the effects of permeability variation on cumulation oil production and oil recovery factor. The recovery factor and cumulative oil production are decreased with increasing heterogeneity. This can happen as the reservoir heterogeneity increases the permeability of the reservoir is decreased. As a result, the flow path of the reservoir fluid is decreased, and the oil recovery is decreased.

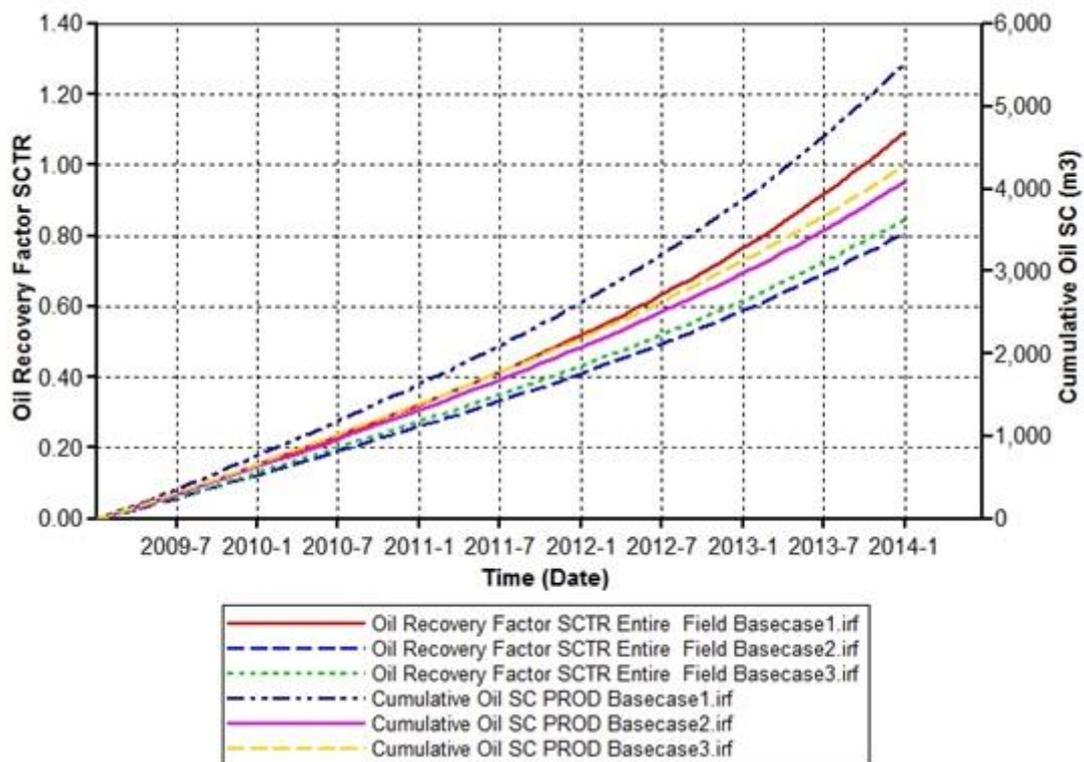


Figure 5.11: Oil recovery factor and cumulative oil production with time

5.10.6. The effect of steam quality

In this study, the effect of steam quality on oil recovery is studied by maintaining other parameters fixed. Four cases have been studied with steam qualities of 0.75, 0.80, 0.85, and 0.9 and their effect on cumulative oil production. Figure 5.12 shows, with increasing steam quality the cumulative oil production is decreased. The low-quality steam can contain the higher portion of water. This water can increase the reservoir pressure which can assist the reservoir oil to move forward in the direction of production well. As a result, the cumulative oil production increases gradually. Although, low-quality steam can increase the cumulative oil production, high-quality steam carries more heat and can reduce the viscosity of the reservoir. As a result, it can have swept higher amount of oil which is in contact with the steam, and the residual oil saturation is significantly decreased.

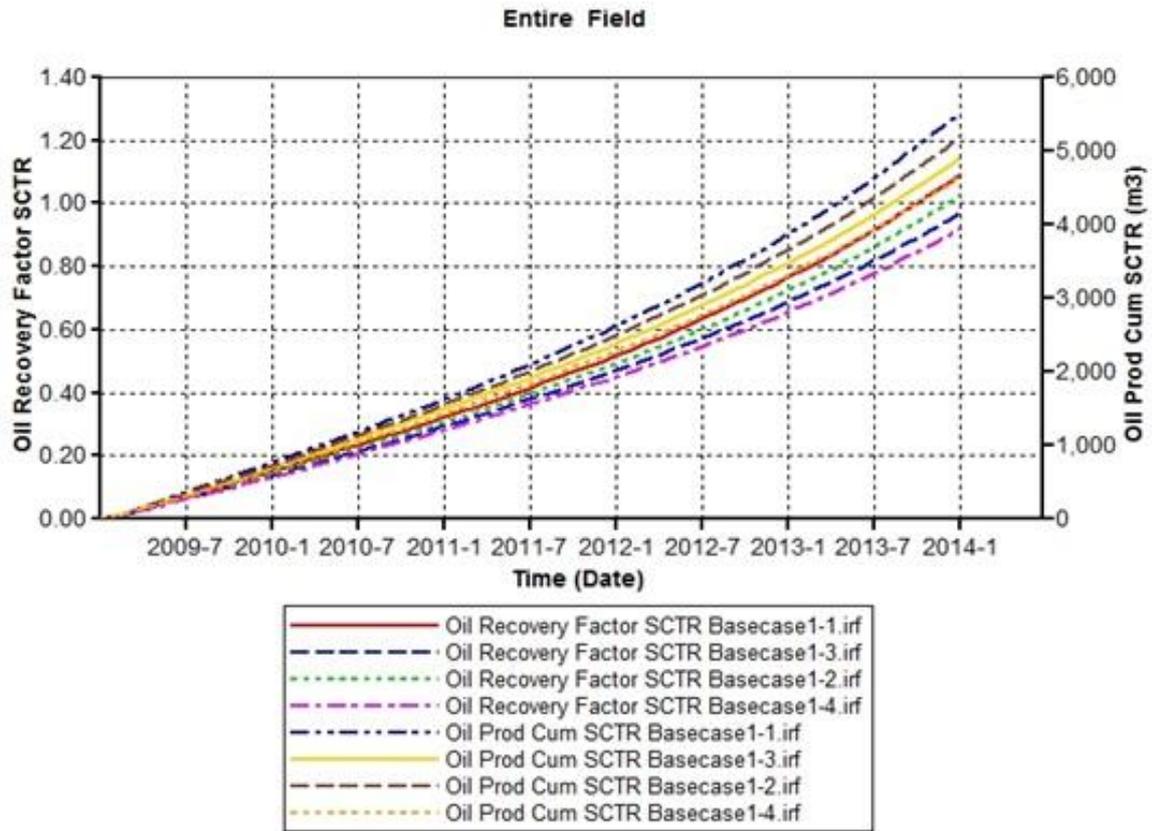


Figure 5.12: Cumulative oil production and oil recovery factor

Figure 5.13 and 5.14 depicts the effect of steam quality on liquid production rate and oil production rate. As the quality of the steam is decreased, the water content in the steam is increased. As a result, the reservoir pressure is increased which will ultimately resultant greater driving force (pressure difference) for the reservoir and hence increased the production. As the steam injection rate is not changed, so the steam oil ratio should be constant after a certain period. The average water saturation is increased with decreasing steam quality which is shown in figure 5.15. As the recovery factor is increased with decreasing steam quality, the hydrocarbon pore volume is also decreased. It is an obvious reason, as the cumulative production is increased with time, the hydrocarbon pore volume must be decreased which is indicated in figure 5.16.

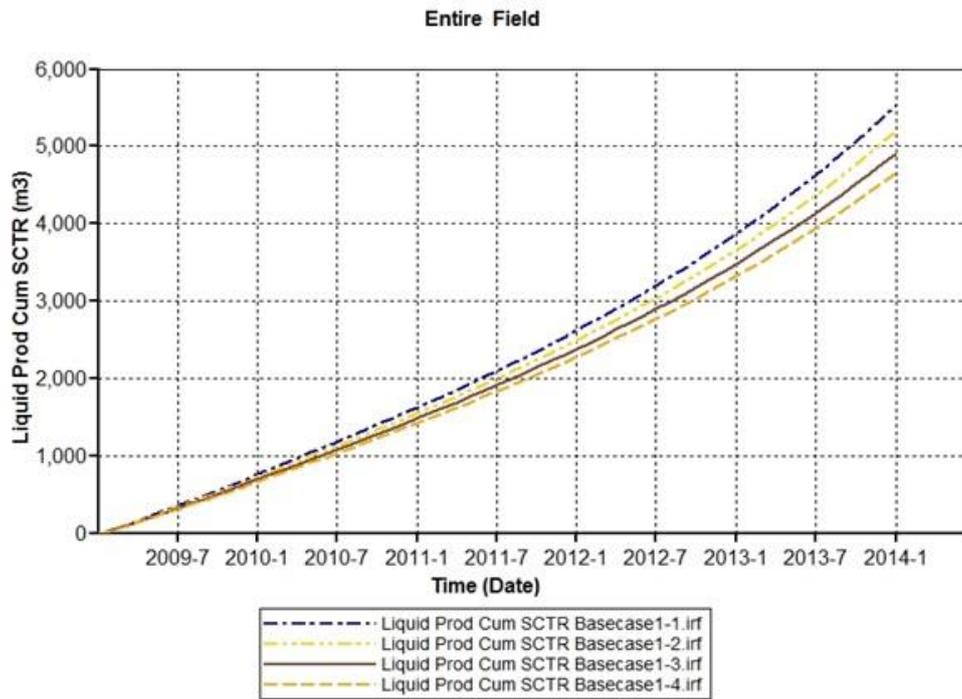


Figure 5.13: Cumulative liquid production

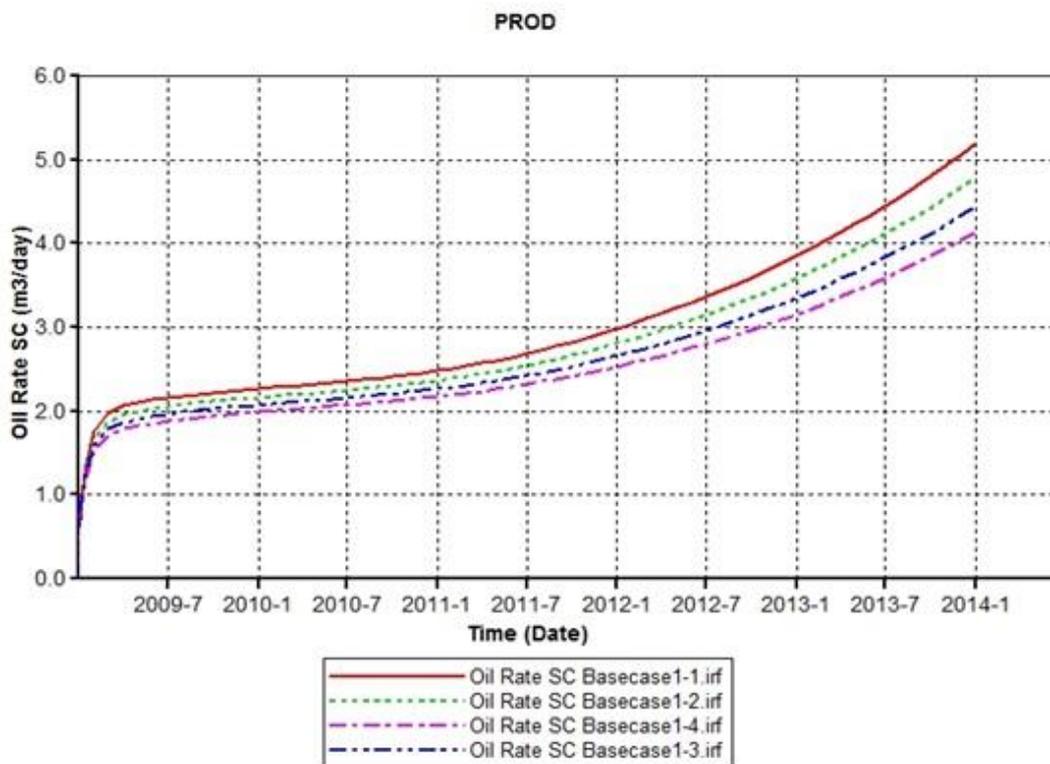


Figure 5.14: Oil rate

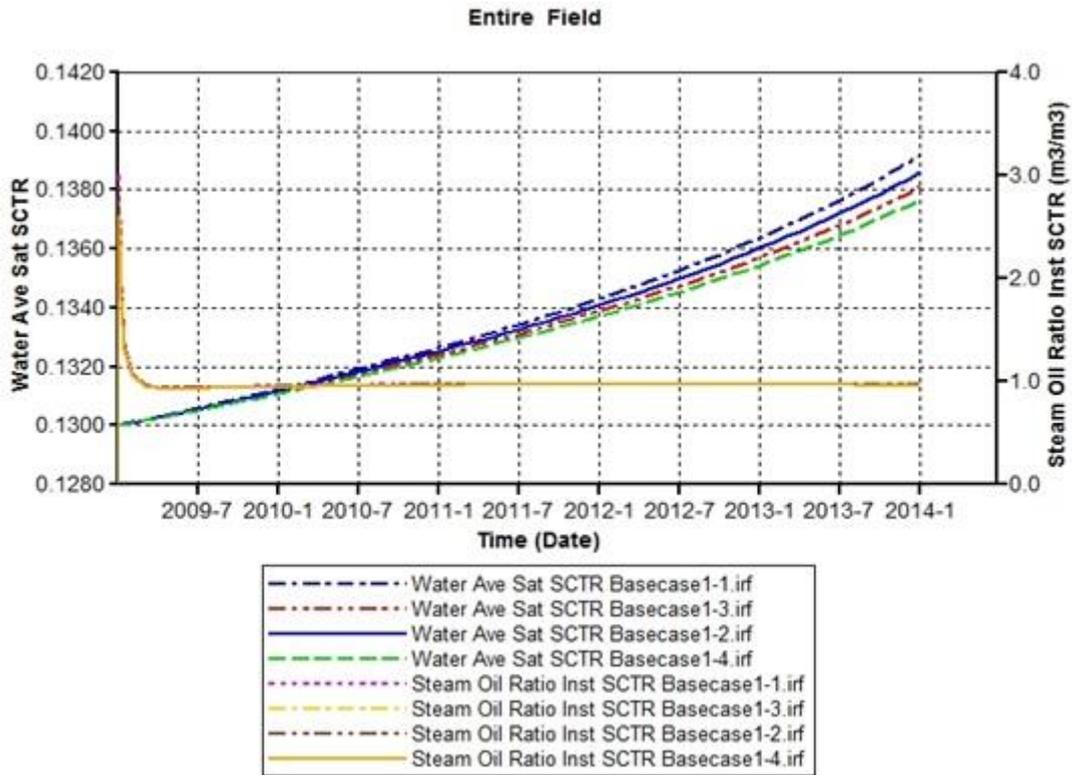


Figure 5.15: Steam-oil ratio and average water saturation

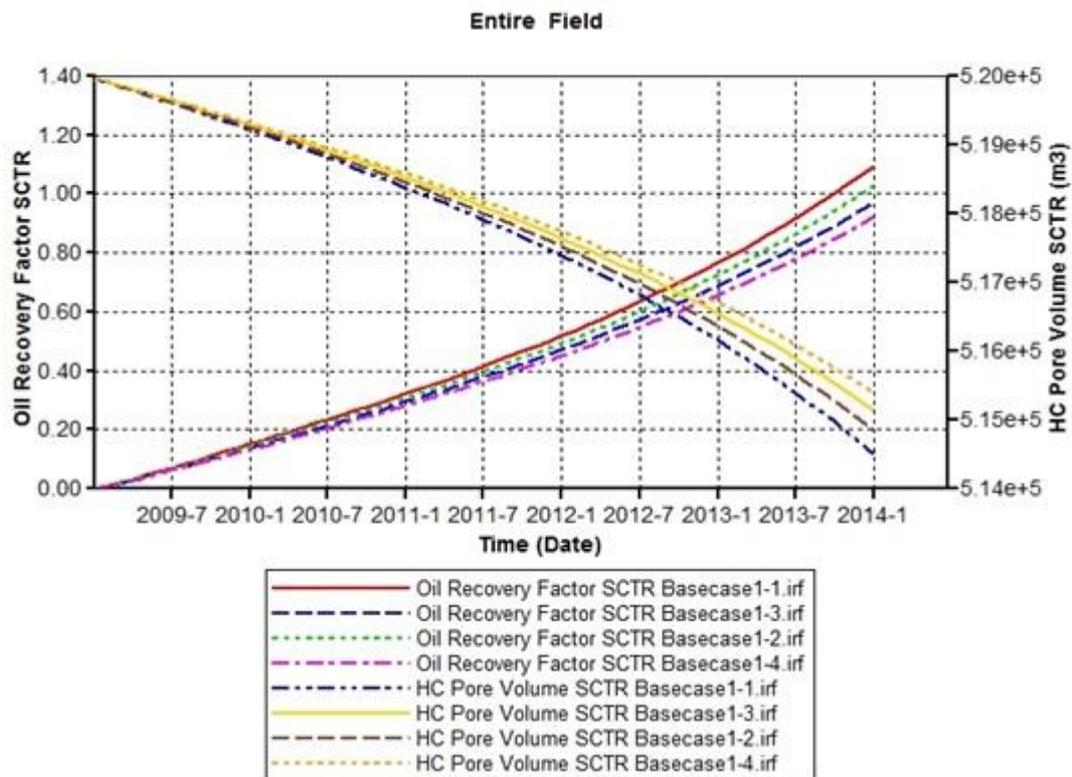


Figure 5.16: Hydrocarbon pore volume and oil recovery factor

Conclusions and recommendations

In this study, a scaled model of the steam flooding process had been developed to predict the performance of this process. Dimensionless numbers had been derived for steam flooding process using inspectional analysis. Dominant dimensionless groups and their relative effects on oil recovery had been estimated using sensitivity analysis. The fluid saturations and relative permeability of water-oil and gas-oil systems are developed using Stone's correlation. The effect of temperature on oil viscosity is also addressed, and the numerical simulation study is performed using CMG STARS software. First, a basecase is run with considering homogeneous reservoir. After that reservoir heterogeneity effect is considered which ultimately have a noteworthy effect on oil recovery. As the reservoir heterogeneity increases the oil recovery is decreased. In addition, the effect of steam quality on oil recovery is also studied to evaluate the performance of a reservoir under the operation of steam flooding process. The residual oil saturation of steam flooding process is essentially independent of initial oil saturation. It is recommended to study the effect of steam additives on different kind of oils which can reduce the interfacial tension. Core flooding is also helpful in understanding steam flooding process for both heavy and lighter oils. The effect of injection rate should be studied further to understand this process and their relative effects on oil recovery.

Acknowledgements

The authors would like to thank School of Graduate Studies of Memorial University of Newfoundland, Research & Development Corporation of Newfoundland and Labrador (RDC), funding no. 210992; and Statoil Canada Ltd., funding no. 211162 for providing financial support to accomplish this research.

Nomenclature

A	Area, m^2	V_f	Fluid Volume, m^3
L	Reservoir Length, m	σ_{go}	Interfacial Tension between Gas and Oil Phase, kg/s^2
W	Reservoir Width, m	σ_{ow}	Interfacial Tension between Oil and Gas Phase, kg/s^2
H	Reservoir Thickness, m	ν	Dynamic Viscosity, s/m^2
c	Compressibility, $m s^2/kg$	μ	Viscosity, kg/ms

ϕ	Porosity, Fraction	ρ	Density, kg/m^3
k	Permeability, m^2	r	Pore Throat Radius, m
k_r	Relative Permeability, m^2/m^2	g	Gravitational Acceleration, m/s^2
P	Pressure, kg/ms^2	τ	Tortuosity
q_i	Injection Rate, m^3/s	K	Thermal Conductivity, $W/m.K$
q_{ia}	Injection Rate of Additive, m^3/s	C_p	Specific Heat Capacity, $j/kg.K$
q_{prod}	Production Rate, m^3/s	h	Enthalpy, j/kg
D_{Ta}	Transverse Dispersion of Additive, m^2/s	L_v	Latent Heat, j/kg
D_{La}	Longitudinal Dispersion of Additive, m^2/s	ξ	Dummy variable for time, s
S	Saturation	Subscript	
θ	Contact Angle	f	Fluid
t	Time, s	o	Oil Phase
T	Reservoir Temperature, $^{\circ}C$	w	Water Phase
E	Additive Concentration	g	Gaseous Phase
U	Total Velocity, m/s	i	Initial
u	Velocity, m/s	r	Rock or Reservoir
V_r	Reservoir Volume, m^3	t	Total

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CHAPTER SIX

Conclusions and Recommendations

6.1. Conclusions

In this study, scaling criteria for steam flooding process is derived from inspectional and dimensional analysis. Mass and energy balance equations are used along with initial and boundary conditions. Different approaches are proposed which can characterize and best fit for steam flooding process. Some of the primary dimensionless groups are eliminated through different elimination techniques to find out the major dimensionless groups for steam flooding process. This study revealed details about the functional relationship between major scaling groups and their expected performance on oil recovery. Four different case study is performed to investigate the effect of each dimensionless groups on oil recovery. A sensitivity analysis is done to find out the dominant and secondary scaling groups which have a greater effect on oil recovery than other groups. The Dykstra-Parsons coefficient is introduced to consider the effect of reservoir heterogeneity on oil recovery. A new combination of the dimensionless group is proposed which has a greater effect on recovery than any other group. Another advantage of this group is that there are more variables involved in the new dimensionless groups than any other group. A numerical simulation study is performed to investigate the effect of different process controlling parameters on oil recovery. The effect of permeability variations and steam quality have been investigated through this study.

Major conclusions are summarized follows:

- Five sets of scaling criteria had been selected, and each set relaxed some of the groups to satisfy that approach.
- Different approach selects different parameters to be relaxed to fulfill that approach.
- Selection of a proper approach to use largely depends on the specific process being modeled.
- Gravitational force can be scaled properly by relaxing geometric similarity. In addition, capillary and viscous forces can be scaled properly for the horizontal well.
- Transverse dispersion and viscous force can be scaled properly while gravitational and capillary effects can be relaxed.
- Dispersion effects, viscous and gravitational forces can have scaled properly, but capillary and heat conduction effects can be relaxed.

- Different scaling groups and their effects on oil recovery had been investigated conveniently.
- Sensitivity analysis had been performed to investigate relative effect of dominant scaling groups.
- A new dimensionless number is proposed which has a greater effect on recovery than other numbers.
- Numerical simulation study had been performed to investigate the effect of permeability variation or reservoir heterogeneity and steam quality on oil recovery.

6.2. Recommendations

To predict the performance of a steam flooding process, a methodology should be developed which can further enhance by addressing some limitations of the current work. Some of the factors should be considered to better understand this process such as steam, oil, brine and additive concentration through porous media. The interaction of dimensionless groups and further improvement of the accuracy of the predicted model should include:

- A better understanding of relative permeability interpolation will give better insight into how each factor can affect the relative permeability curve. The effects of each variable should be investigated, and ultimately the application of these factors should be evaluated to build a more reliable prediction performance.
- Core flooding experiments on the core sample of a reservoir are recommended to test the most suitable oil displacement technique by steam flooding process.
- A multi-core analysis system should be installed in the laboratory to predict the performance of contrasting permeability. Laboratory set up should be designed in a way that it can have the ability to inject fluid from one pump into multiple cores of varying permeability. The results of the multi-core system can be history-matched with reservoir simulator and ultimately applied to developed reservoir model.
- The effect of steam injection rate should be studied further for better understanding the process.
- This study will provide useful guidance to further experimental studies of steam flooding process.

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4 NUMX - Number of condensible components
1 MFORM - *TFORM flag: 1 for *SXY, 2 for *ZH, 3 for *ZT
1 NPTGN - Number of grids
360 NPTSS - Number of matrix blocks
360 NPTCS - Number of blocks including nulls
1 M9PT - *NINEPOINT flag: 1 - no, 2 - yes
3 NDIM - Number of dimensions (= 3 for *REFINE)
0 NREF - Number of refinements per fundamental block
0 MINC - Number of *MINC/*SUBDOMAIN subdivisions
30 NORTH - Number of orthogonalizations
0 NGAUSS - Bandwidth for *SDEGREE *GAUSS
15 NXSVAL - Number of special histories
Run is thermal

Opened output file on unit 13, filename is 'H:\My Documents\Desktop\Oveall
Recovery\Basecase1.out'
Opened SR3-OUT on unit 14, filename is 'H:\My Documents\Desktop\Oveall
Recovery\Basecase1.sr3'
Opened INDEX-OUT on unit 15, filename is 'H:\My Documents\Desktop\Oveall
Recovery\Basecase1.irf'
Opened MAIN-RESULTS-OUT on unit 16, filename is 'H:\My
Documents\Desktop\Oveall Recovery\Basecase1.mrf'
Opened GRID scratchfile on unit 17

===== SUMMARY (from subroutine: INDATA)

=====
Reading of initial data is complete.
Simulation will stop if there were error messages.
0 Warning messages. 0 Error messages.

=====

Global Storage Usage

=====

Section	Bytes	Mbytes	# Objects
STARS	556778	0.531	785
GRMOD0	282844	0.270	445
SOLVINT	225388	0.215	101
ELECTRIC	68356	0.065	27

WMCOM1	54581	0.052	988
VISC	50388	0.048	71
KWCOM1	34719	0.033	48
POINT	28752	0.027	70
WELL	23468	0.022	245
RELPERM	11960	0.011	211
GRMOD1	10228	0.010	121
SR2WRT	8780	0.008	24
GLOBSTORE	7478	0.007	27
PRTCM	6900	0.007	17
SR2COM	6408	0.006	86
SECTOR	3624	0.003	70
PGMCH1	1446	0.001	241
CMGFILE	1184	0.001	18
WELHYD	556	0.001	51
KVAL	520	0.000	41
FLEXWEL	400	0.000	37
PSOLINT	288	0.000	62
GEOMECH	216	0.000	48
PGAIM	184	0.000	38
GRMOD2	124	0.000	30
REACT	68	0.000	13
ADSORP	68	0.000	17
WMCOM5	60	0.000	15
AQUIFER	36	0.000	6
WMCOM2	36	0.000	9
WMCOM4	32	0.000	8
COMPACT	16	0.000	4
PGMCH2	12	0.000	3
INGRDM	0	0.000	0

Total	1385898	1.322	3977

Dimensioning Parameters

- 360 MDPTSS - Matrix blocks, including nulls
- 360 MDPTCS - Total blocks, including nulls
- 360 MDPTPS - Total non-null blocks
- 1 MDPTGN - Grids (fundamental & refined)
- 1 MDNVAM - Sets of Volume/area modifiers
- 1442 MDNEXF - Exterior block faces
- 924 MDPTBC - Total interblock connections

4 NCOMP - Total components (fluid & solid)
 4 NUMY - Fluid components
 4 NUMX - Condensable components
5 NFLOW - Flowing items (fluids + energy)
 0 NSLD - Solid components

1 NTHSET - Compressibility/thermal sets

1 NKROCK - Rel perm rock sets
 1 NKRSET - Rel perm table sets
 21 NKRTBD - Rel perm table size
 11 NVSTBL - Viscosity tables

6 MDNEQ - Equations per block
363 MDSOL - Solver elements (blocks+wells+1)
 2160 MDNEQT - Total grid equations
936 MDPTCN - Interblock & block-well connections
 31 MDNOR - Orthogonalizations + 1
 90 MDJCM - Connections per equation with fill
2809 MDCALP - Submatrices in the Jacobian matrix
 0 MDALP - Size of Jacobian off-diagonal
 0 MDALD - Size of Jacobian diagonal
 0 MDBET - Size of RHS and solution vectors
 0 MDV - Size of solution vector
 0 MDDD - Diagonal entries
 0 MDROW - Columns per equation
2809 MDICLU - 1 + Block entries in each of L & U
 0 MDLU - Size of each of L & U
 0 MDPROW - Size of PARASOL list arrays
90 MDPJCM - PARASOL row storage parameter

WM parameters - Dimensioner output

mdwell = 2
 mdlayr = 12
 mdly1w = 7
 mdlypl = 1
 mdgrup = 2
 mdrgrp = 1
 mdcons = 4
 mdhyvl = 1

```

mdbhen =      100
mdhytb =       1
mdcygr =       1
mdcygp =       2
mdcygs =       2
mdcsgr =       1
mdfevl =       1
mdfcen =       1
mdfctb =       1
mdgcms =      40
mdwcms =      40
mdclmp =       0
mdrlmp =       0
mdlyclmp      1
mdlyrlmp      1

```

Global Storage Usage

=====

Section	Bytes	Mbytes	# Objects
-----	-----	-----	-----
SOLVINT	1577396	1.504	112
STARS	556778	0.531	785
GRMOD0	282844	0.270	445
ELECTRIC	68356	0.065	27
WMCOM1	54581	0.052	988
VISC	50388	0.048	71
KWCOM1	34719	0.033	48
POINT	28752	0.027	70
WELL	23468	0.022	245
SR2COM	21080	0.020	87
RELPERM	11960	0.011	211
GRMOD1	10228	0.010	121
SR2WRT	8780	0.008	24
GLOBSTORE	7478	0.007	27
PRTCM	6900	0.007	17
SECTOR	3624	0.003	70
PGMCH1	1446	0.001	241
CMGFILE	1184	0.001	18
WELHYD	556	0.001	51
KVAL	520	0.000	41
EQTPAR	412	0.000	69

FLEXWEL	400	0.000	37
PSOLINT	360	0.000	75
GEOMECH	216	0.000	48
PGAIM	184	0.000	38
GRMOD2	124	0.000	30
ADSORP	68	0.000	17
REACT	68	0.000	13
WMCOM5	60	0.000	15
AQUIFER	36	0.000	6
WMCOM2	36	0.000	9
WMCOM4	32	0.000	8
COMPACT	16	0.000	4
PGMCH2	12	0.000	3
INGRDM	0	0.000	0

Total	2753062	2.626	4071

Dimensioning Parameters

- 360 MDPTSS - Matrix blocks, including nulls**
- 360 MDPTCS - Total blocks, including nulls**
- 360 MDPTPS - Total non-null blocks**
- 1 MDPTGN - Grids (fundamental & refined)**
- 1 MDNVAM - Sets of Volume/area modifiers**
- 1442 MDNEXF - Exterior block faces**
- 924 MDPTBC - Total interblock connections**

- 4 NCOMP - Total components (fluid & solid)**
- 4 NUMY - Fluid components**
- 4 NUMX - Condensable components**
- 5 NFLOW - Flowing items (fluids + energy)**
- 0 NSLD - Solid components**

- 1 NTHSET - Compressibility/thermal sets**

- 1 NKROCK - Rel perm rock sets**
- 1 NKRSET - Rel perm table sets**
- 21 NKRTBD - Rel perm table size**
- 11 NVSTBL - Viscosity tables**

- 6 MDNEQ - Equations per block**
- 363 MDSOL - Solver elements (blocks+wells+1)**

2160 MDNEQT - Total grid equations
 936 MDPTCN - Interblock & block-well connections
 31 MDNOR - Orthogonalizations + 1
 90 MDJCM - Connections per equation with fill
 2809 MDCALP - Submatrices in the Jacobian matrix
 55572 MDALP - Size of Jacobian off-diagonal
 12962 MDALD - Size of Jacobian diagonal
 2162 MDBET - Size of RHS and solution vectors
 902 MDV - Size of solution vector
 4502 MDDD - Diagonal entries
 475 MDROW - Columns per equation
 2809 MDICLU - 1 + Block entries in each of L & U
 1192 NICLU - Used block entries of L/U
 29440 MDLU - Size of each of L & U
 475 MDPROW - Size of PARASOL list arrays
 90 MDPJCM - PARASOL row storage parameter

 WM parameters - Dimensioner output

mdwell = 2
 mdlayr = 12
 mdly1w = 7
 mdlypl = 1
 mdgrup = 2
 mdrgrp = 1
 mdcons = 4
 mdhyvl = 1
 mdbhen = 100
 mdhytb = 1
 mdcygr = 1
 mdcygp = 2
 mdcygs = 2
 mdcsgr = 1
 mdfcvl = 1
 mdfcen = 1
 mdfctb = 1
 mdgcms = 40
 mdwcms = 40
 mdclmp = 0
 mdrlmp = 0
 mdlyclmp = 1
 mdlyrlmp = 1

STARS TIME STEP SUMMARY

=====												
-----Time Step----- Time----- Production----- --Injection-- Mat ---												
Maximum Changes---												
C	Oil	Gas	Water	GOR	Wat.	Gas	Water	Bal	Pres	Sat		
				Temp								
No.	Size	U			m3	Cut		Err				
days	IT	T	days	yy/mm/dd	m3/d	m3/d	m3/d	/m3	%	m3/d	m3/d	%
					kPa	w/o/g	deg C					

1	1.0e-2	1	1.0e-2	2009/01/01	1.011	17.72	17.53		1.936	8.e-9	1.268	
					0.0000w	8.9e-4						
2	2.3e-2	1	3.3e-2	2009/01/01	.9175	16.08	17.53		1.931	13e-9	2.061	
					0.0000w	1.9e-3						
3	5.3e-2	1	8.7e-2	2009/01/01	.8130	14.25	17.53		1.924	37e-9	2.776	
					0.0000w	4.2e-3						
4	.1250	1	.2122	2009/01/01	.7196	12.61	17.53		1.916	14e-8	3.170	
					0.0000w	9.2e-3						
5	.2892	1	.5014	2009/01/01	.6490	11.38	17.53		1.908	67e-8	3.302	
					0.0001w	2.0e-2						
6	.6689	1	1.170	2009/01/02	.6266	10.98	17.53		1.900	33e-7	3.420	
					0.0001w	4.7e-2						
7	1.547	1	2.717	2009/01/03	.7179	12.58	17.53		1.893	17e-6	3.999	
					0.0003w	.1080						
8	3.571	1	6.288	2009/01/07	.9778	17.14	17.53		1.885	87e-6	5.482	
					0.0007w	.2394						
9	8.212	1	14.50	2009/01/15	1.379	24.17	17.53		1.878	46e-5	7.430	
					0.0017w	.5378						
10	16.50	1	31.00	2009/02/01	1.749	30.66	17.53		1.884	19e-4	6.766	
					0.0033w	1.075						
11	28.00	1	59.00	2009/03/01	1.968	34.50	17.53		1.910	57e-4	4.099	
					0.0057w	1.808						
12	31.00	1	90.00	2009/04/01	2.059	36.10	17.53		1.941	10e-3	1.802	
					0.0064w	1.969						
13	30.00	1	120.0	2009/05/01	2.103	36.87	17.53		1.970	14e-3	.9334	
					0.0063w	1.864						
14	31.00	1	151.0	2009/06/01	2.132	37.38	17.53		1.998	18e-3	.6674	
					0.0066w	1.875						

15	30.00	1	181.0	2009/07/01	2.156	37.80	17.53	2.026	19e-3	.5872
					0.0067w	1.769				
16	31.00	1	212.0	2009/08/01	2.181	38.23	17.53	2.053	24e-3	.6034
					0.0071w	1.775				
17	31.00	1	243.0	2009/09/01	2.202	38.60	17.53	2.076	28e-3	.5010
					0.0073w	1.720				
18	30.00	1	273.0	2009/10/01	2.218	38.88	17.53	2.094	32e-3	.3968
					0.0073w	1.610				
19	31.00	1	304.0	2009/11/01	2.231	39.11	17.53	2.115	28e-3	.3223
					0.0077w	1.605				
20	30.00	1	334.0	2009/12/01	2.246	39.37	17.53	2.135	30e-3	.3878
					0.0078w	1.515				

1

STARS TIME STEP SUMMARY

```

=====
-----
---Time Step--- -----Time----- -----Production----- --Injection-- Mat ---
          C          Oil Gas Water GOR Wat. Gas Water Bal Pres Sat
          Size U          m3 Cut          Err
No. days IT T days yy/mm/dd m3/d m3/d m3/d /m3 % m3/d m3/d %
          kPa w/o/g deg C
-----
21 31.00 1 365.0 2010/01/01 2.263 39.68 17.53 2.154 33e-3 .4419
          0.0083w 1.518
22 31.00 1 396.0 2010/02/01 2.277 39.92 17.53 2.170 35e-3 .3509
          0.0086w 1.470
23 28.00 1 424.0 2010/03/01 2.290 40.14 17.53 2.185 37e-3 .3191
          0.0079w 1.291
24 31.00 1 455.0 2010/04/01 2.303 40.38 17.53 2.205 34e-3 .3411
          0.0089w 1.391
25 30.00 1 485.0 2010/05/01 2.320 40.67 17.53 2.222 36e-3 .4317
          0.0090w 1.321
26 31.00 1 516.0 2010/06/01 2.336 40.95 17.53 2.242 35e-3 .4082
          0.0094w 1.334
27 30.00 1 546.0 2010/07/01 2.353 41.24 17.53 2.259 37e-3 .4283
          0.0093w 1.262
28 31.00 1 577.0 2010/08/01 2.368 41.50 17.53 2.277 37e-3 .3790
          0.0097w 1.274
29 31.00 1 608.0 2010/09/01 2.385 41.81 17.53 2.300 34e-3 .4595
          0.0098w 1.247

```

30	30.00	1	638.0	2010/10/01	2.408	42.21	17.53	2.323	34e-3	.5799
					0.0096w	1.200				
31	31.00	1	669.0	2010/11/01	2.430	42.60	17.53	2.347	33e-3	.5608
					0.0099w	1.221				
32	30.00	1	699.0	2010/12/01	2.452	42.99	17.53	2.371	32e-3	.5647
					0.0095w	1.164				
33	31.00	1	730.0	2011/01/01	2.478	43.43	17.53	2.399	30e-3	.6373
					0.0098w	1.186				
34	31.00	1	761.0	2011/02/01	2.507	43.95	17.53	2.430	28e-3	.7521
					0.0097w	1.173				
35	28.00	1	789.0	2011/03/01	2.537	44.46	17.53	2.460	28e-3	.7378
					0.0087w	1.065				
36	31.00	1	820.0	2011/04/01	2.571	45.07	17.53	2.494	28e-3	.8666
					0.0094w	1.174				
37	30.00	1	850.0	2011/05/01	2.604	45.65	17.53	2.527	28e-3	.8224
					0.0089w	1.130				
38	31.00	1	881.0	2011/06/01	2.639	46.27	17.53	2.564	26e-3	.8832
					0.0090w	1.164				
39	30.00	1	911.0	2011/07/01	2.681	47.00	17.53	2.607	26e-3	1.056
					0.0085w	1.131				
40	31.00	1	942.0	2011/08/01	2.727	47.81	17.53	2.652	26e-3	1.155
					0.0085w	1.178				

1

STARS TIME STEP SUMMARY

```

=====
-----
---Time Step--- -----Time----- -----Production----- --Injection-- Mat ---
          Maximum Changes---
          C          Oil Gas Water GOR Wat. Gas Water Bal Pres Sat
          Size U          m3 Cut          Err
No. days IT T days yy/mm/dd m3/d m3/d m3/d /m3 % m3/d m3/d %
          kPa w/o/g deg C
-----
41 31.00 1 973.0 2011/09/01 2.775 48.65 17.53 2.699 26e-3 1.186
          0.0082w 1.187
42 30.00 1 1003 2011/10/01 2.821 49.46 17.53 2.745 26e-3 1.152
          0.0076w 1.157
43 31.00 1 1034 2011/11/01 2.872 50.35 17.53 2.795 25e-3 1.273
          0.0076w 1.205
44 30.00 1 1064 2011/12/01 2.925 51.27 17.53 2.847 24e-3 1.313
          0.0070w 1.178

```

45	31.00	1	1095	2012/01/01	2.982	52.27	17.53	2.901	24e-3	1.415
					0.0069w	1.240				
46	31.00	1	1126	2012/02/01	3.041	53.31	17.53	2.959	23e-3	1.483
					0.0066w	1.258				
47	29.00	1	1155	2012/03/01	3.100	54.35	17.53	3.017	23e-3	1.483
					0.0061w	1.193				
48	31.00	1	1186	2012/04/01	3.165	55.48	17.53	3.080	22e-3	1.612
					0.0064w	1.296				
49	30.00	1	1216	2012/05/01	3.229	56.60	17.53	3.140	22e-3	1.603
					0.0061w	1.270				
50	31.00	1	1247	2012/06/01	3.295	57.77	17.53	3.206	21e-3	1.654
					0.0063w	1.340				
51	30.00	1	1277	2012/07/01	3.364	58.97	17.53	3.270	21e-3	1.722
					0.0065w	1.326				
52	31.00	1	1308	2012/08/01	3.435	60.21	17.53	3.338	20e-3	1.778
					0.0071w	1.397				
53	31.00	1	1339	2012/09/01	3.509	61.51	17.53	3.416	16e-3	1.872
					0.0075w	1.421				
54	30.00	1	1369	2012/10/01	3.592	62.97	17.53	3.492	16e-3	2.105
					0.0077w	1.419				
55	31.00	1	1400	2012/11/01	3.677	64.46	17.53	3.572	16e-3	2.133
					0.0083w	1.498				
56	30.00	1	1430	2012/12/01	3.762	65.94	17.53	3.654	15e-3	2.114
					0.0086w	1.480				
57	31.00	1	1461	2013/01/01	3.855	67.57	17.53	3.741	15e-3	2.343
					0.0094w	1.572				
58	31.00	1	1492	2013/02/01	3.949	69.22	17.53	3.832	13e-3	2.362
					0.0098w	1.610				
59	28.00	1	1520	2013/03/01	4.039	70.81	17.53	3.917	13e-3	2.275
					0.0092w	1.504				
60	31.00	1	1551	2013/04/01	4.140	72.57	17.53	4.010	13e-3	2.523
					0.0106w	1.708				

1

STARS TIME STEP SUMMARY

```

=====
-----
---Time Step---- -----Time----- -----Production----- --Injection-- Mat ---
                Maximum Changes---
      C          Oil Gas Water GOR Wat. Gas Water Bal Pres Sat
                Size U          m3 Cut          Err

```


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Command-line Arguments: -dimsum
-wd H:\My Documents\Desktop\Oveall Recovery
-log
-f H:\My Documents\Desktop\Oveall Recovery\Basecase2.dat

***** Input/Output files specification :**
Opened data file on unit 11, filename is 'H:\My Documents\Desktop\Oveall
Recovery\Basecase2.dat'
Opened Scratch file on unit 12

Scanning data for dimensioning info . . .
GRID-XOFFSET 0.0000
GRID-YOFFSET 0.0000
GRID-ROTATION 0.0000
GRID-AXES-DIRECTIONS 1.0 -1.0 1.0
Done.

Summary of Dimensions Obtained from Data Scan

4 NCOMP - Number of components
4 NUMY - Number of fluid components
4 NUMX - Number of condensible components
1 MFORM - *TFORM flag: 1 for *SXY, 2 for *ZH, 3 for *ZT
1 NPTGN - Number of grids
360 NPTSS - Number of matrix blocks
360 NPTCS - Number of blocks including nulls
1 M9PT - *NINEPOINT flag: 1 - no, 2 - yes
3 NDIM - Number of dimensions (= 3 for *REFINE)
0 NREF - Number of refinements per fundamental block
0 MINC - Number of *MINC/*SUBDOMAIN subdivisions
30 NORTH - Number of orthogonalizations
0 NGAUSS - Bandwidth for *SDEGREE *GAUSS
16 NXSVAL - Number of special histories
Run is thermal

Opened output file on unit 13, filename is 'H:\My Documents\Desktop\Oveall Recovery\Basecase2.out'
Opened SR3-OUT on unit 14, filename is 'H:\My Documents\Desktop\Oveall Recovery\Basecase2.sr3'
Opened INDEX-OUT on unit 15, filename is 'H:\My Documents\Desktop\Oveall Recovery\Basecase2.irf'
Opened MAIN-RESULTS-OUT on unit 16, filename is 'H:\My Documents\Desktop\Oveall Recovery\Basecase2.mrf'
Opened GRID scratchfile on unit 17

===== SUMMARY (from subroutine: INDATA)

=====
Reading of initial data is complete.
Simulation will stop if there were error messages.
0 Warning messages. 0 Error messages.

=====

Global Storage Usage

=====

Section	Bytes	Mbytes	# Objects
STARS	556778	0.531	785
GRMOD0	282844	0.270	445
SOLVINT	225388	0.215	101
ELECTRIC	68356	0.065	27
WMCOM1	54581	0.052	988
VISC	50388	0.048	71
KWCOM1	34719	0.033	48
POINT	28752	0.027	70
WELL	23468	0.022	245
RELPERM	11960	0.011	211
GRMOD1	10228	0.010	121
SR2WRT	8984	0.009	24
GLOBSTORE	7478	0.007	27
PRTCM	6900	0.007	17
SR2COM	6408	0.006	86
SECTOR	3624	0.003	70
PGMCH1	1446	0.001	241
CMGFILE	1184	0.001	18

WELHYD	556	0.001	51
KVAL	520	0.000	41
FLEXWEL	400	0.000	37
PSOLINT	288	0.000	62
GEOMECH	216	0.000	48
PGAIM	184	0.000	38
GRMOD2	124	0.000	30
REACT	68	0.000	13
ADSORP	68	0.000	17
WMCOM5	60	0.000	15
AQUIFER	36	0.000	6
WMCOM2	36	0.000	9
WMCOM4	32	0.000	8
COMPACT	16	0.000	4
PGMCH2	12	0.000	3
INGRDM	0	0.000	0

Total	1386102	1.322	3977

Dimensioning Parameters

- 360 MDPTSS - Matrix blocks, including nulls
- 360 MDPTCS - Total blocks, including nulls
- 360 MDPTPS - Total non-null blocks
- 1 MDPTGN - Grids (fundamental & refined)
- 1 MDNVAM - Sets of Volume/area modifiers
- 1442 MDNEXF - Exterior block faces
- 924 MDPTBC - Total interblock connections

- 4 NCOMP - Total components (fluid & solid)
 - 4 NUMY - Fluid components
 - 4 NUMX - Condensable components
- 5 NFLOW - Flowing items (fluids + energy)
 - 0 NSLD - Solid components

- 1 NTHSET - Compressibility/thermal sets
 - 1 NKROCK - Rel perm rock sets
 - 1 NKRSET - Rel perm table sets
 - 21 NKRTBD - Rel perm table size
 - 11 NVSTBL - Viscosity tables

6 MDNEQ - Equations per block
363 MDSOL - Solver elements (blocks+wells+1)
2160 MDNEQT - Total grid equations
936 MDPTCN - Interblock & block-well connections
31 MDNOR - Orthogonalizations + 1
90 MDJCM - Connections per equation with fill
2809 MDCALP - Submatrices in the Jacobian matrix
0 MDALP - Size of Jacobian off-diagonal
0 MDALD - Size of Jacobian diagonal
0 MDBET - Size of RHS and solution vectors
0 MDV - Size of solution vector
0 MDDD - Diagonal entries
0 MDROW - Columns per equation
2809 MDICLU - 1 + Block entries in each of L & U
0 MDLU - Size of each of L & U
0 MDPROW - Size of PARASOL list arrays
90 MDPJCM - PARASOL row storage parameter

WM parameters - Dimensioner output

mdwell = 2
mdlayr = 12
mdly1w = 7
mdlypl = 1
mdgrup = 2
mdrgrp = 1
mdcons = 4
mdhyvl = 1
mdbhen = 100
mdhytb = 1
mdcygr = 1
mdcygp = 2
mdcygs = 2
mcdsgr = 1
mdfevl = 1
mdfcen = 1
mdfctb = 1
mdgcms = 40
mdwcms = 40
mdclmp = 0
mdrlmp = 0
mdlyclmp = 1

Global Storage Usage

```

=====
Section      Bytes      Mbytes  # Objects
-----
SOLVINT      1577396      1.504    112
  STARS      556778      0.531    785
  GRMOD0     282844      0.270    445
ELECTRIC     68356      0.065     27
  WMCOM1     54581      0.052    988
    VISC     50388      0.048     71
  KWCOM1     34719      0.033     48
    POINT    28752      0.027     70
    WELL     23468      0.022    245
  SR2COM     21080      0.020     87
RELPERM     11960      0.011    211
  GRMOD1     10228      0.010    121
    SR2WRT     8984      0.009     24
GLOBSTORE     7478      0.007     27
  PRTCM      6900      0.007     17
  SECTOR     3624      0.003     70
  PGMCH1     1446      0.001    241
  CMGFILE     1184      0.001     18
  WELHYD      556      0.001     51
    KVAL      520      0.000     41
  EQTPAR      412      0.000     69
  FLEXWEL     400      0.000     37
  PSOLINT     360      0.000     75
GEOMECH      216      0.000     48
  PGAIM      184      0.000     38
  GRMOD2     124      0.000     30
  ADSORP      68      0.000     17
  REACT       68      0.000     13
  WMCOM5      60      0.000     15
  AQUIFER     36      0.000     6
  WMCOM2      36      0.000     9
  WMCOM4      32      0.000     8
  COMPACT     16      0.000     4
  PGMCH2     12      0.000     3
  INGRDM      0      0.000     0
  
```

-----	-----	-----	-----
Total	2753266	2.626	4071

Dimensioning Parameters

360 MDPTSS - Matrix blocks, including nulls
360 MDPTCS - Total blocks, including nulls
360 MDPTPS - Total non-null blocks
1 MDPTGN - Grids (fundamental & refined)
1 MDNVAM - Sets of Volume/area modifiers
1442 MDNEXF - Exterior block faces
924 MDPTBC - Total interblock connections

4 NCOMP - Total components (fluid & solid)
4 NUMY - Fluid components
4 NUMX - Condensable components
5 NFLOW - Flowing items (fluids + energy)
0 NSLD - Solid components

1 NTHSET - Compressibility/thermal sets

1 NKROCK - Rel perm rock sets
1 NKRSET - Rel perm table sets
21 NKRTBD - Rel perm table size
11 NVSTBL - Viscosity tables

6 MDNEQ - Equations per block
363 MDSOL - Solver elements (blocks+wells+1)
2160 MDNEQT - Total grid equations
936 MDPTCN - Interblock & block-well connections
31 MDNOR - Orthogonalizations + 1
90 MDJCM - Connections per equation with fill
2809 MDCALP - Submatrices in the Jacobian matrix
55572 MDALP - Size of Jacobian off-diagonal
12962 MDALD - Size of Jacobian diagonal
2162 MDBET - Size of RHS and solution vectors
902 MDV - Size of solution vector
4502 MDDD - Diagonal entries
475 MDROW - Columns per equation
2809 MDICLU - 1 + Block entries in each of L & U
1192 NICLU - Used block entries of L/U
29440 MDLU - Size of each of L & U

475 MDPROW - Size of PARASOL list arrays
 90 MDPJCM - PARASOL row storage parameter

 WM parameters - Dimensioner output

mdwell = 2
 mdlayr = 12
 mdly1w = 7
 mdlypl = 1
 mdgrup = 2
 mdrgrp = 1
 mdcons = 4
 mdhyvl = 1
 mdbhen = 100
 mdhytb = 1
 mdcygr = 1
 mdcygp = 2
 mdcygs = 2
 mdcsg = 1
 mdfevl = 1
 mdfcen = 1
 mdfctb = 1
 mdgcms = 40
 mdwcms = 40
 mdclmp = 0
 mdrlmp = 0
 mdlyclmp = 1
 mdlyrlmp = 1

1

STARS TIME STEP SUMMARY

=====

---Time Step---	Time	Production				--Injection--		Mat				
C	Oil	Gas	Water	GOR	Wat.	Gas	Water	Bal	Pres	Sat		
	Maximum Changes---											
	Size	U			m3	Cut		Err				
No. days	IT	T	days	yy/mm/dd	m3/d	m3/d	m3/d	/m3	%	m3/d	m3/d	%
					kPa	w/o/g	deg C					

1	1.0e-2	1	1.0e-2	2009/01/01	.8494	14.89	17.53	1.625	6.e-9	1.108
					0.0000w	8.6e-4				
2	2.3e-2	1	3.3e-2	2009/01/01	.7785	13.65	17.53	1.621	10e-9	1.858
					0.0000w	1.9e-3				
3	5.4e-2	1	8.7e-2	2009/01/01	.6938	12.16	17.53	1.616	27e-9	2.623
					0.0000w	4.1e-3				
4	.1252	1	.2124	2009/01/01	.6142	10.77	17.53	1.609	10e-8	3.104
					0.0000w	9.2e-3				
5	.2896	1	.5021	2009/01/01	.5511	9.660	17.53	1.602	50e-8	3.290
					0.0001w	2.0e-2				
6	.6700	1	1.172	2009/01/02	.5206	9.125	17.53	1.596	24e-7	3.392
					0.0001w	4.7e-2				
7	1.549	1	2.721	2009/01/03	.5717	10.02	17.53	1.590	12e-6	3.827
					0.0003w	.1082				
8	3.578	1	6.300	2009/01/07	.7583	13.29	17.53	1.583	63e-6	5.078
					0.0007w	.2382				
9	8.238	1	14.54	2009/01/15	1.077	18.88	17.53	1.577	33e-5	7.172
					0.0017w	.5298				
10	16.46	1	31.00	2009/02/01	1.400	24.54	17.53	1.579	13e-4	7.064
					0.0033w	1.001				
11	28.00	1	59.00	2009/03/01	1.609	28.20	17.53	1.594	42e-4	4.643
					0.0057w	1.579				
12	31.00	1	90.00	2009/04/01	1.699	29.78	17.53	1.615	74e-4	2.064
					0.0064w	1.690				
13	30.00	1	120.0	2009/05/01	1.739	30.48	17.53	1.635	10e-3	.9735
					0.0063w	1.594				
14	31.00	1	151.0	2009/06/01	1.762	30.89	17.53	1.654	13e-3	.6110
					0.0066w	1.597				
15	30.00	1	181.0	2009/07/01	1.780	31.20	17.53	1.672	15e-3	.4796
					0.0066w	1.496				
16	31.00	1	212.0	2009/08/01	1.795	31.46	17.53	1.689	17e-3	.4240
					0.0070w	1.497				
17	31.00	1	243.0	2009/09/01	1.808	31.69	17.53	1.705	20e-3	.3811
					0.0072w	1.447				
18	30.00	1	273.0	2009/10/01	1.818	31.88	17.53	1.718	23e-3	.3077
					0.0071w	1.353				
19	31.00	1	304.0	2009/11/01	1.827	32.03	17.53	1.731	22e-3	.2620
					0.0075w	1.349				
20	30.00	1	334.0	2009/12/01	1.836	32.19	17.53	1.743	24e-3	.2672
					0.0076w	1.261				

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STARS TIME STEP SUMMARY

37	30.00	1	850.0	2011/05/01	2.019	35.39	17.53	1.963	29e-3	.5786
					0.0086w	.8716				
38	31.00	1	881.0	2011/06/01	2.039	35.74	17.53	1.984	29e-3	.5961
					0.0087w	.8931				
39	30.00	1	911.0	2011/07/01	2.058	36.07	17.53	2.004	28e-3	.5707
					0.0083w	.8577				
40	31.00	1	942.0	2011/08/01	2.079	36.44	17.53	2.028	26e-3	.6309
					0.0083w	.8892				

1

STARS TIME STEP SUMMARY

```

=====
-----
---Time Step--- -----Time----- -----Production----- --Injection-- Mat ---
                Maximum Changes---
      C          Oil Gas Water GOR Wat. Gas Water Bal Pres Sat
                Size U          m3 Cut          Err
      No. days IT T days yy/mm/dd m3/d m3/d m3/d /m3 % m3/d m3/d %
                kPa w/o/g deg C
-----
41 31.00 1 973.0 2011/09/01 2.104 36.87 17.53 2.052 25e-3 .7549
                0.0081w .8871
42 30.00 1 1003 2011/10/01 2.128 37.30 17.53 2.077 24e-3 .7219
                0.0076w .8571
43 31.00 1 1034 2011/11/01 2.156 37.79 17.53 2.106 24e-3 .8467
                0.0076w .8876
44 30.00 1 1064 2011/12/01 2.185 38.31 17.53 2.136 24e-3 .8811
                0.0071w .8666
45 31.00 1 1095 2012/01/01 2.217 38.86 17.53 2.166 24e-3 .9309
                0.0071w .9061
46 31.00 1 1126 2012/02/01 2.248 39.41 17.53 2.198 23e-3 .9316
                0.0068w .9150
47 29.00 1 1155 2012/03/01 2.279 39.95 17.53 2.228 23e-3 .9198
                0.0061w .8644
48 31.00 1 1186 2012/04/01 2.312 40.52 17.53 2.263 21e-3 .9781
                0.0062w .9335
49 30.00 1 1216 2012/05/01 2.349 41.18 17.53 2.299 21e-3 1.125
                0.0058w .9290
50 31.00 1 1247 2012/06/01 2.388 41.85 17.53 2.336 20e-3 1.145
                0.0058w .9766
51 30.00 1 1277 2012/07/01 2.426 42.53 17.53 2.374 20e-3 1.152
                0.0055w .9587

```

52	31.00	1	1308	2012/08/01	2.467	43.25	17.53	2.414	20e-3	1.229
					0.0057w	1.005				
53	31.00	1	1339	2012/09/01	2.509	43.98	17.53	2.454	19e-3	1.231
					0.0058w	1.019				
54	30.00	1	1369	2012/10/01	2.553	44.76	17.53	2.499	19e-3	1.350
					0.0059w	1.013				
55	31.00	1	1400	2012/11/01	2.602	45.61	17.53	2.546	19e-3	1.443
					0.0064w	1.069				
56	30.00	1	1430	2012/12/01	2.648	46.42	17.53	2.590	18e-3	1.386
					0.0065w	1.052				
57	31.00	1	1461	2013/01/01	2.697	47.27	17.53	2.636	18e-3	1.449
					0.0070w	1.107				
58	31.00	1	1492	2013/02/01	2.746	48.13	17.53	2.683	18e-3	1.457
					0.0073w	1.126				
59	28.00	1	1520	2013/03/01	2.790	48.91	17.53	2.728	17e-3	1.336
					0.0068w	1.032				
60	31.00	1	1551	2013/04/01	2.844	49.85	17.53	2.779	17e-3	1.626
					0.0079w	1.179				

1

STARS TIME STEP SUMMARY

```

=====
-----
---Time Step--- -----Time----- -----Production----- --Injection-- Mat ---
          C          Oil Gas Water GOR Wat. Gas Water Bal Pres Sat
          Size U          m3 Cut          Err
No. days IT T days yy/mm/dd m3/d m3/d m3/d /m3 % m3/d m3/d %
          kPa w/o/g deg C
-----
61 30.00 1 1581 2013/05/01 2.896 50.76 17.53 2.830 16e-3 1.541
          0.0078w 1.157
62 31.00 1 1612 2013/06/01 2.952 51.75 17.53 2.885 15e-3 1.702
          0.0085w 1.215
63 30.00 1 1642 2013/07/01 3.010 52.76 17.53 2.939 15e-3 1.723
          0.0085w 1.196
64 31.00 1 1673 2013/08/01 3.069 53.80 17.53 2.995 15e-3 1.769
          0.0091w 1.257
65 31.00 1 1704 2013/09/01 3.129 54.86 17.53 3.056 13e-3 1.808
          0.0094w 1.279
66 30.00 1 1734 2013/10/01 3.193 55.98 17.53 3.116 13e-3 1.920
          0.0094w 1.281

```


Opened Scratch file on unit 12

Scanning data for dimensioning info . . .

GRID-XOFFSET 0.0000

GRID-YOFFSET 0.0000

GRID-ROTATION 0.0000

GRID-AXES-DIRECTIONS 1.0 -1.0 1.0

Done.

Summary of Dimensions Obtained from Data Scan

4 NCOMP - Number of components

4 NUMY - Number of fluid components

4 NUMX - Number of condensible components

1 MFORM - *TFORM flag: 1 for *SXY, 2 for *ZH, 3 for *ZT

1 NPTGN - Number of grids

360 NPTSS - Number of matrix blocks

360 NPTCS - Number of blocks including nulls

1 M9PT - *NINEPOINT flag: 1 - no, 2 - yes

3 NDIM - Number of dimensions (= 3 for *REFINE)

0 NREF - Number of refinements per fundamental block

0 MINC - Number of *MINC/*SUBDOMAIN subdivisions

30 NORTH - Number of orthogonalizations

0 NGAUSS - Bandwidth for *SDEGREE *GAUSS

16 NXSVAL - Number of special histories

Run is thermal

Opened output file on unit 13, filename is 'H:\My Documents\Desktop\Oveall
Recovery\Basecase3.out'

Opened SR3-OUT on unit 14, filename is 'H:\My Documents\Desktop\Oveall
Recovery\Basecase3.sr3'

Opened INDEX-OUT on unit 15, filename is 'H:\My Documents\Desktop\Oveall
Recovery\Basecase3.irf'

Opened MAIN-RESULTS-OUT on unit 16, filename is 'H:\My
Documents\Desktop\Oveall Recovery\Basecase3.mrf'

Opened GRID scratchfile on unit 17

===== SUMMARY (from subroutine: INDATA)

=====

Reading of initial data is complete.

Simulation will stop if there were error messages.

0 Warning messages. 0 Error messages.

Global Storage Usage

Section	Bytes	Mbytes	# Objects
STARS	556778	0.531	785
GRMOD0	282844	0.270	445
SOLVINT	225388	0.215	101
ELECTRIC	68356	0.065	27
WMCOM1	54581	0.052	988
VISC	50388	0.048	71
KWCOM1	34719	0.033	48
POINT	28752	0.027	70
WELL	23468	0.022	245
RELPERM	11960	0.011	211
GRMOD1	10228	0.010	121
SR2WRT	8984	0.009	24
GLOBSTORE	7478	0.007	27
PRTCM	6900	0.007	17
SR2COM	6408	0.006	86
SECTOR	3624	0.003	70
PGMCH1	1446	0.001	241
CMGFILE	1184	0.001	18
WELHYD	556	0.001	51
KVAL	520	0.000	41
FLEXWEL	400	0.000	37
PSOLINT	288	0.000	62
GEOMECH	216	0.000	48
PGAIM	184	0.000	38
GRMOD2	124	0.000	30
REACT	68	0.000	13
ADSORP	68	0.000	17
WMCOM5	60	0.000	15
AQUIFER	36	0.000	6
WMCOM2	36	0.000	9
WMCOM4	32	0.000	8
COMPACT	16	0.000	4
PGMCH2	12	0.000	3

INGRDM	0	0.000	0
-----	-----	-----	-----
Total	1386102	1.322	3977

Dimensioning Parameters

- 360 MDPTSS - Matrix blocks, including nulls**
- 360 MDPTCS - Total blocks, including nulls**
- 360 MDPTPS - Total non-null blocks**
- 1 MDPTGN - Grids (fundamental & refined)**
- 1 MDNVAM - Sets of Volume/area modifiers**
- 1442 MDNEXF - Exterior block faces**
- 924 MDPTBC - Total interblock connections**

- 4 NCOMP - Total components (fluid & solid)**
- 4 NUMY - Fluid components**
- 4 NUMX - Condensable components**
- 5 NFLOW - Flowing items (fluids + energy)**
- 0 NSLD - Solid components**

- 1 NTHSET - Compressibility/thermal sets**

- 1 NKROCK - Rel perm rock sets**
- 1 NKRSET - Rel perm table sets**
- 21 NKRTBD - Rel perm table size**
- 11 NVSTBL - Viscosity tables**

- 6 MDNEQ - Equations per block**
- 363 MDSOL - Solver elements (blocks+wells+1)**
- 2160 MDNEQT - Total grid equations**
- 936 MDPTCN - Interblock & block-well connections**
- 31 MDNOR - Orthogonalizations + 1**
- 90 MDJCM - Connections per equation with fill**
- 2809 MDCALP - Submatrices in the Jacobian matrix**
- 0 MDALP - Size of Jacobian off-diagonal**
- 0 MDALD - Size of Jacobian diagonal**
- 0 MDBET - Size of RHS and solution vectors**
- 0 MDV - Size of solution vector**
- 0 MDDD - Diagonal entries**
- 0 MDROW - Columns per equation**
- 2809 MDICLU - 1 + Block entries in each of L & U**
- 0 MDLU - Size of each of L & U**

0 MDPROW - Size of PARASOL list arrays
90 MDPJCM - PARASOL row storage parameter

WM parameters - Dimensioner output

mdwell = 2
 mdlayr = 12
 mdly1w = 7
 mdlypl = 1
 mdgrup = 2
 mdrgrp = 1
 mdcons = 4
 mdhyvl = 1
 mdbhen = 100
 mdhytb = 1
 mdcygr = 1
 mdcygp = 2
 mdcygs = 2
 mdcsg = 1
 mdfcvl = 1
 mdfcen = 1
 mdfctb = 1
 mdgcms = 40
 mdwcms = 40
 mdclmp = 0
 mdrmp = 0
 mdlyclmp = 1
 mdlyrlmp = 1

Global Storage Usage

=====

Section	Bytes	Mbytes	# Objects
SOLVINT	1577396	1.504	112
STARS	556778	0.531	785
GRMOD0	282844	0.270	445
ELECTRIC	68356	0.065	27
WMCOM1	54581	0.052	988
VISC	50388	0.048	71

KWCOM1	34719	0.033	48
POINT	28752	0.027	70
WELL	23468	0.022	245
SR2COM	20632	0.020	87
RELPERM	11960	0.011	211
GRMOD1	10228	0.010	121
SR2WRT	8984	0.009	24
GLOBSTORE	7478	0.007	27
PRTCM	6900	0.007	17
SECTOR	3624	0.003	70
PGMCH1	1446	0.001	241
CMGFILE	1184	0.001	18
WELHYD	556	0.001	51
KVAL	520	0.000	41
EQTPAR	412	0.000	69
FLEXWEL	400	0.000	37
PSOLINT	360	0.000	75
GEOMECH	216	0.000	48
PGAIM	184	0.000	38
GRMOD2	124	0.000	30
ADSORP	68	0.000	17
REACT	68	0.000	13
WMCOM5	60	0.000	15
AQUIFER	36	0.000	6
WMCOM2	36	0.000	9
WMCOM4	32	0.000	8
COMPACT	16	0.000	4
PGMCH2	12	0.000	3
INGRDM	0	0.000	0

Total	2752818	2.625	4071

Dimensioning Parameters

- 360 MDPTSS - Matrix blocks, including nulls
- 360 MDPTCS - Total blocks, including nulls
- 360 MDPTPS - Total non-null blocks
- 1 MDPTGN - Grids (fundamental & refined)
- 1 MDNVAM - Sets of Volume/area modifiers
- 1442 MDNEXF - Exterior block faces
- 924 MDPTBC - Total interblock connections

4 NCOMP - Total components (fluid & solid)
 4 NUMY - Fluid components
 4 NUMX - Condensable components
5 NFLOW - Flowing items (fluids + energy)
 0 NSLD - Solid components

1 NTHSET - Compressibility/thermal sets

1 NKROCK - Rel perm rock sets
 1 NKRSET - Rel perm table sets
 21 NKRTBD - Rel perm table size
 11 NVSTBL - Viscosity tables

6 MDNEQ - Equations per block
363 MDSOL - Solver elements (blocks+wells+1)
 2160 MDNEQT - Total grid equations
936 MDPTCN - Interblock & block-well connections
 31 MDNOR - Orthogonalizations + 1
 90 MDJCM - Connections per equation with fill
2809 MDCALP - Submatrices in the Jacobian matrix
 55572 MDALP - Size of Jacobian off-diagonal
 12962 MDALD - Size of Jacobian diagonal
2162 MDBET - Size of RHS and solution vectors
 902 MDV - Size of solution vector
 4502 MDDD - Diagonal entries
 475 MDROW - Columns per equation
2809 MDICLU - 1 + Block entries in each of L & U
 1192 NICLU - Used block entries of L/U
 29440 MDLU - Size of each of L & U
 475 MDPROW - Size of PARASOL list arrays
90 MDPJCM - PARASOL row storage parameter

WM parameters - Dimensioner output

mdwell = 2
 mdlayr = 12
 mdly1w = 7
 mdlypl = 1
 mdgrup = 2
 mdrgrp = 1
 mdcons = 4
 mdhyvl = 1

mdbhen = 100
 mdhytb = 1
 mdcygr = 1
 mdcygp = 2
 mdcygs = 2
 mdcsgr = 1
 mdfevl = 1
 mdfcen = 1
 mdfctb = 1
 mdgcms = 40
 mdwcms = 40
 mdclmp = 0
 mdrimp = 0
 mdlyclmp = 1
 mdlyrlmp = 1

1

STARS TIME STEP SUMMARY

=====											

---Time Step--- -----Time----- -----Production----- --Injection-- Mat ---											
Maximum Changes---											
C	Oil	Gas	Water	GOR	Wat.	Gas	Water	Bal	Pres	Sat	
				Temp							
No.	days	IT	T	Size	U	yy/mm/dd	m3/d	m3/d	m3/d	Cut	Err
				days							
							kPa	w/o/g	deg C		

1	1.0e-2	1	1.0e-2	2009/01/01	.8966	15.72	17.53	1.706	6.e-9	1.138	
					0.0000w	8.1e-4					
2	2.3e-2	1	3.3e-2	2009/01/01	.8194	14.36	17.53	1.702	10e-9	1.908	
					0.0000w	1.7e-3					
3	5.4e-2	1	8.7e-2	2009/01/01	.7289	12.78	17.53	1.696	29e-9	2.654	
					0.0000w	3.9e-3					
4	.1251	1	.2124	2009/01/01	.6452	11.31	17.53	1.689	11e-8	3.106	
					0.0000w	8.5e-3					
5	.2896	1	.5020	2009/01/01	.5796	10.16	17.53	1.682	53e-8	3.275	
					0.0001w	1.9e-2					
6	.6698	1	1.172	2009/01/02	.5508	9.655	17.53	1.675	26e-7	3.379	
					0.0001w	4.3e-2					
7	1.549	1	2.721	2009/01/03	.6121	10.73	17.53	1.668	13e-6	3.849	
					0.0003w	9.9e-2					

8	3.577	1	6.298	2009/01/07	.8177	14.33	17.53	1.661	67e-6	5.154
					0.0007w	.2257				
9	8.234	1	14.53	2009/01/15	1.158	20.29	17.53	1.655	35e-5	7.193
					0.0015w	.5073				
10	16.47	1	31.00	2009/02/01	1.491	26.14	17.53	1.657	14e-4	6.902
					0.0031w	.9835				
11	28.00	1	59.00	2009/03/01	1.701	29.82	17.53	1.674	44e-4	4.406
					0.0053w	1.613				
12	31.00	1	90.00	2009/04/01	1.789	31.37	17.53	1.696	78e-4	1.934
					0.0060w	1.726				
13	30.00	1	120.0	2009/05/01	1.829	32.07	17.53	1.718	11e-3	.9334
					0.0059w	1.618				
14	31.00	1	151.0	2009/06/01	1.854	32.50	17.53	1.738	14e-3	.6123
					0.0061w	1.618				
15	30.00	1	181.0	2009/07/01	1.871	32.79	17.53	1.758	14e-3	.4483
					0.0059w	1.518				
16	31.00	1	212.0	2009/08/01	1.888	33.09	17.53	1.778	15e-3	.4726
					0.0061w	1.524				
17	31.00	1	243.0	2009/09/01	1.904	33.38	17.53	1.796	18e-3	.4524
					0.0062w	1.477				
18	30.00	1	273.0	2009/10/01	1.917	33.61	17.53	1.811	21e-3	.3588
					0.0061w	1.384				
19	31.00	1	304.0	2009/11/01	1.928	33.80	17.53	1.825	24e-3	.3024
					0.0065w	1.382				
20	30.00	1	334.0	2009/12/01	1.936	33.94	17.53	1.838	22e-3	.2242
					0.0063w	1.292				

1

STARS TIME STEP SUMMARY

=====												

---Time Step---	Time	Production	---Injection---			Mat			---			
Maximum Changes---												
C	Oil	Gas	Water	GOR	Wat.	Gas	Water	Bal	Pres	Sat		
	Size	U			m3	Cut		Err				
No. days	IT	T	days	yy/mm/dd	m3/d	m3/d	m3/d	/m3	%	m3/d	m3/d	%
					kPa	w/o/g	deg C					
21	31.00	1	365.0	2010/01/01	1.945	34.09	17.53	1.851	24e-3	.2594		
					0.0067w	1.304						
22	31.00	1	396.0	2010/02/01	1.954	34.25	17.53	1.864	24e-3	.2682		
					0.0068w	1.265						

23	28.00	1	424.0	2010/03/01	1.963	34.42	17.53	1.875	26e-3	.2741
					0.0063w	1.111				
24	31.00	1	455.0	2010/04/01	1.972	34.56	17.53	1.885	28e-3	.2420
					0.0072w	1.194				
25	30.00	1	485.0	2010/05/01	1.979	34.70	17.53	1.897	27e-3	.2222
					0.0071w	1.121				
26	31.00	1	516.0	2010/06/01	1.990	34.88	17.53	1.909	28e-3	.3091
					0.0074w	1.139				
27	30.00	1	546.0	2010/07/01	1.998	35.03	17.53	1.919	29e-3	.2457
					0.0073w	1.077				
28	31.00	1	577.0	2010/08/01	2.007	35.18	17.53	1.930	30e-3	.2543
					0.0077w	1.086				
29	31.00	1	608.0	2010/09/01	2.017	35.35	17.53	1.942	32e-3	.2926
					0.0079w	1.060				
30	30.00	1	638.0	2010/10/01	2.025	35.50	17.53	1.954	31e-3	.2568
					0.0077w	1.002				
31	31.00	1	669.0	2010/11/01	2.037	35.71	17.53	1.967	32e-3	.3484
					0.0080w	1.023				
32	30.00	1	699.0	2010/12/01	2.048	35.91	17.53	1.981	32e-3	.3326
					0.0078w	.9756				
33	31.00	1	730.0	2011/01/01	2.061	36.14	17.53	1.997	31e-3	.3842
					0.0081w	.9925				
34	31.00	1	761.0	2011/02/01	2.076	36.39	17.53	2.012	32e-3	.4251
					0.0082w	.9768				
35	28.00	1	789.0	2011/03/01	2.088	36.61	17.53	2.025	31e-3	.3538
					0.0075w	.8693				
36	31.00	1	820.0	2011/04/01	2.104	36.89	17.53	2.044	29e-3	.4609
					0.0082w	.9505				
37	30.00	1	850.0	2011/05/01	2.123	37.22	17.53	2.064	29e-3	.5512
					0.0079w	.9165				
38	31.00	1	881.0	2011/06/01	2.143	37.56	17.53	2.084	29e-3	.5619
					0.0081w	.9424				
39	30.00	1	911.0	2011/07/01	2.163	37.91	17.53	2.104	29e-3	.5706
					0.0078w	.9069				
40	31.00	1	942.0	2011/08/01	2.183	38.27	17.53	2.127	27e-3	.5899
					0.0080w	.9322				

1

STARS TIME STEP SUMMARY

```

=====
-----
---Time Step--- -----Time----- -----Production----- --Injection-- Mat ---
Maximum Changes---

```

C	Oil	Gas	Water	GOR	Wat. Gas	Water	Bal	Pres	Sat
				Temp					
No.	days	IT	Size	U	m3/d	m3/d	m3/d	Cut	Err
		T	days	yy/mm/dd	m3/d	m3/d	m3/d	/m3	m3/d
					kPa	w/o/g	deg C		m3/d
									%
41	31.00	1	973.0	2011/09/01	2.207	38.69	17.53		2.151
					0.0079w	.9271			26e-3
42	30.00	1	1003	2011/10/01	2.232	39.12	17.53		2.175
					0.0075w	.8943			26e-3
43	31.00	1	1034	2011/11/01	2.257	39.57	17.53		2.203
					0.0076w	.9219			25e-3
44	30.00	1	1064	2011/12/01	2.285	40.06	17.53		2.233
					0.0071w	.9019			23e-3
45	31.00	1	1095	2012/01/01	2.319	40.65	17.53		2.265
					0.0072w	.9368			23e-3
46	31.00	1	1126	2012/02/01	2.353	41.24	17.53		2.298
					0.0070w	.9411			23e-3
47	29.00	1	1155	2012/03/01	2.384	41.79	17.53		2.328
					0.0064w	.8839			22e-3
48	31.00	1	1186	2012/04/01	2.419	42.41	17.53		2.364
					0.0066w	.9547			21e-3
49	30.00	1	1216	2012/05/01	2.456	43.05	17.53		2.399
					0.0062w	.9348			21e-3
50	31.00	1	1247	2012/06/01	2.494	43.72	17.53		2.437
					0.0062w	.9769			21e-3
51	30.00	1	1277	2012/07/01	2.534	44.43	17.53		2.477
					0.0058w	.9583			20e-3
52	31.00	1	1308	2012/08/01	2.577	45.18	17.53		2.518
					0.0057w	1.004			20e-3
53	31.00	1	1339	2012/09/01	2.619	45.92	17.53		2.560
					0.0055w	1.013			20e-3
54	30.00	1	1369	2012/10/01	2.663	46.68	17.53		2.602
					0.0051w	.9924			19e-3
55	31.00	1	1400	2012/11/01	2.711	47.52	17.53		2.648
					0.0053w	1.048			19e-3
56	30.00	1	1430	2012/12/01	2.758	48.34	17.53		2.695
					0.0051w	1.031			18e-3
57	31.00	1	1461	2013/01/01	2.810	49.26	17.53		2.743
					0.0053w	1.086			18e-3
58	31.00	1	1492	2013/02/01	2.860	50.13	17.53		2.791
					0.0056w	1.100			18e-3
59	28.00	1	1520	2013/03/01	2.907	50.95	17.53		2.837
					0.0053w	1.007			18e-3

60 31.00 1 1551 2013/04/01 2.961 51.90 17.53 2.889 18e-3 1.549
 0.0061w 1.132
 1

STARS TIME STEP SUMMARY

```

=====
-----
---Time Step--- -----Time----- -----Production----- --Injection-- Mat ---
      C          Oil Gas Water GOR Wat. Gas Water Bal Pres Sat
                Size U          m3 Cut          Err
No. days IT T days yy/mm/dd m3/d m3/d m3/d /m3 % m3/d m3/d %
                kPa w/o/g deg C
-----
61 30.00 1 1581 2013/05/01 3.014 52.83 17.53 2.940 17e-3 1.516
                0.0062w 1.112
62 31.00 1 1612 2013/06/01 3.071 53.83 17.53 2.997 16e-3 1.625
                0.0067w 1.166
63 30.00 1 1642 2013/07/01 3.131 54.88 17.53 3.053 16e-3 1.725
                0.0067w 1.162
64 31.00 1 1673 2013/08/01 3.194 55.98 17.53 3.113 15e-3 1.784
                0.0072w 1.226
65 31.00 1 1704 2013/09/01 3.257 57.09 17.53 3.173 15e-3 1.809
                0.0075w 1.251
66 30.00 1 1734 2013/10/01 3.320 58.20 17.53 3.233 15e-3 1.803
                0.0076w 1.233
67 31.00 1 1765 2013/11/01 3.386 59.36 17.53 3.296 15e-3 1.880
                0.0082w 1.297
68 30.00 1 1795 2013/12/01 3.451 60.50 17.53 3.360 14e-3 1.863
                0.0082w 1.276
69 31.00 1 1826 2014/01/01 3.525 61.79 17.53 3.429 13e-3 2.109
                0.0088w 1.346
  
```

Stopping end time reached time = 1826.00000 days 1 Jan 2014

it,it-nin,icytot,nrep2,mtfail,IMPES: 69 69 69 0 0 0%
 iter_sol_tot: 413
 Host Computer: iic1024pc11

Date and Time of End of Run: Oct 13, 2017 12:38:35

Elapsed Time to End of Run: 0 hr, 0 min, 5 sec

4 NUMY - Number of fluid components
4 NUMX - Number of condensible components
1 MFORM - *TFORM flag: 1 for *SXY, 2 for *ZH, 3 for *ZT
1 NPTGN - Number of grids
360 NPTSS - Number of matrix blocks
360 NPTCS - Number of blocks including nulls
1 M9PT - *NINEPOINT flag: 1 - no, 2 - yes
3 NDIM - Number of dimensions (= 3 for *REFINE)
0 NREF - Number of refinements per fundamental block
0 MINC - Number of *MINC/*SUBDOMAIN subdivisions
30 NORTH - Number of orthogonalizations
0 NGAUSS - Bandwidth for *SDEGREE *GAUSS
15 NXSVAL - Number of special histories
Run is thermal

Opened output file on unit 13, filename is 'H:\My Documents\Desktop\Oveall Recovery\Steam quality\Basecase1-1.out'

Opened SR3-OUT on unit 14, filename is 'H:\My Documents\Desktop\Oveall Recovery\Steam quality\Basecase1-1.sr3'

Opened INDEX-OUT on unit 15, filename is 'H:\My Documents\Desktop\Oveall Recovery\Steam quality\Basecase1-1.irf'

Opened MAIN-RESULTS-OUT on unit 16, filename is 'H:\My Documents\Desktop\Oveall Recovery\Steam quality\Basecase1-1.mrf'

Opened GRID scratchfile on unit 17

=====**SUMMARY (from subroutine: INDATA)**=====

Reading of initial data is complete.
Simulation will stop if there were error messages.
0 Warning messages. 0 Error messages.

=====
=====

Global Storage Usage

=====

Section	Bytes	Mbytes	# Objects
STARS	556778	0.531	785
GRMOD0	282844	0.270	445
SOLVINT	225388	0.215	101

ELECTRIC	68356	0.065	27
WMCOM1	54581	0.052	988
VISC	50388	0.048	71
KWCOM1	34719	0.033	48
POINT	28752	0.027	70
WELL	23468	0.022	245
RELPERM	11960	0.011	211
GRMOD1	10228	0.010	121
SR2WRT	8780	0.008	24
GLOBSTORE	7478	0.007	27
PRTCM	6900	0.007	17
SR2COM	6408	0.006	86
SECTOR	3624	0.003	70
PGMCH1	1446	0.001	241
CMGFILE	1184	0.001	18
WELHYD	556	0.001	51
KVAL	520	0.000	41
FLEXWEL	400	0.000	37
PSOLINT	288	0.000	62
GEOMECH	216	0.000	48
PGAIM	184	0.000	38
GRMOD2	124	0.000	30
REACT	68	0.000	13
ADSORP	68	0.000	17
WMCOM5	60	0.000	15
AQUIFER	36	0.000	6
WMCOM2	36	0.000	9
WMCOM4	32	0.000	8
COMPACT	16	0.000	4
PGMCH2	12	0.000	3
INGRDM	0	0.000	0

Total	1385898	1.322	3977

Dimensioning Parameters

360 MDPTSS - Matrix blocks, including nulls
360 MDPTCS - Total blocks, including nulls
360 MDPTPS - Total non-null blocks
1 MDPTGN - Grids (fundamental & refined)
1 MDNVAM - Sets of Volume/area modifiers
1442 MDNEXF - Exterior block faces

924 MDPTBC - Total interblock connections

4 NCOMP - Total components (fluid & solid)

4 NUMY - Fluid components

4 NUMX - Condensable components

5 NFLOW - Flowing items (fluids + energy)

0 NSLD - Solid components

1 NTHSET - Compressibility/thermal sets

1 NKROCK - Rel perm rock sets

1 NKRSET - Rel perm table sets

21 NKRTBD - Rel perm table size

11 NVSTBL - Viscosity tables

6 MDNEQ - Equations per block

363 MDSOL - Solver elements (blocks+wells+1)

2160 MDNEQT - Total grid equations

936 MDPTCN - Interblock & block-well connections

31 MDNOR - Orthogonalizations + 1

90 MDJCM - Connections per equation with fill

2809 MDCALP - Submatrices in the Jacobian matrix

0 MDALP - Size of Jacobian off-diagonal

0 MDALD - Size of Jacobian diagonal

0 MDBET - Size of RHS and solution vectors

0 MDV - Size of solution vector

0 MDDD - Diagonal entries

0 MDROW - Columns per equation

2809 MDICLU - 1 + Block entries in each of L & U

0 MDLU - Size of each of L & U

0 MDPROW - Size of PARASOL list arrays

90 MDPJCM - PARASOL row storage parameter

WM parameters - Dimensioner output

mdwell = 2
mdlayr = 12
mdly1w = 7
mdlypl = 1
mdgrup = 2
mdrgrp = 1
mdcons = 4

mdhyvl = 1
mdbhen = 100
mdhytb = 1
mdcygr = 1
mdcygp = 2
mdcygs = 2
mcdsgr = 1
mdfcvl = 1
mdfcen = 1
mdfctb = 1
mdgcms = 40
mdwcms = 40
mdclmp = 0
mdrlmp = 0
mdlyclmp = 1
mdlyrlmp = 1

Global Storage Usage

=====

Section	Bytes	Mbytes	# Objects
SOLVINT	1577396	1.504	112
STARS	556778	0.531	785
GRMOD0	282844	0.270	445
ELECTRIC	68356	0.065	27
WMCOM1	54581	0.052	988
VISC	50388	0.048	71
KWCOM1	34719	0.033	48
POINT	28752	0.027	70
WELL	23468	0.022	245
SR2COM	21080	0.020	87
RELPERM	11960	0.011	211
GRMOD1	10228	0.010	121
SR2WRT	8780	0.008	24
GLOBSTORE	7478	0.007	27
PRTCM	6900	0.007	17
SECTOR	3624	0.003	70
PGMCH1	1446	0.001	241
CMGFILE	1184	0.001	18
WELHYD	556	0.001	51
KVAL	520	0.000	41

EQTPAR	412	0.000	69
FLEXWEL	400	0.000	37
PSOLINT	360	0.000	75
GEOMECH	216	0.000	48
PGAIM	184	0.000	38
GRMOD2	124	0.000	30
ADSORP	68	0.000	17
REACT	68	0.000	13
WMCOM5	60	0.000	15
AQUIFER	36	0.000	6
WMCOM2	36	0.000	9
WMCOM4	32	0.000	8
COMPACT	16	0.000	4
PGMCH2	12	0.000	3
INGRDM	0	0.000	0

Total	2753062	2.626	4071

Dimensioning Parameters

360 MDPTSS - Matrix blocks, including nulls
360 MDPTCS - Total blocks, including nulls
360 MDPTPS - Total non-null blocks
1 MDPTGN - Grids (fundamental & refined)
1 MDNVAM - Sets of Volume/area modifiers
1442 MDNEXF - Exterior block faces
924 MDPTBC - Total interblock connections

4 NCOMP - Total components (fluid & solid)
4 NUMY - Fluid components
4 NUMX - Condensable components
5 NFLOW - Flowing items (fluids + energy)
0 NSLD - Solid components

1 NTHSET - Compressibility/thermal sets

1 NKROCK - Rel perm rock sets
1 NKRSET - Rel perm table sets
21 NKRTBD - Rel perm table size
11 NVSTBL - Viscosity tables

6 MDNEQ - Equations per block

363 MDSOL - Solver elements (blocks+wells+1)
2160 MDNEQT - Total grid equations
936 MDPTCN - Interblock & block-well connections
31 MDNOR - Orthogonalizations + 1
90 MDJCM - Connections per equation with fill
2809 MDCALP - Submatrices in the Jacobian matrix
55572 MDALP - Size of Jacobian off-diagonal
12962 MDALD - Size of Jacobian diagonal
2162 MDBET - Size of RHS and solution vectors
902 MDV - Size of solution vector
4502 MDDD - Diagonal entries
475 MDROW - Columns per equation
2809 MDICLU - 1 + Block entries in each of L & U
1192 NICLU - Used block entries of L/U
29440 MDLU - Size of each of L & U
475 MDPROW - Size of PARASOL list arrays
90 MDPJCM - PARASOL row storage parameter

WM parameters - Dimensioner output

mdwell = 2
mdlayr = 12
mdly1w = 7
mdlypl = 1
mdgrup = 2
mdrgrp = 1
mdcons = 4
mdhyvl = 1
mdbhen = 100
mdhytb = 1
mdcygr = 1
mdcygp = 2
mdcygs = 2
mdcsgr = 1
mdfcvl = 1
mdfcen = 1
mdfctb = 1
mdgcms = 40
mdwcms = 40
mdclmp = 0
mdrlmp = 0
mdlyclmp = 1

mdlyrlmp 1

1

STARS TIME STEP SUMMARY

=====

---Time Step---		-----Time-----		-----Production-----				--Injection--		Mat ---			
Maximum Changes---													
C	Oil	Gas	Water	GOR	Wat.	Gas	Water	Bal	Pres	Sat			
Temp	Size	U		m3	Cut	Err							
No.	days	IT	T	days	yy/mm/dd	m3/d	m3/d	m3/d	/m3	%	m3/d	m3/d	%
kPa	w/o/g	deg	C										

1	1.0e-2	1	1.0e-2	2009/01/01	1.011	17.72	17.53	1.936	8.e-9	1.268	0.0000w	8.9e-4	
2	2.3e-2	1	3.3e-2	2009/01/01	.9175	16.08	17.53	1.931	13e-9	2.061	0.0000w	1.9e-3	
3	5.3e-2	1	8.7e-2	2009/01/01	.8130	14.25	17.53	1.924	37e-9	2.776	0.0000w	4.2e-3	
4	.1250	1	.2122	2009/01/01	.7196	12.61	17.53	1.916	14e-8	3.170	0.0000w	9.2e-3	
5	.2892	1	.5014	2009/01/01	.6490	11.38	17.53	1.908	67e-8	3.302	0.0001w	2.0e-2	
6	.6689	1	1.170	2009/01/02	.6266	10.98	17.53	1.900	33e-7	3.420	0.0001w	4.7e-2	
7	1.547	1	2.717	2009/01/03	.7179	12.58	17.53	1.893	17e-6	3.999	0.0003w	.1080	
8	3.571	1	6.288	2009/01/07	.9778	17.14	17.53	1.885	87e-6	5.482	0.0007w	.2394	
9	8.212	1	14.50	2009/01/15	1.379	24.17	17.53	1.878	46e-5	7.430	0.0017w	.5378	
10	16.50	1	31.00	2009/02/01	1.749	30.66	17.53	1.884	19e-4	6.766	0.0033w	1.075	
11	28.00	1	59.00	2009/03/01	1.968	34.50	17.53	1.910	57e-4	4.099	0.0057w	1.808	
12	31.00	1	90.00	2009/04/01	2.059	36.10	17.53	1.941	10e-3	1.802	0.0064w	1.969	
13	30.00	1	120.0	2009/05/01	2.103	36.87	17.53	1.970	14e-3	.9334	0.0063w	1.864	
14	31.00	1	151.0	2009/06/01	2.132	37.38	17.53	1.998	18e-3	.6674	0.0066w	1.875	

15	30.00	1	181.0	2009/07/01	2.156	37.80	17.53	2.026	19e-3	.5872
0.0067w 1.769										
16	31.00	1	212.0	2009/08/01	2.181	38.23	17.53	2.053	24e-3	.6034
0.0071w 1.775										
17	31.00	1	243.0	2009/09/01	2.202	38.60	17.53	2.076	28e-3	.5010
0.0073w 1.720										
18	30.00	1	273.0	2009/10/01	2.218	38.88	17.53	2.094	32e-3	.3968
0.0073w 1.610										
19	31.00	1	304.0	2009/11/01	2.231	39.11	17.53	2.115	28e-3	.3223
0.0077w 1.605										
20	30.00	1	334.0	2009/12/01	2.246	39.37	17.53	2.135	30e-3	.3878
0.0078w 1.515										

1

STARS TIME STEP SUMMARY

```

=====
-----
---Time Step---- -----Time----- -----Production----- --Injection-- Mat ---
Maximum Changes---
      C          Oil Gas Water GOR  Wat. Gas Water Bal Pres Sat
Temp
      Size  U          m3  Cut      Err
No. days IT T days  yy/mm/dd  m3/d  m3/d  m3/d  /m3   %   m3/d  m3/d  %
kPa   w/o/g deg C
-----
21 31.00  1  365.0 2010/01/01 2.263 39.68   17.53   2.154 33e-3 .4419
0.0083w 1.518
22 31.00  1  396.0 2010/02/01 2.277 39.92   17.53   2.170 35e-3 .3509
0.0086w 1.470
23 28.00  1  424.0 2010/03/01 2.290 40.14   17.53   2.185 37e-3 .3191
0.0079w 1.291
24 31.00  1  455.0 2010/04/01 2.303 40.38   17.53   2.205 34e-3 .3411
0.0089w 1.391
25 30.00  1  485.0 2010/05/01 2.320 40.67   17.53   2.222 36e-3 .4317
0.0090w 1.321
26 31.00  1  516.0 2010/06/01 2.336 40.95   17.53   2.242 35e-3 .4082
0.0094w 1.334
27 30.00  1  546.0 2010/07/01 2.353 41.24   17.53   2.259 37e-3 .4283
0.0093w 1.262
28 31.00  1  577.0 2010/08/01 2.368 41.50   17.53   2.277 37e-3 .3790
0.0097w 1.274
29 31.00  1  608.0 2010/09/01 2.385 41.81   17.53   2.300 34e-3 .4595
0.0098w 1.247

```

30	30.00	1	638.0	2010/10/01	2.408	42.21	17.53	2.323	34e-3	.5799
0.0096w 1.200										
31	31.00	1	669.0	2010/11/01	2.430	42.60	17.53	2.347	33e-3	.5608
0.0099w 1.221										
32	30.00	1	699.0	2010/12/01	2.452	42.99	17.53	2.371	32e-3	.5647
0.0095w 1.164										
33	31.00	1	730.0	2011/01/01	2.478	43.43	17.53	2.399	30e-3	.6373
0.0098w 1.186										
34	31.00	1	761.0	2011/02/01	2.507	43.95	17.53	2.430	28e-3	.7521
0.0097w 1.173										
35	28.00	1	789.0	2011/03/01	2.537	44.46	17.53	2.460	28e-3	.7378
0.0087w 1.065										
36	31.00	1	820.0	2011/04/01	2.571	45.07	17.53	2.494	28e-3	.8666
0.0094w 1.174										
37	30.00	1	850.0	2011/05/01	2.604	45.65	17.53	2.527	28e-3	.8224
0.0089w 1.130										
38	31.00	1	881.0	2011/06/01	2.639	46.27	17.53	2.564	26e-3	.8832
0.0090w 1.164										
39	30.00	1	911.0	2011/07/01	2.681	47.00	17.53	2.607	26e-3	1.056
0.0085w 1.131										
40	31.00	1	942.0	2011/08/01	2.727	47.81	17.53	2.652	26e-3	1.155
0.0085w 1.178										
1										

STARS TIME STEP SUMMARY

```

=====
-----
---Time Step--- -----Time----- -----Production----- --Injection-- Mat ---
Maximum Changes---
          C           Oil Gas Water GOR  Wat. Gas Water Bal Pres Sat
Temp
          Size  U           m3  Cut           Err
          No. days IT T days  yy/mm/dd  m3/d  m3/d  m3/d  /m3  %  m3/d  m3/d  %
          kPa   w/o/g deg C
-----
41 31.00  1  973.0  2011/09/01  2.775  48.65  17.53  2.699  26e-3  1.186
0.0082w 1.187
42 30.00  1  1003  2011/10/01  2.821  49.46  17.53  2.745  26e-3  1.152
0.0076w 1.157
43 31.00  1  1034  2011/11/01  2.872  50.35  17.53  2.795  25e-3  1.273
0.0076w 1.205
44 30.00  1  1064  2011/12/01  2.925  51.27  17.53  2.847  24e-3  1.313
0.0070w 1.178

```

45	31.00	1	1095	2012/01/01	2.982	52.27	17.53	2.901	24e-3	1.415
0.0069w 1.240										
46	31.00	1	1126	2012/02/01	3.041	53.31	17.53	2.959	23e-3	1.483
0.0066w 1.258										
47	29.00	1	1155	2012/03/01	3.100	54.35	17.53	3.017	23e-3	1.483
0.0061w 1.193										
48	31.00	1	1186	2012/04/01	3.165	55.48	17.53	3.080	22e-3	1.612
0.0064w 1.296										
49	30.00	1	1216	2012/05/01	3.229	56.60	17.53	3.140	22e-3	1.603
0.0061w 1.270										
50	31.00	1	1247	2012/06/01	3.295	57.77	17.53	3.206	21e-3	1.654
0.0063w 1.340										
51	30.00	1	1277	2012/07/01	3.364	58.97	17.53	3.270	21e-3	1.722
0.0065w 1.326										
52	31.00	1	1308	2012/08/01	3.435	60.21	17.53	3.338	20e-3	1.778
0.0071w 1.397										
53	31.00	1	1339	2012/09/01	3.509	61.51	17.53	3.416	16e-3	1.872
0.0075w 1.421										
54	30.00	1	1369	2012/10/01	3.592	62.97	17.53	3.492	16e-3	2.105
0.0077w 1.419										
55	31.00	1	1400	2012/11/01	3.677	64.46	17.53	3.572	16e-3	2.133
0.0083w 1.498										
56	30.00	1	1430	2012/12/01	3.762	65.94	17.53	3.654	15e-3	2.114
0.0086w 1.480										
57	31.00	1	1461	2013/01/01	3.855	67.57	17.53	3.741	15e-3	2.343
0.0094w 1.572										
58	31.00	1	1492	2013/02/01	3.949	69.22	17.53	3.832	13e-3	2.362
0.0098w 1.610										
59	28.00	1	1520	2013/03/01	4.039	70.81	17.53	3.917	13e-3	2.275
0.0092w 1.504										
60	31.00	1	1551	2013/04/01	4.140	72.57	17.53	4.010	13e-3	2.523
0.0106w 1.708										

1

STARS TIME STEP SUMMARY

```

=====
-----
---Time Step--- -----Time----- -----Production----- --Injection-- Mat ---
Maximum Changes---
          C          Oil Gas Water GOR Wat. Gas Water Bal Pres Sat
Temp
          Size U          m3 Cut          Err

```

No. days IT T days yy/mm/dd m3/d m3/d m3/d /m3 % m3/d m3/d %
kPa w/o/g deg C

```

-----
 61 30.00  1 1581 2013/05/01 4.237 74.28    17.53    4.102 13e-3 2.443
0.0107w 1.690
 62 31.00  1 1612 2013/06/01 4.340 76.08    17.53    4.199 13e-3 2.584
0.0114w 1.785
 63 30.00  1 1642 2013/07/01 4.442 77.87    17.53    4.301 11e-3 2.568
0.0113w 1.763
 64 31.00  1 1673 2013/08/01 4.560 79.93    17.53    4.411 11e-3 2.944
0.0119w 1.876
 65 31.00  1 1704 2013/09/01 4.681 82.05    17.53    4.524 11e-3 3.031
0.0121w 1.927
 66 30.00  1 1734 2013/10/01 4.801 84.17    17.53    4.639 10e-3 3.000
0.0118w 1.912
 67 31.00  1 1765 2013/11/01 4.930 86.43    17.53    4.760 10e-3 3.201
0.0122w 2.037
 68 30.00  1 1795 2013/12/01 5.058 88.66    17.53    4.882 96e-4 3.170
0.0117w 2.020
 69 31.00  1 1826 2014/01/01 5.197 91.10    17.53    5.017 81e-4 3.468
0.0119w 2.142

```

Stopping end time reached time = 1826.00000 days 1 Jan 2014

it,it-nin,icytot,nrep2,mtfail,IMPES: 69 69 69 0 0 0%
iter_sol_tot: 425
Host Computer: iic1024pc11

Date and Time of End of Run: Oct 13, 2017 14:01:52

Elapsed Time to End of Run: 0 hr, 0 min, 5 sec

Opened LOG FILE on unit 10, filename is 'H:\My Documents\Desktop\Oveall Recovery\Steam quality\Basecase1-2.log'

```

*
*
*          STARS 2016.10
*
*  Advanced Process and Thermal Reservoir Simulator
*
*  General Release for Win x64
*
*  2016-Jul-04 11:18:17
*
*
*          (c) Copyright 1977 - 2016
*
*  Computer Modelling Group Ltd., Calgary, Canada
*

```

* All Rights Reserved *

Command-line Arguments: -dimsum

-wd H:\My Documents\Desktop\Oveall Recovery\Steam quality
-log
-f H:\My Documents\Desktop\Oveall Recovery\Steam quality\Basecase1-

2.dat

***** Input/Output files specification :**

Opened data file on unit 11, filename is 'H:\My Documents\Desktop\Oveall Recovery\Steam quality\Basecase1-2.dat'

Opened Scratch file on unit 12

Scanning data for dimensioning info . . .

GRID-XOFFSET 0.0000
GRID-YOFFSET 0.0000
GRID-ROTATION 0.0000
GRID-AXES-DIRECTIONS 1.0 -1.0 1.0

Done.

Summary of Dimensions Obtained from Data Scan

4 NCOMP - Number of components
4 NUMY - Number of fluid components
4 NUMX - Number of condensible components
1 MFORM - *TFORM flag: 1 for *SXY, 2 for *ZH, 3 for *ZT
1 NPTGN - Number of grids
360 NPTSS - Number of matrix blocks
360 NPTCS - Number of blocks including nulls
1 M9PT - *NINEPOINT flag: 1 - no, 2 - yes
3 NDIM - Number of dimensions (= 3 for *REFINE)
0 NREF - Number of refinements per fundamental block
0 MINC - Number of *MINC/*SUBDOMAIN subdivisions
30 NORTH - Number of orthogonalizations
0 NGAUSS - Bandwidth for *SDEGREE *GAUSS
15 NXSVAL - Number of special histories
Run is thermal

Opened output file on unit 13, filename is 'H:\My Documents\Desktop\Oveall Recovery\Steam quality\Basecase1-2.out'

Opened SR3-OUT on unit 14, filename is 'H:\My Documents\Desktop\Oveall Recovery\Steam quality\Basecase1-2.sr3'

Opened INDEX-OUT on unit 15, filename is 'H:\My Documents\Desktop\Oveall Recovery\Steam quality\Basecase1-2.irf'

Opened MAIN-RESULTS-OUT on unit 16, filename is 'H:\My Documents\Desktop\Oveall Recovery\Steam quality\Basecase1-2.mrf'

Opened GRID scratchfile on unit 17

===== SUMMARY (from subroutine: INDATA)

=====
 Reading of initial data is complete.
 Simulation will stop if there were error messages.
 0 Warning messages. 0 Error messages.

=====
 =====

Global Storage Usage

=====

Section	Bytes	Mbytes	# Objects
STARS	556778	0.531	785
GRMOD0	282844	0.270	445
SOLVINT	225388	0.215	101
ELECTRIC	68356	0.065	27
WMCOM1	54581	0.052	988
VISC	50388	0.048	71
KWCOM1	34719	0.033	48
POINT	28752	0.027	70
WELL	23468	0.022	245
RELPERM	11960	0.011	211
GRMOD1	10228	0.010	121
SR2WRT	8780	0.008	24
GLOBSTORE	7478	0.007	27
PRTCM	6900	0.007	17
SR2COM	6408	0.006	86
SECTOR	3624	0.003	70
PGMCH1	1446	0.001	241
CMGFILE	1184	0.001	18

WELHYD	556	0.001	51
KVAL	520	0.000	41
FLEXWEL	400	0.000	37
PSOLINT	288	0.000	62
GEOMECH	216	0.000	48
PGAIM	184	0.000	38
GRMOD2	124	0.000	30
REACT	68	0.000	13
ADSORP	68	0.000	17
WMCOM5	60	0.000	15
AQUIFER	36	0.000	6
WMCOM2	36	0.000	9
WMCOM4	32	0.000	8
COMPACT	16	0.000	4
PGMCH2	12	0.000	3
INGRDM	0	0.000	0

Total	1385898	1.322	3977

Dimensioning Parameters

- 360 MDPTSS - Matrix blocks, including nulls
- 360 MDPTCS - Total blocks, including nulls
- 360 MDPTPS - Total non-null blocks
- 1 MDPTGN - Grids (fundamental & refined)
- 1 MDNVAM - Sets of Volume/area modifiers
- 1442 MDNEXF - Exterior block faces
- 924 MDPTBC - Total interblock connections

- 4 NCOMP - Total components (fluid & solid)
- 4 NUMY - Fluid components
- 4 NUMX - Condensable components
- 5 NFLOW - Flowing items (fluids + energy)
- 0 NSLD - Solid components

- 1 NTHSET - Compressibility/thermal sets

- 1 NKROCK - Rel perm rock sets
- 1 NKRSET - Rel perm table sets
- 21 NKRTBD - Rel perm table size
- 11 NVSTBL - Viscosity tables

6 MDNEQ - Equations per block
363 MDSOL - Solver elements (blocks+wells+1)
2160 MDNEQT - Total grid equations
936 MDPTCN - Interblock & block-well connections
31 MDNOR - Orthogonalizations + 1
90 MDJCM - Connections per equation with fill
2809 MDCALP - Submatrices in the Jacobian matrix
0 MDALP - Size of Jacobian off-diagonal
0 MDALD - Size of Jacobian diagonal
0 MDBET - Size of RHS and solution vectors
0 MDV - Size of solution vector
0 MDDD - Diagonal entries
0 MDROW - Columns per equation
2809 MDICLU - 1 + Block entries in each of L & U
0 MDLU - Size of each of L & U
0 MDPROW - Size of PARASOL list arrays
90 MDPJCM - PARASOL row storage parameter

WM parameters - Dimensioner output

mdwell = 2
mdlayr = 12
mdly1w = 7
mdlypl = 1
mdgrup = 2
mdrgrp = 1
mdcons = 4
mdhyvl = 1
mdbhen = 100
mdhytb = 1
mdcygr = 1
mdcygp = 2
mdcygs = 2
mdcsgr = 1
mdfcvl = 1
mdfcen = 1
mdfctb = 1
mdgcms = 40
mdwcms = 40
mdclmp = 0
mdrlmp = 0
mdlyclmp = 1

Global Storage Usage

=====

Section	Bytes	Mbytes	# Objects
SOLVINT	1577396	1.504	112
STARS	556778	0.531	785
GRMOD0	282844	0.270	445
ELECTRIC	68356	0.065	27
WMCOM1	54581	0.052	988
VISC	50388	0.048	71
KWCOM1	34719	0.033	48
POINT	28752	0.027	70
WELL	23468	0.022	245
SR2COM	21080	0.020	87
RELPERM	11960	0.011	211
GRMOD1	10228	0.010	121
SR2WRT	8780	0.008	24
GLOBSTORE	7478	0.007	27
PRTCM	6900	0.007	17
SECTOR	3624	0.003	70
PGMCH1	1446	0.001	241
CMGFILE	1184	0.001	18
WELHYD	556	0.001	51
KVAL	520	0.000	41
EQTPAR	412	0.000	69
FLEXWEL	400	0.000	37
PSOLINT	360	0.000	75
GEOMECH	216	0.000	48
PGAIM	184	0.000	38
GRMOD2	124	0.000	30
ADSORP	68	0.000	17
REACT	68	0.000	13
WMCOM5	60	0.000	15
AQUIFER	36	0.000	6
WMCOM2	36	0.000	9
WMCOM4	32	0.000	8
COMPACT	16	0.000	4
PGMCH2	12	0.000	3
INGRDM	0	0.000	0

Total	2753062	2.626	4071
-------	---------	-------	------

Dimensioning Parameters

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1 NKRSET - Rel perm table sets
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363 MDSOL - Solver elements (blocks+wells+1)
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936 MDPTCN - Interblock & block-well connections
31 MDNOR - Orthogonalizations + 1
90 MDJCM - Connections per equation with fill
2809 MDCALP - Submatrices in the Jacobian matrix
55572 MDALP - Size of Jacobian off-diagonal
12962 MDALD - Size of Jacobian diagonal
2162 MDBET - Size of RHS and solution vectors
902 MDV - Size of solution vector
4502 MDDD - Diagonal entries
475 MDROW - Columns per equation
2809 MDICLU - 1 + Block entries in each of L & U
1192 NICLU - Used block entries of L/U
29440 MDLU - Size of each of L & U

475 MDPROW - Size of PARASOL list arrays
 90 MDPJCM - PARASOL row storage parameter

 WM parameters - Dimensioner output

mdwell = 2
 mdlayr = 12
 mdly1w = 7
 mdlypl = 1
 mdgrup = 2
 mdrgrp = 1
 mdcons = 4
 mdhyvl = 1
 mdbhen = 100
 mdhytb = 1
 mdcygr = 1
 mdcygp = 2
 mdcygs = 2
 mdcsg = 1
 mdfcvl = 1
 mdfcen = 1
 mdfctb = 1
 mdgcms = 40
 mdwcms = 40
 mdclmp = 0
 mdrlmp = 0
 mdlyclmp = 1
 mdlyrlmp = 1

1

STARS TIME STEP SUMMARY

=====
 =====
 ---Time Step--- -----Time----- -----Production----- --Injection-- Mat ---
 Maximum Changes---
 C Oil Gas Water GOR Wat. Gas Water Bal Pres Sat
 Temp
 Size U m3 Cut Err
 No. days IT T days yy/mm/dd m3/d m3/d m3/d /m3 % m3/d m3/d %
 kPa w/o/g deg C

1	1.0e-2	1	1.0e-2	2009/01/01	1.011	17.72	17.53	1.826	8.e-9	1.201
0.0000w 8.6e-4										
2	2.3e-2	1	3.3e-2	2009/01/01	.9175	16.08	17.53	1.821	12e-9	1.953
0.0000w 1.8e-3										
3	5.3e-2	1	8.7e-2	2009/01/01	.8130	14.25	17.53	1.815	34e-9	2.631
0.0000w 4.0e-3										
4	.1251	1	.2123	2009/01/01	.7195	12.61	17.53	1.807	13e-8	3.006
0.0000w 9.0e-3										
5	.2896	1	.5019	2009/01/01	.6486	11.37	17.53	1.800	62e-8	3.132
0.0001w 2.0e-2										
6	.6701	1	1.172	2009/01/02	.6240	10.94	17.53	1.793	31e-7	3.237
0.0001w 4.6e-2										
7	1.550	1	2.722	2009/01/03	.7070	12.39	17.53	1.787	16e-6	3.761
0.0003w .1058										
8	3.581	1	6.303	2009/01/07	.9486	16.63	17.53	1.780	80e-6	5.120
0.0007w .2348										
9	8.243	1	14.55	2009/01/15	1.323	23.19	17.53	1.776	42e-5	6.936
0.0016w .5285										
10	16.45	1	31.00	2009/02/01	1.667	29.22	17.53	1.783	17e-4	6.300
0.0031w 1.051										
11	28.00	1	59.00	2009/03/01	1.872	32.82	17.53	1.809	52e-4	3.850
0.0054w 1.774										
12	31.00	1	90.00	2009/04/01	1.959	34.34	17.53	1.839	95e-4	1.716
0.0061w 1.933										
13	30.00	1	120.0	2009/05/01	2.001	35.08	17.53	1.868	13e-3	.9083
0.0060w 1.832										
14	31.00	1	151.0	2009/06/01	2.030	35.58	17.53	1.895	17e-3	.6645
0.0063w 1.845										
15	30.00	1	181.0	2009/07/01	2.052	35.97	17.53	1.923	14e-3	.5248
0.0062w 1.736										
16	31.00	1	212.0	2009/08/01	2.077	36.41	17.53	1.949	18e-3	.6239
0.0068w 1.750										
17	31.00	1	243.0	2009/09/01	2.099	36.79	17.53	1.973	22e-3	.5332
0.0070w 1.698										
18	30.00	1	273.0	2009/10/01	2.117	37.10	17.53	1.993	25e-3	.4302
0.0069w 1.593										
19	31.00	1	304.0	2009/11/01	2.131	37.36	17.53	2.011	27e-3	.3653
0.0073w 1.591										
20	30.00	1	334.0	2009/12/01	2.145	37.60	17.53	2.032	27e-3	.3440
0.0074w 1.499										

1

STARS TIME STEP SUMMARY

=====													

---Time Step--- -----Time----- -----Production----- --Injection-- Mat ---													
Maximum Changes---													
C	Oil	Gas	Water	GOR	Wat.	Gas	Water	Bal	Pres	Sat			
Temp					m3	Cut	Err						
Size	U												
No.	days	IT	T	days	yy/mm/dd	m3/d	m3/d	m3/d	/m3	%	m3/d	m3/d	%
kPa	w/o/g	deg	C										

21	31.00	1	365.0	2010/01/01	2.162	37.90	17.53	2.052	31e-3	.4392			
0.0079w	1.506												
22	31.00	1	396.0	2010/02/01	2.178	38.17	17.53	2.069	34e-3	.3879			
0.0081w	1.461												
23	28.00	1	424.0	2010/03/01	2.189	38.37	17.53	2.084	33e-3	.2866			
0.0075w	1.285												
24	31.00	1	455.0	2010/04/01	2.203	38.61	17.53	2.100	33e-3	.3532			
0.0085w	1.382												
25	30.00	1	485.0	2010/05/01	2.219	38.89	17.53	2.119	36e-3	.4161			
0.0085w	1.311												
26	31.00	1	516.0	2010/06/01	2.234	39.16	17.53	2.137	36e-3	.3847			
0.0090w	1.326												
27	30.00	1	546.0	2010/07/01	2.250	39.45	17.53	2.155	38e-3	.4258			
0.0089w	1.256												
28	31.00	1	577.0	2010/08/01	2.266	39.73	17.53	2.172	40e-3	.4018			
0.0093w	1.271												
29	31.00	1	608.0	2010/09/01	2.280	39.97	17.53	2.190	38e-3	.3597			
0.0094w	1.243												
30	30.00	1	638.0	2010/10/01	2.299	40.30	17.53	2.212	36e-3	.4818			
0.0092w	1.189												
31	31.00	1	669.0	2010/11/01	2.321	40.68	17.53	2.235	36e-3	.5613			
0.0096w	1.212												
32	30.00	1	699.0	2010/12/01	2.341	41.04	17.53	2.257	36e-3	.5189			
0.0093w	1.157												
33	31.00	1	730.0	2011/01/01	2.364	41.43	17.53	2.281	34e-3	.5607			
0.0096w	1.181												
34	31.00	1	761.0	2011/02/01	2.388	41.86	17.53	2.307	32e-3	.6193			
0.0095w	1.165												
35	28.00	1	789.0	2011/03/01	2.414	42.31	17.53	2.335	31e-3	.6516			
0.0085w	1.042												
36	31.00	1	820.0	2011/04/01	2.444	42.85	17.53	2.366	30e-3	.7761			
0.0093w	1.160												

37	30.00	1	850.0	2011/05/01	2.476	43.41	17.53	2.397	30e-3	.8021
0.0089w 1.118										
38	31.00	1	881.0	2011/06/01	2.509	43.98	17.53	2.429	30e-3	.8160
0.0090w 1.151										
39	30.00	1	911.0	2011/07/01	2.540	44.53	17.53	2.462	28e-3	.7824
0.0085w 1.110										
40	31.00	1	942.0	2011/08/01	2.579	45.21	17.53	2.504	26e-3	.9760
0.0085w 1.149										

1

STARS TIME STEP SUMMARY

```

=====
-----
---Time Step--- -----Time----- -----Production----- --Injection-- Mat ---
Maximum Changes---
          C          Oil Gas Water GOR Wat. Gas Water Bal Pres Sat
Temp
          Size U          m3 Cut          Err
          No. days IT T days yy/mm/dd m3/d m3/d m3/d /m3 % m3/d m3/d %
          kPa w/o/g deg C
-----
41 31.00 1 973.0 2011/09/01 2.622 45.97 17.53 2.546 25e-3 1.085
0.0083w 1.157
42 30.00 1 1003 2011/10/01 2.667 46.75 17.53 2.588 25e-3 1.108
0.0078w 1.130
43 31.00 1 1034 2011/11/01 2.713 47.55 17.53 2.633 24e-3 1.144
0.0077w 1.178
44 30.00 1 1064 2011/12/01 2.759 48.37 17.53 2.678 24e-3 1.168
0.0072w 1.149
45 31.00 1 1095 2012/01/01 2.808 49.23 17.53 2.726 24e-3 1.210
0.0072w 1.192
46 31.00 1 1126 2012/02/01 2.860 50.13 17.53 2.777 23e-3 1.299
0.0069w 1.215
47 29.00 1 1155 2012/03/01 2.911 51.03 17.53 2.827 22e-3 1.273
0.0061w 1.152
48 31.00 1 1186 2012/04/01 2.969 52.04 17.53 2.884 21e-3 1.450
0.0064w 1.251
49 30.00 1 1216 2012/05/01 3.028 53.09 17.53 2.939 21e-3 1.494
0.0061w 1.229
50 31.00 1 1247 2012/06/01 3.090 54.16 17.53 2.998 21e-3 1.526
0.0062w 1.285
51 30.00 1 1277 2012/07/01 3.150 55.22 17.53 3.056 21e-3 1.508
0.0060w 1.268

```

52	31.00	1	1308	2012/08/01	3.215	56.37	17.53	3.118	21e-3	1.640
0.0064w 1.339										
53	31.00	1	1339	2012/09/01	3.282	57.53	17.53	3.182	20e-3	1.670
0.0068w 1.367										
54	30.00	1	1369	2012/10/01	3.349	58.71	17.53	3.247	20e-3	1.689
0.0070w 1.345										
55	31.00	1	1400	2012/11/01	3.422	59.99	17.53	3.320	18e-3	1.840
0.0076w 1.428										
56	30.00	1	1430	2012/12/01	3.500	61.35	17.53	3.393	18e-3	1.964
0.0077w 1.414										
57	31.00	1	1461	2013/01/01	3.582	62.80	17.53	3.471	17e-3	2.064
0.0085w 1.495										
58	31.00	1	1492	2013/02/01	3.667	64.28	17.53	3.552	16e-3	2.129
0.0090w 1.535										
59	28.00	1	1520	2013/03/01	3.748	65.70	17.53	3.627	16e-3	2.040
0.0085w 1.417										
60	31.00	1	1551	2013/04/01	3.840	67.32	17.53	3.714	16e-3	2.311
0.0098w 1.621										

1

STARS TIME STEP SUMMARY

```

=====
-----
---Time Step---- -----Time----- -----Production----- --Injection-- Mat ---
Maximum Changes---
          C          Oil Gas Water GOR Wat. Gas Water Bal Pres Sat
Temp
          Size U          m3 Cut          Err
          No. days IT T days yy/mm/dd m3/d m3/d m3/d /m3 % m3/d m3/d %
          kPa w/o/g deg C
-----
61 30.00 1 1581 2013/05/01 3.931 68.91 17.53 3.799 16e-3 2.277
0.0099w 1.610
62 31.00 1 1612 2013/06/01 4.026 70.57 17.53 3.888 16e-3 2.388
0.0106w 1.705
63 30.00 1 1642 2013/07/01 4.119 72.20 17.53 3.975 16e-3 2.326
0.0106w 1.687
64 31.00 1 1673 2013/08/01 4.216 73.91 17.53 4.070 15e-3 2.438
0.0113w 1.782
65 31.00 1 1704 2013/09/01 4.322 75.76 17.53 4.173 13e-3 2.662
0.0116w 1.819
66 30.00 1 1734 2013/10/01 4.433 77.71 17.53 4.276 13e-3 2.784
0.0114w 1.820

```

67 31.00 1 1765 2013/11/01 4.550 79.76 17.53 4.386 13e-3 2.931
0.0119w 1.932
68 30.00 1 1795 2013/12/01 4.668 81.82 17.53 4.496 12e-3 2.920
0.0117w 1.927
69 31.00 1 1826 2014/01/01 4.793 84.02 17.53 4.615 12e-3 3.107
0.0120w 2.043

Stopping end time reached time = 1826.00000 days 1 Jan 2014

it,it-nin,icytot,nrep2,mfail,IMPES: 69 69 69 0 0 0%

iter_sol_tot: 423

Host Computer: iic1024pc11

Date and Time of End of Run: Oct 13, 2017 14:03:33

Elapsed Time to End of Run: 0 hr, 0 min, 6 sec

Opened LOG FILE on unit 10, filename is 'H:\My Documents\Desktop\Oveall Recovery\Steam quality\Basecase1-3.log'

```

*
*
*          STARS 2016.10
*
*    Advanced Process and Thermal Reservoir Simulator
*
*    General Release for Win x64
*
*    2016-Jul-04 11:18:17
*
*
*    (c) Copyright 1977 - 2016
*
*    Computer Modelling Group Ltd., Calgary, Canada
*
*    All Rights Reserved
*
*

```

Command-line Arguments: -dimsum

-wd H:\My Documents\Desktop\Oveall Recovery\Steam quality

-log

-f H:\My Documents\Desktop\Oveall Recovery\Steam quality\Basecase1-

3.dat

***** Input/Output files specification :**

Opened data file on unit 11, filename is 'H:\My Documents\Desktop\Oveall Recovery\Steam quality\Basecase1-3.dat'

Opened Scratch file on unit 12

Scanning data for dimensioning info . . .

GRID-XOFFSET 0.0000
GRID-YOFFSET 0.0000
GRID-ROTATION 0.0000
GRID-AXES-DIRECTIONS 1.0 -1.0 1.0

Done.

Summary of Dimensions Obtained from Data Scan

4 NCOMP - Number of components
4 NUMY - Number of fluid components
4 NUMX - Number of condensible components
1 MFORM - *TFORM flag: 1 for *SXY, 2 for *ZH, 3 for *ZT
1 NPTGN - Number of grids
360 NPTSS - Number of matrix blocks
360 NPTCS - Number of blocks including nulls
1 M9PT - *NINEPOINT flag: 1 - no, 2 - yes
3 NDIM - Number of dimensions (= 3 for *REFINE)
0 NREF - Number of refinements per fundamental block
0 MINC - Number of *MINC/*SUBDOMAIN subdivisions
30 NORTH - Number of orthogonalizations
0 NGAUSS - Bandwidth for *SDEGREE *GAUSS
15 NXSVAL - Number of special histories
Run is thermal

Opened output file on unit 13, filename is 'H:\My Documents\Desktop\Oveall Recovery\Steam quality\Basecase1-3.out'

Opened SR3-OUT on unit 14, filename is 'H:\My Documents\Desktop\Oveall Recovery\Steam quality\Basecase1-3.sr3'

Opened INDEX-OUT on unit 15, filename is 'H:\My Documents\Desktop\Oveall Recovery\Steam quality\Basecase1-3.irf'

Opened MAIN-RESULTS-OUT on unit 16, filename is 'H:\My Documents\Desktop\Oveall Recovery\Steam quality\Basecase1-3.mrf'

Opened GRID scratchfile on unit 17

===== SUMMARY (from subroutine: INDATA)

=====

Reading of initial data is complete.

Simulation will stop if there were error messages.

0 Warning messages. 0 Error messages.

=====
=====

Global Storage Usage

=====
=====

Section	Bytes	Mbytes	# Objects
STARS	556778	0.531	785
GRMOD0	282844	0.270	445
SOLVINT	225388	0.215	101
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VISC	50388	0.048	71
KWCOM1	34719	0.033	48
POINT	28752	0.027	70
WELL	23468	0.022	245
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GRMOD1	10228	0.010	121
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GLOBSTORE	7478	0.007	27
PRTCM	6900	0.007	17
SR2COM	6408	0.006	86
SECTOR	3624	0.003	70
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CMGFILE	1184	0.001	18
WELHYD	556	0.001	51
KVAL	520	0.000	41
FLEXWEL	400	0.000	37
PSOLINT	288	0.000	62
GEOMECH	216	0.000	48
PGAIM	184	0.000	38
GRMOD2	124	0.000	30
REACT	68	0.000	13
ADSORP	68	0.000	17
WMCOM5	60	0.000	15
AQUIFER	36	0.000	6
WMCOM2	36	0.000	9
WMCOM4	32	0.000	8

COMPACT	16	0.000	4
PGMCH2	12	0.000	3
INGRDM	0	0.000	0

Total	1385898	1.322	3977

Dimensioning Parameters

360 MDPTSS - Matrix blocks, including nulls
360 MDPTCS - Total blocks, including nulls
360 MDPTPS - Total non-null blocks
1 MDPTGN - Grids (fundamental & refined)
1 MDNVAM - Sets of Volume/area modifiers
1442 MDNEXF - Exterior block faces
924 MDPTBC - Total interblock connections

4 NCOMP - Total components (fluid & solid)
4 NUMY - Fluid components
4 NUMX - Condensable components
5 NFLOW - Flowing items (fluids + energy)
0 NSLD - Solid components

1 NTHSET - Compressibility/thermal sets

1 NKROCK - Rel perm rock sets
1 NKRSET - Rel perm table sets
21 NKRTBD - Rel perm table size
11 NVSTBL - Viscosity tables

6 MDNEQ - Equations per block
363 MDSOL - Solver elements (blocks+wells+1)
2160 MDNEQT - Total grid equations
936 MDPTCN - Interblock & block-well connections
31 MDNOR - Orthogonalizations + 1
90 MDJCM - Connections per equation with fill
2809 MDCALP - Submatrices in the Jacobian matrix
0 MDALP - Size of Jacobian off-diagonal
0 MDALD - Size of Jacobian diagonal
0 MDBET - Size of RHS and solution vectors
0 MDV - Size of solution vector
0 MDDD - Diagonal entries
0 MDROW - Columns per equation

2809 MDICLU - 1 + Block entries in each of L & U
0 MDLU - Size of each of L & U
0 MDPROW - Size of PARASOL list arrays
90 MDPJCM - PARASOL row storage parameter

WM parameters - Dimensioner output

mdwell = 2
mdlayr = 12
mdly1w = 7
mdlypl = 1
mdgrup = 2
mdrgrp = 1
mdcons = 4
mdhyvl = 1
mdbhen = 100
mdhytb = 1
mdcygr = 1
mdcygp = 2
mdcygs = 2
mdcsgr = 1
mdfcvl = 1
mdfcen = 1
mdfctb = 1
mdgcms = 40
mdwcms = 40
mdclmp = 0
mdrlmp = 0
mdlyclmp = 1
mdlyrlmp = 1

Global Storage Usage

=====

Section	Bytes	Mbytes	# Objects
SOLVINT	1577396	1.504	112
STARS	556778	0.531	785
GRMOD0	282844	0.270	445
ELECTRIC	68356	0.065	27

WMCOM1	54581	0.052	988
VISC	50388	0.048	71
KWCOM1	34719	0.033	48
POINT	28752	0.027	70
WELL	23468	0.022	245
SR2COM	21080	0.020	87
RELPERM	11960	0.011	211
GRMOD1	10228	0.010	121
SR2WRT	8780	0.008	24
GLOBSTORE	7478	0.007	27
PRTCM	6900	0.007	17
SECTOR	3624	0.003	70
PGMCH1	1446	0.001	241
CMGFILE	1184	0.001	18
WELHYD	556	0.001	51
KVAL	520	0.000	41
EQTPAR	412	0.000	69
FLEXWEL	400	0.000	37
PSOLINT	360	0.000	75
GEOMECH	216	0.000	48
PGAIM	184	0.000	38
GRMOD2	124	0.000	30
ADSORP	68	0.000	17
REACT	68	0.000	13
WMCOM5	60	0.000	15
AQUIFER	36	0.000	6
WMCOM2	36	0.000	9
WMCOM4	32	0.000	8
COMPACT	16	0.000	4
PGMCH2	12	0.000	3
INGRDM	0	0.000	0

Total	2753062	2.626	4071

Dimensioning Parameters

360 MDPTSS - Matrix blocks, including nulls
360 MDPTCS - Total blocks, including nulls
360 MDPTPS - Total non-null blocks
1 MDPTGN - Grids (fundamental & refined)
1 MDNVAM - Sets of Volume/area modifiers
1442 MDNEXF - Exterior block faces

924 MDPTBC - Total interblock connections

4 NCOMP - Total components (fluid & solid)

4 NUMY - Fluid components

4 NUMX - Condensable components

5 NFLOW - Flowing items (fluids + energy)

0 NSLD - Solid components

1 NTHSET - Compressibility/thermal sets

1 NKROCK - Rel perm rock sets

1 NKRSET - Rel perm table sets

21 NKRTBD - Rel perm table size

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363 MDSOL - Solver elements (blocks+wells+1)

2160 MDNEQT - Total grid equations

936 MDPTCN - Interblock & block-well connections

31 MDNOR - Orthogonalizations + 1

90 MDJCM - Connections per equation with fill

2809 MDCALP - Submatrices in the Jacobian matrix

55572 MDALP - Size of Jacobian off-diagonal

12962 MDALD - Size of Jacobian diagonal

2162 MDBET - Size of RHS and solution vectors

902 MDV - Size of solution vector

4502 MDDD - Diagonal entries

475 MDROW - Columns per equation

2809 MDICLU - 1 + Block entries in each of L & U

1192 NICLU - Used block entries of L/U

29440 MDLU - Size of each of L & U

475 MDPROW - Size of PARASOL list arrays

90 MDPJCM - PARASOL row storage parameter

WM parameters - Dimensioner output

mdwell = 2
mdlayr = 12
mdly1w = 7
mdlypl = 1
mdgrup = 2
mdrgrp = 1

```

mdcons =      4
mdhyvl =      1
mdbhen =     100
mdhytb =      1
mdcygr =      1
mdcygp =      2
mdcygs =      2
mdcsgr =      1
mdfcvl =      1
mdfcen =      1
mdfctb =      1
mdgcms =     40
mdwcms =     40
mdclmp =      0
mdrlmp =      0
mdlyclmp     1
mdlyrlmp     1

```

1

STARS TIME STEP SUMMARY

```

=====
-----
---Time Step---- -----Time----- -----Production----- --Injection-- Mat ---
Maximum Changes---
          C          Oil Gas Water GOR Wat. Gas Water Bal Pres Sat
Temp
          Size U          m3 Cut          Err
          No. days IT T days yy/mm/dd m3/d m3/d m3/d /m3 % m3/d m3/d %
          kPa w/o/g deg C
-----
1 1.0e-2 1 1.0e-2 2009/01/01 1.011 17.72 17.53 1.727 7.e-9 1.141
0.0000w 8.4e-4
2 2.3e-2 1 3.3e-2 2009/01/01 .9175 16.08 17.53 1.723 11e-9 1.856
0.0000w 1.8e-3
3 5.4e-2 1 8.7e-2 2009/01/01 .8130 14.25 17.53 1.717 32e-9 2.502
0.0000w 4.0e-3
4 .1252 1 .2125 2009/01/01 .7195 12.61 17.53 1.710 12e-8 2.860
0.0000w 8.8e-3
5 .2899 1 .5024 2009/01/01 .6483 11.36 17.53 1.704 57e-8 2.980
0.0001w 1.9e-2
6 .6711 1 1.173 2009/01/02 .6217 10.90 17.53 1.698 28e-7 3.073
0.0001w 4.5e-2

```

7	1.553	1	2.727	2009/01/03	.6973	12.22	17.53	1.693	14e-6	3.548
0.0003w .1038										
8	3.590	1	6.317	2009/01/07	.9225	16.17	17.53	1.687	74e-6	4.794
0.0006w .2307										
9	8.271	1	14.59	2009/01/15	1.272	22.30	17.53	1.684	39e-5	6.490
0.0015w .5201										
10	16.41	1	31.00	2009/02/01	1.593	27.93	17.53	1.692	15e-4	5.882
0.0030w 1.029										
11	28.00	1	59.00	2009/03/01	1.786	31.31	17.53	1.717	48e-4	3.623
0.0051w 1.742										
12	31.00	1	90.00	2009/04/01	1.868	32.75	17.53	1.748	87e-4	1.637
0.0058w 1.901										
13	30.00	1	120.0	2009/05/01	1.909	33.47	17.53	1.776	12e-3	.8829
0.0057w 1.803										
14	31.00	1	151.0	2009/06/01	1.938	33.97	17.53	1.803	16e-3	.6590
0.0060w 1.818										
15	30.00	1	181.0	2009/07/01	1.960	34.35	17.53	1.829	15e-3	.5296
0.0059w 1.713										
16	31.00	1	212.0	2009/08/01	1.984	34.78	17.53	1.856	18e-3	.6052
0.0064w 1.727										
17	31.00	1	243.0	2009/09/01	2.006	35.17	17.53	1.880	22e-3	.5381
0.0066w 1.678										
18	30.00	1	273.0	2009/10/01	2.025	35.49	17.53	1.901	25e-3	.4506
0.0066w 1.577										
19	31.00	1	304.0	2009/11/01	2.041	35.77	17.53	1.919	29e-3	.3969
0.0070w 1.579										
20	30.00	1	334.0	2009/12/01	2.053	35.99	17.53	1.938	27e-3	.3060
0.0069w 1.479										
1										

STARS TIME STEP SUMMARY

```

=====
-----
---Time Step--- -----Time----- -----Production----- --Injection-- Mat ---
Maximum Changes---
      C           Oil  Gas  Water  GOR  Wat. Gas  Water  Bal  Pres  Sat
Temp
      Size  U           m3  Cut           Err
      No. days IT T days  yy/mm/dd  m3/d  m3/d  m3/d  /m3  %  m3/d  m3/d  %
kPa  w/o/g deg C
-----
21 31.00  1  365.0  2010/01/01  2.069  36.27  17.53  1.958  29e-3  .4167
0.0075w 1.495

```

22	31.00	1	396.0	2010/02/01	2.086	36.57	17.53	1.977	32e-3	.4286
0.0078w 1.453										
23	28.00	1	424.0	2010/03/01	2.099	36.80	17.53	1.991	34e-3	.3235
0.0072w 1.278										
24	31.00	1	455.0	2010/04/01	2.113	37.04	17.53	2.007	36e-3	.3569
0.0082w 1.377										
25	30.00	1	485.0	2010/05/01	2.125	37.25	17.53	2.024	33e-3	.2990
0.0080w 1.298										
26	31.00	1	516.0	2010/06/01	2.142	37.54	17.53	2.042	36e-3	.4394
0.0086w 1.319										
27	30.00	1	546.0	2010/07/01	2.156	37.79	17.53	2.060	34e-3	.3606
0.0085w 1.251										
28	31.00	1	577.0	2010/08/01	2.173	38.10	17.53	2.078	36e-3	.4450
0.0090w 1.267										
29	31.00	1	608.0	2010/09/01	2.189	38.37	17.53	2.094	38e-3	.3912
0.0091w 1.242										
30	30.00	1	638.0	2010/10/01	2.202	38.60	17.53	2.112	35e-3	.3382
0.0088w 1.177										
31	31.00	1	669.0	2010/11/01	2.223	38.97	17.53	2.134	35e-3	.5491
0.0093w 1.205										
32	30.00	1	699.0	2010/12/01	2.243	39.32	17.53	2.155	36e-3	.5020
0.0091w 1.152										
33	31.00	1	730.0	2011/01/01	2.263	39.67	17.53	2.177	35e-3	.5136
0.0094w 1.176										
34	31.00	1	761.0	2011/02/01	2.284	40.04	17.53	2.201	33e-3	.5394
0.0093w 1.162										
35	28.00	1	789.0	2011/03/01	2.306	40.42	17.53	2.224	31e-3	.5470
0.0084w 1.037										
36	31.00	1	820.0	2011/04/01	2.333	40.90	17.53	2.252	30e-3	.6955
0.0092w 1.139										
37	30.00	1	850.0	2011/05/01	2.362	41.40	17.53	2.281	29e-3	.7149
0.0088w 1.107										
38	31.00	1	881.0	2011/06/01	2.393	41.96	17.53	2.312	29e-3	.7985
0.0090w 1.141										
39	30.00	1	911.0	2011/07/01	2.424	42.49	17.53	2.342	29e-3	.7601
0.0085w 1.101										
40	31.00	1	942.0	2011/08/01	2.455	43.04	17.53	2.374	29e-3	.7861
0.0086w 1.135										

1

STARS TIME STEP SUMMARY

=====

=====

---Time Step---		-----Time-----		-----Production-----			--Injection--		Mat ---		
Maximum Changes---											
C	Oil	Gas	Water	GOR	Wat.	Gas	Water	Bal	Pres	Sat	
Temp											
Size	U		m3	Cut		Err					
No. days	IT T	days	yy/mm/dd	m3/d	m3/d	m3/d	/m3	%	m3/d	m3/d	%
kPa	w/o/g	deg C									
41	31.00	1	973.0	2011/09/01	2.488	43.61	17.53	2.413	23e-3	.8215	
0.0083w	1.133										
42	30.00	1	1003	2011/10/01	2.530	44.35	17.53	2.451	22e-3	1.061	
0.0079w	1.107										
43	31.00	1	1034	2011/11/01	2.574	45.11	17.53	2.493	23e-3	1.090	
0.0079w	1.154										
44	30.00	1	1064	2011/12/01	2.615	45.85	17.53	2.533	22e-3	1.039	
0.0074w	1.127										
45	31.00	1	1095	2012/01/01	2.662	46.66	17.53	2.576	23e-3	1.155	
0.0073w	1.174										
46	31.00	1	1126	2012/02/01	2.705	47.42	17.53	2.620	22e-3	1.071	
0.0071w	1.174										
47	29.00	1	1155	2012/03/01	2.749	48.20	17.53	2.665	21e-3	1.121	
0.0064w	1.107										
48	31.00	1	1186	2012/04/01	2.801	49.10	17.53	2.714	20e-3	1.291	
0.0065w	1.214										
49	30.00	1	1216	2012/05/01	2.853	50.01	17.53	2.766	18e-3	1.297	
0.0061w	1.191										
50	31.00	1	1247	2012/06/01	2.910	51.00	17.53	2.818	18e-3	1.425	
0.0062w	1.246										
51	30.00	1	1277	2012/07/01	2.963	51.95	17.53	2.871	17e-3	1.339	
0.0059w	1.220										
52	31.00	1	1308	2012/08/01	3.024	53.00	17.53	2.927	17e-3	1.513	
0.0061w	1.289										
53	31.00	1	1339	2012/09/01	3.084	54.06	17.53	2.985	16e-3	1.506	
0.0062w	1.314										
54	30.00	1	1369	2012/10/01	3.144	55.12	17.53	3.043	16e-3	1.519	
0.0063w	1.292										
55	31.00	1	1400	2012/11/01	3.210	56.27	17.53	3.105	16e-3	1.655	
0.0069w	1.364										
56	30.00	1	1430	2012/12/01	3.275	57.41	17.53	3.168	14e-3	1.622	
0.0070w	1.345										
57	31.00	1	1461	2013/01/01	3.347	58.67	17.53	3.239	13e-3	1.812	
0.0076w	1.435										
58	31.00	1	1492	2013/02/01	3.426	60.05	17.53	3.312	13e-3	2.000	
0.0080w	1.471										

59 28.00 1 1520 2013/03/01 3.498 61.32 17.53 3.380 13e-3 1.812
0.0077w 1.357
60 31.00 1 1551 2013/04/01 3.580 62.75 17.53 3.457 12e-3 2.052
0.0090w 1.538
1

STARS TIME STEP SUMMARY

=====

---Time Step--- -----Time----- -----Production----- --Injection-- Mat ---
Maximum Changes---
C Oil Gas Water GOR Wat. Gas Water Bal Pres Sat
Temp
Size U m3 Cut Err
No. days IT T days yy/mm/dd m3/d m3/d m3/d /m3 % m3/d m3/d %
kPa w/o/g deg C

61 30.00 1 1581 2013/05/01 3.662 64.20 17.53 3.534 12e-3 2.065
0.0091w 1.523
62 31.00 1 1612 2013/06/01 3.751 65.75 17.53 3.617 12e-3 2.224
0.0098w 1.629
63 30.00 1 1642 2013/07/01 3.838 67.27 17.53 3.699 12e-3 2.180
0.0099w 1.616
64 31.00 1 1673 2013/08/01 3.929 68.87 17.53 3.784 12e-3 2.295
0.0105w 1.710
65 31.00 1 1704 2013/09/01 4.022 70.50 17.53 3.872 11e-3 2.322
0.0110w 1.749
66 30.00 1 1734 2013/10/01 4.115 72.14 17.53 3.961 11e-3 2.353
0.0110w 1.725
67 31.00 1 1765 2013/11/01 4.220 73.98 17.53 4.062 10e-3 2.631
0.0116w 1.839
68 30.00 1 1795 2013/12/01 4.328 75.86 17.53 4.163 10e-3 2.689
0.0114w 1.829
69 31.00 1 1826 2014/01/01 4.444 77.89 17.53 4.271 99e-4 2.900
0.0118w 1.951

Stopping end time reached time = 1826.00000 days 1 Jan 2014

it,it-nin,icytot,nrep2,mf fail,IMPES: 69 69 69 0 0 0%
iter_sol_tot: 421
Host Computer: iic1024pc11

Date and Time of End of Run: Oct 13, 2017 14:04:42

4 NUMY - Number of fluid components
4 NUMX - Number of condensible components
1 MFORM - *TFORM flag: 1 for *SXY, 2 for *ZH, 3 for *ZT
1 NPTGN - Number of grids
360 NPTSS - Number of matrix blocks
360 NPTCS - Number of blocks including nulls
1 M9PT - *NINEPOINT flag: 1 - no, 2 - yes
3 NDIM - Number of dimensions (= 3 for *REFINE)
0 NREF - Number of refinements per fundamental block
0 MINC - Number of *MINC/*SUBDOMAIN subdivisions
30 NORTH - Number of orthogonalizations
0 NGAUSS - Bandwidth for *SDEGREE *GAUSS
15 NXSVAL - Number of special histories
Run is thermal

Opened output file on unit 13, filename is 'H:\My Documents\Desktop\Oveall Recovery\Steam quality\Basecase1-4.out'

Opened SR3-OUT on unit 14, filename is 'H:\My Documents\Desktop\Oveall Recovery\Steam quality\Basecase1-4.sr3'

Opened INDEX-OUT on unit 15, filename is 'H:\My Documents\Desktop\Oveall Recovery\Steam quality\Basecase1-4.irf'

Opened MAIN-RESULTS-OUT on unit 16, filename is 'H:\My Documents\Desktop\Oveall Recovery\Steam quality\Basecase1-4.mrf'

Opened GRID scratchfile on unit 17

===== SUMMARY (from subroutine: INDATA)

=====
Reading of initial data is complete.
Simulation will stop if there were error messages.
0 Warning messages. 0 Error messages.

=====

Global Storage Usage

=====

Section	Bytes	Mbytes	# Objects
STARS	556778	0.531	785
GRMOD0	282844	0.270	445
SOLVINT	225388	0.215	101

ELECTRIC	68356	0.065	27
WMCOM1	54581	0.052	988
VISC	50388	0.048	71
KWCOM1	34719	0.033	48
POINT	28752	0.027	70
WELL	23468	0.022	245
RELPERM	11960	0.011	211
GRMOD1	10228	0.010	121
SR2WRT	8780	0.008	24
GLOBSTORE	7478	0.007	27
PRTCM	6900	0.007	17
SR2COM	6408	0.006	86
SECTOR	3624	0.003	70
PGMCH1	1446	0.001	241
CMGFILE	1184	0.001	18
WELHYD	556	0.001	51
KVAL	520	0.000	41
FLEXWEL	400	0.000	37
PSOLINT	288	0.000	62
GEOMECH	216	0.000	48
PGAIM	184	0.000	38
GRMOD2	124	0.000	30
REACT	68	0.000	13
ADSORP	68	0.000	17
WMCOM5	60	0.000	15
AQUIFER	36	0.000	6
WMCOM2	36	0.000	9
WMCOM4	32	0.000	8
COMPACT	16	0.000	4
PGMCH2	12	0.000	3
INGRDM	0	0.000	0

Total	1385898	1.322	3977

Dimensioning Parameters

360 MDPTSS - Matrix blocks, including nulls
360 MDPTCS - Total blocks, including nulls
360 MDPTPS - Total non-null blocks
1 MDPTGN - Grids (fundamental & refined)
1 MDNVAM - Sets of Volume/area modifiers
1442 MDNEXF - Exterior block faces

924 MDPTBC - Total interblock connections

- 4 NCOMP - Total components (fluid & solid)**
- 4 NUMY - Fluid components**
- 4 NUMX - Condensable components**
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1 NTHSET - Compressibility/thermal sets

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- 1 NKRSET - Rel perm table sets**
- 21 NKRTBD - Rel perm table size**
- 11 NVSTBL - Viscosity tables**

6 MDNEQ - Equations per block

- 363 MDSOL - Solver elements (blocks+wells+1)**
- 2160 MDNEQT - Total grid equations**
- 936 MDPTCN - Interblock & block-well connections**
- 31 MDNOR - Orthogonalizations + 1**
- 90 MDJCM - Connections per equation with fill**
- 2809 MDCALP - Submatrices in the Jacobian matrix**
 - 0 MDALP - Size of Jacobian off-diagonal**
 - 0 MDALD - Size of Jacobian diagonal**
 - 0 MDBET - Size of RHS and solution vectors**
 - 0 MDV - Size of solution vector**
 - 0 MDDD - Diagonal entries**
 - 0 MDROW - Columns per equation**
- 2809 MDICLU - 1 + Block entries in each of L & U**
 - 0 MDLU - Size of each of L & U**
 - 0 MDPROW - Size of PARASOL list arrays**
 - 90 MDPJCM - PARASOL row storage parameter**

WM parameters - Dimensioner output

mdwell = 2
mdlayr = 12
mdly1w = 7
mdlypl = 1
mdgrup = 2
mdrgrp = 1
mdcons = 4

mdhyvl = 1
mdbhen = 100
mdhytb = 1
mdcygr = 1
mdcygp = 2
mdcygs = 2
mcdsgr = 1
mdfcvl = 1
mdfcen = 1
mdfctb = 1
mdgcms = 40
mdwcms = 40
mdclmp = 0
mdrlmp = 0
mdlyclmp = 1
mdlyrlmp = 1

Global Storage Usage

=====

Section	Bytes	Mbytes	# Objects
SOLVINT	1577396	1.504	112
STARS	556778	0.531	785
GRMOD0	282844	0.270	445
ELECTRIC	68356	0.065	27
WMCOM1	54581	0.052	988
VISC	50388	0.048	71
KWCOM1	34719	0.033	48
POINT	28752	0.027	70
WELL	23468	0.022	245
SR2COM	21080	0.020	87
RELPERM	11960	0.011	211
GRMOD1	10228	0.010	121
SR2WRT	8780	0.008	24
GLOBSTORE	7478	0.007	27
PRTCM	6900	0.007	17
SECTOR	3624	0.003	70
PGMCH1	1446	0.001	241
CMGFILE	1184	0.001	18
WELHYD	556	0.001	51
KVAL	520	0.000	41

EQTPAR	412	0.000	69
FLEXWEL	400	0.000	37
PSOLINT	360	0.000	75
GEOMECH	216	0.000	48
PGAIM	184	0.000	38
GRMOD2	124	0.000	30
ADSORP	68	0.000	17
REACT	68	0.000	13
WMCOM5	60	0.000	15
AQUIFER	36	0.000	6
WMCOM2	36	0.000	9
WMCOM4	32	0.000	8
COMPACT	16	0.000	4
PGMCH2	12	0.000	3
INGRDM	0	0.000	0

Total	2753062	2.626	4071

Dimensioning Parameters

- 360 MDPTSS - Matrix blocks, including nulls**
- 360 MDPTCS - Total blocks, including nulls**
- 360 MDPTPS - Total non-null blocks**
- 1 MDPTGN - Grids (fundamental & refined)**
- 1 MDNVAM - Sets of Volume/area modifiers**
- 1442 MDNEXF - Exterior block faces**
- 924 MDPTBC - Total interblock connections**

- 4 NCOMP - Total components (fluid & solid)**
- 4 NUMY - Fluid components**
- 4 NUMX - Condensable components**
- 5 NFLOW - Flowing items (fluids + energy)**
- 0 NSLD - Solid components**

- 1 NTHSET - Compressibility/thermal sets**

- 1 NKROCK - Rel perm rock sets**
- 1 NKRSET - Rel perm table sets**
- 21 NKRTBD - Rel perm table size**
- 11 NVSTBL - Viscosity tables**

- 6 MDNEQ - Equations per block**

363 MDSOL - Solver elements (blocks+wells+1)
2160 MDNEQT - Total grid equations
936 MDPTCN - Interblock & block-well connections
31 MDNOR - Orthogonalizations + 1
90 MDJCM - Connections per equation with fill
2809 MDCALP - Submatrices in the Jacobian matrix
55572 MDALP - Size of Jacobian off-diagonal
12962 MDALD - Size of Jacobian diagonal
2162 MDBET - Size of RHS and solution vectors
902 MDV - Size of solution vector
4502 MDDD - Diagonal entries
475 MDROW - Columns per equation
2809 MDICLU - 1 + Block entries in each of L & U
1192 NICLU - Used block entries of L/U
29440 MDLU - Size of each of L & U
475 MDPROW - Size of PARASOL list arrays
90 MDPJCM - PARASOL row storage parameter

WM parameters - Dimensioner output

mdwell = 2
mdlayr = 12
mdly1w = 7
mdlypl = 1
mdgrup = 2
mdrgrp = 1
mdcons = 4
mdhyvl = 1
mdbhen = 100
mdhytb = 1
mdcygr = 1
mdcygp = 2
mdcygs = 2
mdcsgr = 1
mdfcvl = 1
mdfcen = 1
mdfctb = 1
mdgcms = 40
mdwcms = 40
mdclmp = 0
mdrlmp = 0
mdlyclmp = 1

mdlyrlmp 1

1

STARS TIME STEP SUMMARY

```

=====
-----
---Time Step--- -----Time----- -----Production----- --Injection-- Mat ---
Maximum Changes---
          C          Oil Gas Water GOR Wat. Gas Water Bal Pres Sat
Temp
          Size U          m3 Cut          Err
          No. days IT T days yy/mm/dd m3/d m3/d m3/d /m3 % m3/d m3/d %
          kPa w/o/g deg C
-----
1 1.0e-2 1 1.0e-2 2009/01/01 1.011 17.72 17.53 1.638 6.e-9 1.088
0.0000w 8.2e-4
2 2.3e-2 1 3.3e-2 2009/01/01 .9175 16.08 17.53 1.634 10e-9 1.769
0.0000w 1.7e-3
3 5.4e-2 1 8.7e-2 2009/01/01 .8129 14.25 17.53 1.629 29e-9 2.386
0.0000w 3.9e-3
4 .1253 1 .2126 2009/01/01 .7194 12.61 17.53 1.623 11e-8 2.728
0.0000w 8.6e-3
5 .2902 1 .5028 2009/01/01 .6480 11.36 17.53 1.618 53e-8 2.843
0.0000w 1.9e-2
6 .6720 1 1.175 2009/01/02 .6196 10.86 17.53 1.612 26e-7 2.925
0.0001w 4.4e-2
7 1.556 1 2.731 2009/01/03 .6885 12.07 17.53 1.607 13e-6 3.355
0.0003w .1020
8 3.598 1 6.329 2009/01/07 .8988 15.76 17.53 1.603 69e-6 4.500
0.0006w .2270
9 8.297 1 14.63 2009/01/15 1.226 21.50 17.53 1.601 36e-5 6.088
0.0014w .5124
10 16.37 1 31.00 2009/02/01 1.527 26.76 17.53 1.610 14e-4 5.505
0.0028w 1.009
11 28.00 1 59.00 2009/03/01 1.708 29.94 17.53 1.635 44e-4 3.417
0.0049w 1.714
12 31.00 1 90.00 2009/04/01 1.786 31.32 17.53 1.665 79e-4 1.562
0.0055w 1.871
13 30.00 1 120.0 2009/05/01 1.826 32.01 17.53 1.693 11e-3 .8577
0.0054w 1.777
14 31.00 1 151.0 2009/06/01 1.854 32.50 17.53 1.720 14e-3 .6515
0.0057w 1.793

```

15	30.00	1	181.0	2009/07/01	1.876	32.89	17.53	1.744	15e-3	.5315
0.0056w 1.691										
16	31.00	1	212.0	2009/08/01	1.899	33.30	17.53	1.771	17e-3	.5734
0.0061w 1.706										
17	31.00	1	243.0	2009/09/01	1.922	33.69	17.53	1.795	21e-3	.5490
0.0063w 1.660										
18	30.00	1	273.0	2009/10/01	1.941	34.02	17.53	1.816	24e-3	.4673
0.0063w 1.562										
19	31.00	1	304.0	2009/11/01	1.958	34.32	17.53	1.836	27e-3	.4217
0.0067w 1.567										
20	30.00	1	334.0	2009/12/01	1.970	34.54	17.53	1.853	28e-3	.3072
0.0066w 1.470										
1										

STARS TIME STEP SUMMARY

```

=====
-----
---Time Step---- -----Time----- -----Production----- --Injection-- Mat ---
Maximum Changes---
      C          Oil Gas Water GOR Wat. Gas Water Bal Pres Sat
Temp
      Size U          m3 Cut      Err
      No. days IT T days yy/mm/dd m3/d m3/d m3/d /m3 % m3/d m3/d %
      kPa w/o/g deg C
-----
21 31.00 1 365.0 2010/01/01 1.985 34.80 17.53 1.873 28e-3 .3813
0.0072w 1.482
22 31.00 1 396.0 2010/02/01 2.003 35.11 17.53 1.892 30e-3 .4508
0.0074w 1.444
23 28.00 1 424.0 2010/03/01 2.017 35.35 17.53 1.908 32e-3 .3492
0.0069w 1.273
24 31.00 1 455.0 2010/04/01 2.030 35.59 17.53 1.924 33e-3 .3351
0.0078w 1.373
25 30.00 1 485.0 2010/05/01 2.043 35.82 17.53 1.939 34e-3 .3416
0.0077w 1.296
26 31.00 1 516.0 2010/06/01 2.057 36.05 17.53 1.957 32e-3 .3398
0.0081w 1.306
27 30.00 1 546.0 2010/07/01 2.073 36.33 17.53 1.973 34e-3 .4107
0.0082w 1.247
28 31.00 1 577.0 2010/08/01 2.088 36.60 17.53 1.992 33e-3 .3908
0.0086w 1.265
29 31.00 1 608.0 2010/09/01 2.105 36.89 17.53 2.009 35e-3 .4263
0.0088w 1.241

```

30	30.00	1	638.0	2010/10/01	2.119	37.14	17.53	2.024	36e-3	.3655
0.0086w 1.178										
31	31.00	1	669.0	2010/11/01	2.134	37.41	17.53	2.043	33e-3	.3829
0.0089w 1.195										
32	30.00	1	699.0	2010/12/01	2.154	37.75	17.53	2.064	34e-3	.5145
0.0088w 1.148										
33	31.00	1	730.0	2011/01/01	2.174	38.10	17.53	2.085	34e-3	.5050
0.0091w 1.173										
34	31.00	1	761.0	2011/02/01	2.193	38.45	17.53	2.106	33e-3	.4973
0.0091w 1.159										
35	28.00	1	789.0	2011/03/01	2.212	38.77	17.53	2.127	31e-3	.4710
0.0082w 1.036										
36	31.00	1	820.0	2011/04/01	2.235	39.18	17.53	2.151	30e-3	.5992
0.0090w 1.135										
37	30.00	1	850.0	2011/05/01	2.261	39.63	17.53	2.178	29e-3	.6474
0.0087w 1.090										
38	31.00	1	881.0	2011/06/01	2.289	40.13	17.53	2.207	28e-3	.7109
0.0089w 1.131										
39	30.00	1	911.0	2011/07/01	2.319	40.65	17.53	2.236	28e-3	.7492
0.0085w 1.093										
40	31.00	1	942.0	2011/08/01	2.350	41.19	17.53	2.266	28e-3	.7674
0.0086w 1.127										
1										

STARS TIME STEP SUMMARY

```

=====
-----
---Time Step--- -----Time----- -----Production----- --Injection-- Mat ---
Maximum Changes---
      C          Oil Gas Water GOR  Wat. Gas Water Bal Pres Sat
Temp
      Size  U          m3  Cut          Err
      No. days IT T days  yy/mm/dd  m3/d  m3/d  m3/d  /m3  %  m3/d  m3/d  %
      kPa   w/o/g deg C
-----
41 31.00  1  973.0 2011/09/01 2.380 41.72  17.53  2.296 28e-3 .7566
0.0084w 1.125
42 30.00  1 1003 2011/10/01 2.410 42.25  17.53  2.331 23e-3 .7613
0.0079w 1.087
43 31.00  1 1034 2011/11/01 2.451 42.96  17.53  2.369 23e-3 1.031
0.0080w 1.132
44 30.00  1 1064 2011/12/01 2.491 43.66  17.53  2.407 23e-3 .9976
0.0075w 1.105

```

45	31.00	1	1095	2012/01/01	2.532	44.39	17.53	2.446	23e-3	1.027
0.0075w 1.153										
46	31.00	1	1126	2012/02/01	2.573	45.11	17.53	2.486	23e-3	1.030
0.0072w 1.154										
47	29.00	1	1155	2012/03/01	2.613	45.80	17.53	2.525	22e-3	.9793
0.0065w 1.086										
48	31.00	1	1186	2012/04/01	2.658	46.59	17.53	2.570	21e-3	1.135
0.0067w 1.172										
49	30.00	1	1216	2012/05/01	2.705	47.42	17.53	2.614	21e-3	1.182
0.0062w 1.158										
50	31.00	1	1247	2012/06/01	2.755	48.29	17.53	2.662	21e-3	1.245
0.0062w 1.214										
51	30.00	1	1277	2012/07/01	2.805	49.16	17.53	2.710	21e-3	1.248
0.0059w 1.187										
52	31.00	1	1308	2012/08/01	2.857	50.09	17.53	2.761	20e-3	1.317
0.0060w 1.242										
53	31.00	1	1339	2012/09/01	2.914	51.08	17.53	2.815	20e-3	1.424
0.0060w 1.267										
54	30.00	1	1369	2012/10/01	2.969	52.05	17.53	2.866	20e-3	1.386
0.0058w 1.252										
55	31.00	1	1400	2012/11/01	3.026	53.05	17.53	2.923	19e-3	1.430
0.0063w 1.312										
56	30.00	1	1430	2012/12/01	3.087	54.12	17.53	2.980	19e-3	1.535
0.0064w 1.299										
57	31.00	1	1461	2013/01/01	3.151	55.24	17.53	3.041	18e-3	1.600
0.0070w 1.368										
58	31.00	1	1492	2013/02/01	3.219	56.44	17.53	3.106	17e-3	1.724
0.0074w 1.408										
59	28.00	1	1520	2013/03/01	3.283	57.56	17.53	3.167	17e-3	1.608
0.0070w 1.304										
60	31.00	1	1551	2013/04/01	3.358	58.87	17.53	3.238	16e-3	1.886
0.0081w 1.479										

1

STARS TIME STEP SUMMARY

```

=====
-----
---Time Step---- -----Time----- -----Production----- --Injection-- Mat ---
Maximum Changes---
          C          Oil Gas Water GOR Wat. Gas Water Bal Pres Sat
Temp
          Size  U          m3  Cut          Err

```

No. days IT T days yy/mm/dd m3/d m3/d m3/d /m3 % m3/d m3/d %
kPa w/o/g deg C

```

-----
 61 30.00  1 1581 2013/05/01 3.433 60.17    17.53    3.307 16e-3 1.864
0.0084w 1.464
 62 31.00  1 1612 2013/06/01 3.513 61.58    17.53    3.380 17e-3 2.013
0.0091w 1.550
 63 30.00  1 1642 2013/07/01 3.591 62.95    17.53    3.456 16e-3 1.960
0.0092w 1.543
 64 31.00  1 1673 2013/08/01 3.677 64.45    17.53    3.536 16e-3 2.156
0.0099w 1.638
 65 31.00  1 1704 2013/09/01 3.764 65.98    17.53    3.617 15e-3 2.196
0.0103w 1.680
 66 30.00  1 1734 2013/10/01 3.850 67.50    17.53    3.699 15e-3 2.165
0.0102w 1.661
 67 31.00  1 1765 2013/11/01 3.942 69.11    17.53    3.785 15e-3 2.304
0.0110w 1.756
 68 30.00  1 1795 2013/12/01 4.034 70.71    17.53    3.875 13e-3 2.297
0.0110w 1.736
 69 31.00  1 1826 2014/01/01 4.139 72.55    17.53    3.972 13e-3 2.637
0.0116w 1.860

```

Stopping end time reached time = 1826.00000 days 1 Jan 2014

it,it-nin,icytot,nrep2,mtfail,IMPES: 69 69 69 0 0 0%

iter_sol_tot: 417

Host Computer: iic1024pc11

Date and Time of End of Run: Oct 13, 2017 14:05:41

Elapsed Time to End of Run: 0 hr, 0 min, 7 sec