OCCUPATIONAL HEALTH AND THE ANALYTICAL AND NUMERICAL MODELING OF AIRFLOW PATTERNS IN THE INDUSTRIAL ENVIRONMENT

BRAD J. PELLEY

Occupational Health and the Analytical and Numerical Modeling of Airflow Patterns in the Industrial Environment

by

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Abstract

Possibly the world's first research on breathing problems among snow crab processing workers took place in Newfoundland in the 1970's. Preventing/mitigating these problems is of paramount importance as the snow crab industry is a major contributor to the regional economy in rural Newfoundland and Labrador communities. Crab asthma is caused by overexposure to the dusts, mists, fumes or aerosols that are generated during various processes. During these processes, proteins in the crab may become airborne and can enter the lungs and breathing tubes. A recent study suggests that very low levels of allergen will need to be achieved in crab processing plants to prevent respiratory symptoms from occurring among sensitized workers. Prior to the study described in this report, there had been no air sampling of allergen levels in snow crab processing plants in Newfoundland and Labrador. Air sampling has been carried out in four crab processing plants in Newfoundland and Labrador to identify the problematic areas. Allergen contamination concentrations have been identified and related to specific areas of the processing plants and to the individual processes themselves.

A variety of ventilation methods have been examined with local exhausting of the workplace comprising the majority of the investigated techniques. Centerline velocity profiles for overhead, slotted, and canopy local exhaust hoods proposed in previous research have been examined. Numerical modeling of the cleaning, sawing, and batch cooling processes was carried out in both an idealistic and realistic plant domain to determine the airflow patterns in and around these individual processes, as well as determining possible capture velocities from imposed velocity profiles. Velocity profiles have been obtained for the space in the vicinity of the hood face rather than just along the centerline. Velocity and pressure contours were also determined to ascertain the degree of contaminant capture. All numerical results for idealistic and realistic plant environments have been investigated, discussed, and presented.

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This work would not have been possible without the support and contributions of a select few.

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Nomenclature

PBZ = Personal Breathing Zone
HVAC = Heating, Ventilation, and Air Conditioning
PDE = Partial Differential Equation
FVM = Finite Volume Method
μ = dynamic viscosity
ρ = density, kg/m^3
m= mass flow, kg/s
τ_{xx} = partial u/partial x
g = gravity, m/s^2
u = velocity in the x-direction, m/s
v = velocity in the y-direction, m/s
w = velocity in the z-direction, m/s
φ = velocity potential
p = pressure, kPa
ω = particle rotation
ν = kinematic viscosity
ψ = stream function
Q = volumetric Flow Rate, m^3/s
A_f = hood face area, m^2
L_e = effective length, m
R = hood radius, m
V_{max} = maximum velocity along hood centerline, m/s
P = hood face perimeter, m
D = height of a canopy hood above the process, m
V_c = capture Velocity, m/s
V_f = hood Face Velocity, m/s
V_x = velocity at a distance x from the hood face, m/s
x = vertical distance from source to hood face, m
w = hood face width, m
L = hood face length, m
FTP = fan total pressure, kPa
FSP = fan static pressure, kPa
TP = total pressure, kPa
SP = static pressure, kPa
VP = velocity pressure, kPa
C_o = concentration at the source, ng/m^3
C_x = concentration at a distance x from the source, ng/m^3
D = coefficient of turbulent diffusion
OH = Overhead
Slot = Slotted
Can = Canopy
Fl = Flanged
W = Worker Interaction
Dyn = Dynamic

Chapter 1

Introduction

The need for a clean, comfortable and safe environment for people to work and live in is a common necessity worldwide. Providing a comfortable and healthy indoor environment for building occupants is the primary concern of Heating, Ventilation and Air Conditioning (HVAC) engineers. Virtually every residential, commercial, industrial, and institutional building in every industrial country of the world has some sort of HVAC system in place to control the working environment year round. As a result the heating, ventilation, and air conditioning industry continues to grow each year as new factories, laboratories, and offices are constructed.

The quality of indoor air is increasingly being recognized as an essential factor for overall health and comfort because up to 90% of a typical person's time is spent indoors and a large fraction of that time is spent in a residential or commercial environment (Chen 1992). Health concerns, coupled with ever increasing energy costs demand that companies closely control their working environment without wasting unnecessary money and manpower. To accomplish this a better understanding of the design parameters that govern comfort and indoor air quality (IAQ) are essential to good HVAC system design. For example, supply of acceptable air, removal of unacceptable air, proper operation and maintenance of building systems, probable airflow patterns inside and outside the enclosure, and control of internal and external pollutants are just a few important design considerations that need to be examined. While building structures become increasingly complex, the basics of good HVAC system design have not changed, only the methods and tools available to accomplish the design (McQuiston et al. 1988). Traditionally, HVAC system designs have been examined and evaluated via expensive and time-consuming physical methods such as wind tunnel testing. The study of full scale systems using controlled experiments is often difficult or impossible due to economic constraints and drastically increased analysis times associated with physical testing. These problems have been partially addressed by implementing a Computational Fluid Dynamic, or CFD approach. Simply put, CFD is mainly the analysis of systems involving heat transfer and fluid flow by means of a computer-based simulation. Fluid dynamic modeling can be used to identify ventilation problems in existing installed systems and aid in the design and implementation of new systems.

Over the past decade there has been a global increase in the use of computational fluid dynamics in a wide range of industrial settings evoking numerous applications. Recent advances in CFD technology combined with the surging growth of computer resources have resulted in CFD becoming an attractive analysis method and design tool for many industries worldwide. CFD techniques are now being used to either augment or totally replace complicated physical experimentation due to the high obtainable degree of accuracy at a fraction of the cost. According to (Horstman 1988) a method has been developed that predicts the velocity distribution, airflow circulation pattern, and airborne contamination distribution within a ventilated volume. Although the ventilated volume described in this case applies to an aircraft passenger cabin, the work presented in this thesis will use similar techniques and apply them to typical industrial plant processes encountered in the snow crab industry in Newfoundland and Labrador.

The main focus of the research presented here makes use of experimental and theoretical data, as well as numerical simulations produced using current CFD techniques to determine air flow patterns, velocity distributions, pressure distributions, and species transport characteristics. The ultimate goal is to use this information to try and identify velocity distributions in and around local exhaust hoods and processing equipment to help develop control methodologies that can be implemented in the snow crab industry. After a review of the applicable numerical and empirical literature it was decided that a finite volume method for CFD analysis to determine the airflow characteristics would be applied. Commercial CFD packages such as Fluent make use of the finite volume method which can approximate the complex governing equations of fluid and heat flow with relative ease using numerical methods techniques. While the mathematical techniques involved are not new, the governing equations are still too complex to be solved without utilizing a CFD package such as Fluent.

A well known commercial CFD code was ultimately chosen to carry out this portion of the study due to its availability to the public, up to date revisions, and wide range of users in a vast array of disciplines thus providing an excellent database of help and guidance. The chosen code was Fluent (v6.0) due to its ability to perform approximations with the discretized Reynolds Averaged Navier-Stokes (RANS) equations and its treatment of viscous effects and turbulence. In addition, this program has the ability to trace particles embedded in air streams and can determine the nature of their movement in response to varying air flow patterns, pressure variations, temperature gradients, and variations in relative humidity. This is particularly important in the snow crab industry in which aerosolized proteins from the meat and shell of the crab and other biological and chemical toxins are thought to have a strong correlation to cases of snow crab occupational asthma.

1.1 Problem Discussion

Snow crab occupational asthma (OA) is mediated through an allergic mechanism involving the production of specific antibodies to an allergen. The allergen thought to cause snow crab OA is found in the meat, shell, cooking water, steam and most likely the water vapor produced during the processing of snow crab (Ortega and Berardinelli 1998). The mechanism of sensitization is either via inhalation of the aerosolized allergens or tactile contact with the skin and eyes when butchering, cooking, steaming, crushing and cleaning the crab in processing plants. Published studies to date have not included a full analysis of plant enclosures with respect to airflow patterns, contaminant concentrations and associated ventilation systems or lack thereof. The work presented in this thesis looks mainly at the airflow patterns within a typical crab processing plant, how they are affected by turbulent structures and how they facilitate contaminant transport. This research was carried out as a part of a 3-year interdisciplinary study on snow crab OA in Newfoundland and Labrador, Canada. The crab asthma project has several major components;

- self-administered questionnaires on beliefs and concerns about the health effects of working with crab among management, workers and health professionals
- training sessions with health professionals related to the diagnosis and treatment of asthma and occupational asthma
- air sampling to confirm allergen levels in different areas of participating plants and between plants with different layouts, and processing and ventilation systems
- research comparing allergen levels associated with processing crab raw versus processing crab cooked

- numerical modeling of air flows in typical plant environments and incorporating different process technologies designs to help identify ways to reduce allergen exposures
- chemical research on the composition of aerosolized proteins associated with crab processing
- immunological research comparing reactivity to proteins in raw and cooked crab in the sera of sensitized participants
- research comparing the prevalence of allergy to and occupational asthma to snow crab in the four participating plants and risk factors for the development of these conditions
- research on reported factors affecting compliance with the peak expiratory flow protocol used in the study
- and research on the quality of life and social and economic impacts of allergy and occupational asthma to snow crab in the study communities

An interdisciplinary approach helps to ensure a robust research approach.

This thesis reports on an investigation into the velocity distribution, airflow circulation pattens, and airborne contamination generation and distribution within an enclosed volume (snow crab plant). In the past it has been difficult to accurately predict the effectiveness of designed ventilation systems, mainly due to the complex interaction of the system components with objects in the ventilated space (Horstman 1988). In instances when a formal mechanical ventilation system is not present as is the case in some of the crab plants the difficulties are similar to the ones proposed by Horstman. It is the goal of this research to identify velocity distributions and airflow circulation patterns present in a 'typical plant', determine their effect on airborne contaminants and explore local and general contaminant control methodologies. To achieve this goal a computer numerical simulation approach has been undertaken in conjunction with an analysis of the building envelope as it pertains to HVAC design considerations.

A commercial CFD package was used to meet the requirements for this component rather than attempting to develop a specific CFD code. Since development of a specialized code was not the intent of this research a commercial package was indeed capable of examining the problem at hand. The CFD software chosen was Fluent (v6.0) and associated geometry generation program Gambit(v1.3). This software is used in a variety of industries such as biomedical, oil and gas, automotive, aerospace and HVAC. Fluent utilizes the finite volume method to integrate the governing equations and discretize whereby approximations are substituted for terms in the integrated equation representing flow processes, converts the integral equations into a system of algebraic equations, and then solves the algebraic equations using an iterative approach. Application of these methods is necessary to attain the required airflow data needed to describe flow characteristics in a typical plant.

In summary, the primary objectives of the air sampling and ventilation components of the crab asthma study that will be examined are;

1. identify concentrations of allergens in different areas of participating crab plants consisting of different layouts, ventilation systems, process technologies and end products in order to improve the existing knowledge regarding processes that contribute to aerosolization and influence allergen concentrations;

2. assess levels of exposure to known chemical respiratory irritants (sulfites) associated with snow crab processing;

3. map exposures to allergens onto the processing layout of these plants and link

them to the prevalence of OA to snow crab within the plant labour forces;

4. compare allergen concentrations with overall production concentrations and different end products during the time of air sampling;
5. document temperature and humidity concentrations in the plants during the air sampling period and correlate with allergen sampling results;
6. identify any ventilation systems present and assess air flows in different areas of the plants;
7. identify potential sources of allergens and potential movement of allergens within the plants;
8. numerically model airflows around local hood configurations to determine their contaminant capturing ability;
9. develop recommendations on plant design, production process design and on a ventilation system that should reduce concentrations of air borne allergens in the plant;
10. where employers carry out recommended changes in their plants, reassess allergen concentrations in the wake of these changes;
11. to conduct an experiment comparing yields and allergen levels associated with the cleaning and sawing of raw versus cooked crab sections.

1.2 Previous Research

Possibly the world's first research on breathing problems among snow crab processing workers took place in Newfoundland in the 1970's but there was little follow-up in Newfoundland to that original work. In 1984, Dr. Andre Cartier, a respirologist from Hopital Sacre Coeur in Montreal headed up a study of snow crab processing workers on the Magdalene Islands. In plants that had been operating for about three years with little ventilation and where cookers were not enclosed and separately ventilated this study found approximately 15% of processing workers had occupational asthma to snow crab.

The Quebec researchers identified the health problem experienced by workers as a form of occupational asthma caused by sensitization to an allergen aerosolized during the cooking and possibly other manipulation of the snow crab during processing. They recommended cooling of the cooked crab prior to processing and enclosing and separately venting the cooking processes. In response to that research, Quebec put in place plant inspections and requirements for enclosing cooking areas, cooling cooked crab prior to processing, and a system for the detection, diagnosis and compensation of occupational asthma to snow crab among processing workers (Neis 1995).

A recent study suggests that very low levels of allergen will need to be achieved in crab processing plants to prevent respiratory symptoms from occurring among sensitized workers. This study, done in an open-air fish market, found detectable concentrations of fish allergen linked to respiratory symptoms among people with fish allergies. These allergens were aerosolized through passive evaporation from fish that were on display (i.e. they were not being cooked or processed) (Taylor et al. 2000).

Ortega and Berardinelli describe a study undertaken in a crab processing facility in Dutch Harbor, Alaska in 1999. Management was concerned about respiratory illness among workers in the form of bronchitis and asthma. The study objectives were to understand the nature of the illness, identify contamination sources, identify relationships between processing exposures and health outcomes, and to develop strategies to prevent further illness. Although the study was somewhat limited due to the relatively small size of the sample population, collected data provided some interesting results. Development of new respiratory problems and asthma among various crab processing workers over 6 weeks of crab processing was evident and seemed to be occupationally linked. Investigation into the concentration of antigens measured in a crab processing factory by Griffin et al (1994) showed that 23% of workers had work-related respiratory symptoms and 37% of the workers had IgE antibodies specific for crab meat extract. Using high volume air samplers cutting, grinding and mincing operations produced antigens as high as 115 ng/m^3 in comparison to a maximum of 4 ng/m^3 in areas where no operations were present.

A system for air sampling allergens in snow crab processing plants was developed by Mark Swanson at the Mayo clinic in Rochester, Minnesota, USA. Since the development of this technique Mr. Swanson has analyzed air samples taken in a wide variety of different snow crab processing environments and contexts including Alaska, Quebec and elsewhere. These studies have included snow crab processing plants and snow crab processing on board factory freezer trawlers. Published results from one study conducted in Quebec in the late 1990s show peak allergen concentrations at approximately 5,000 ng/m^3 from personal air filters in the butchering (crab cracking) area of the plant. The next highest concentrations were near the outlet of the cooling basin (604 ng/m^3), followed by the sorting and cleaning areas (approximately 200 ng/m^3 (Weytjens et al. 1999)). In that study, the sample for the butchering area was taken in the area adjacent to the cooker. The cooker was separated from the butchering area by a plastic curtain (Malo et al 1997). This and other published studies of allergen levels associated with snow crab processing have not included sufficient information on enclosures, airflows and the ventilation systems in the plants involved making it difficult to isolate the origins of allergens identified in air samples. Allergen levels associated with different production processes have also not been studied systematically.

HVAC system literature that is based on the premise that the systems themselves act as contaminant emission sources that affect Indoor Air Quality (IAQ) has been evaluated by Batterman et al (1995). Several HVAC components are cited frequently as emission sources that include biological growth and bioaerosol generation in the presence of moisture generated as a result of a number of factors such as poorly designed humidifying systems or just poor control of the humidity. Other problems have been identified such as migration of contaminants, entrainment, and infiltration of both outdoor and indoor pollutants. With this in mind, the importance of understanding the mechanics of room airflows is of paramount importance. Chen (1992) developed appropriate models for the prediction of room air motion using both computational results and experimental data. It proved difficult to determine whether or not a room airflow was a local artificially induced turbulent airflow, transitional airflow, or fully developed airflow. However, very few room airflows are actually laminar thus more work needed to be done with particular attention paid to turbulent structures and their interaction with room airflows.

The use of Computational Fluid Dynamic modeling in specific shellfish allergen types of ventilation situations can be compared to its previous use in a variety of other similar published air contamination scenarios. A method developed by Horstman (1988) predicts the velocity distribution, airflow circulation pattern, and airborne contamination distribution in a ventilated aircraft passenger cabin and can also be applied to other volumes such as buildings or enclosures. Although Horstman used a finite differencing technique to solve the Navier-Stokes equations instead of the finite volume technique used in the upcoming analysis completed in this thesis, the end results are comparable. The velocity distribution prediction examined by Horstman was validated using a numerical simulation package.

Early conceived empirically-derived velocity contours are still the standard for the design of ventilation systems. Work by Dalla Valle (1952), Fletcher (1977, 1978, 1982), Conroy and Ellenbecker (1989), and Flynn and Ellenbecker (1985) on centerline air velocity profiles normal to a local hood face provided quantitative techniques in the design of local exhaust hoods. In particular, work by Dalla Valle (1932) reported that the results of an empirical study under negative pressure could be characterized by constant velocity contours radiating outward from the hood opening depicting velocity decaying radially outward from the hood opening. The problem is that the centerline velocity equations describe the velocity along the centerline at a point outside of the hood but do not define the velocity distribution across the hood face thus making them very limited.

Difficulties in predicting the effectiveness of ventilation systems has been evident in the past, primarily because of the complex interaction of the system components with the ventilated space (Horstman 1988). This concern was addressed by Varley et al. (1997) where the effects of turbulent structures on hood design was studied. The practice of sizing exhaust hoods based solely on velocity distribution neglects any occurrence that may in fact influence the effectiveness of the exhaust hood. Varley states that turbulent structures created by the presence of cross drafts, room air turbulence, and flow separation around objects within the vicinity of the hood are all but ignored when one solely relies on the velocity-contour technique. He ultimately concludes that CFD is the most valuable tool for modeling flow for ventilation systems and the surrounding environment.

Chapter two reviews literature on occupational asthma and industrial hygiene. It then provides a general introduction into environmental health issues, HVAC systems and the basic fundamentals of Computational Fluid Dynamics and how they have been applied to the proposed airflow problems. Chapter three will present all the collected data and results from the study as well as a discussion on the findings. Chapter four will focus on a ventilation methods and design, centerline velocity profiles, potential flow theory, supply air, and fan design. Chapter five will deal with contaminant motion, velocity profiles, and numerical simulations of cleaning/sorting, sawing, and batch cooking processes. Chapter six will present conclusions and recommendations based on the work presented in this thesis.

Chapter 2

Environmental Health and Occupational Asthma (OA)

The one area in the field of environmental health that seems to be the most defined and studied is occupational health and its relationship to workplace contaminants. Specifically, occupational health issues in the snow crab industry in Newfoundland and Labrador have prompted the need to conduct research into this area. Occupational asthma to snow crab is a specific type of work related asthma associated with processing snow crab. Crab asthma, as with asthma in general, is a chronic inflammatory disorder of the airways whereby the inflammation makes the airways chronically sensitive, or hypersensitive. When this occurs, airflow is limited and exacerbations cause intermittent respiratory symptoms, including shortness of breath, wheezing, chest tightness, and cough. Diagnosis of asthma is difficult and requires an understanding of the the underlying disorder that leads to asthma as well as being able to recognize the available pertinent information. In occupational asthma cases, worker exposure to dusts, fumes, gases, and organic particulate compounds the asthmatic responses (Ortega and Berardinelli, 1998).

Snow crab in particular has been implicated in cases of occupational asthma among processing workers (Cartier et al, 1986) where the allergic mechanism is most likely mediated by an IgE allergic response. Initial reports from a study done in a crab processing facility in Alaska seem to suggest that asthma in crab processing workers is an immunologically mediated process with a latency period resulting in both immediate and late occurring symptoms (Ortega and Berardinelli, 1998). Research on other occupational allergens (Cullinan et al, 1994; Houba at al, 1996) suggests that the level of exposure to crab allergens may be a factor in the development of the disease stating the higher the exposure the greater the risk of sensitization. This has not, however, been confirmed. Although snow crab has been processed in Newfoundland and Labrador since the 1960s there has been little research on the health risks of potentially dangerous snow crab OA.

The IgE response to high molecular weight antigens from snow crab occurs during cooking, steaming, washing, sawing, crushing, scrubbing or scraping crab in the processing plants. Once these antigens become airborne they can enter the lungs and breathing tubes causing a variety of abnormal responses. These responses, or sensitization can develop after weeks or even years of exposure. When sensitization occurs, the body's immune system produces special proteins, called antibodies, to neutralize foreign materials like these proteins. These antibodies stay in the blood stream for long periods of time to defend the body against future exposures to the proteins. In the case of crab asthma, when the sensitized worker is re-exposed the antibodies developed by their body's defense system react to the crab proteins by releasing natural substances. These natural substances are responsible for the symptoms of asthma and allergy associated with crab asthma. Once sensitization occurs, the worker can immediately be removed from the workplace for an extended period of time and still suffer from the symptoms should they be placed back in the workplace. In addition, workers who continue to be exposed to the allergen after the development of occupational asthma run the risk of developing chronic asthma triggered by exercise, cold air, smoke, as well as the allergen.

Primary prevention involves minimizing the extent to which snow crab allergens become airborne. When processing techniques that inevitably aerosolize the allergen cannot be avoided then the allergen needs to be contained and efficiently removed from the working environment. The structure and effectiveness of a ventilation system design are key in the minimization of worker exposure and health related problems.

The role of HVAC engineers in delivering clean, appropriately conditioned air and removing airborne contaminants is vital, both in industrial and nonindustrial environments (ASHRAE Handbook (Fundamentals), 2001). Activities such as cleaning, production processes, maintenance, materials use, and other specific work related events may indeed be unavoidable and somewhat unpredictable factors in system design. Some of the factors that influence worker comfort are humidity, temperature, air movement and air quality (with regard to detectable odors), dusts, as well as chemical and biological particulate. A well designed air-handling system can simultaneously control these factors and maintain a reasonably comfortable work environment and thus promote better overall health. In order to effectively design a ventilation system that will remove as many hazardous contaminants as possible, the nature of the contaminants, their effect on exposed personnel, and the methods by which they will be measured and analyzed need to be determined.

2.1 Industrial Hygiene and Air Contaminants

Industrial hygiene is a branch of science that deals with predicting, recognizing, evaluating, and controlling all conditions that may be present in the workplace such that workers do not become ill or suffer any health related injuries. It is based on the fact that most airborne contaminants become toxic only if their concentration levels exceed a maximum allowable limit for a specified period. Although the Immediately Dangerous to Life and Health (IDLH) toxicity limit is rarely a factor in HVAC design it should be considered when analyzing any work environment. It is important to note that ventilation airflow within a workplace enclosure should never reach a level where the concentration of any airborne contaminant could rise to or above the specified IDLH level. Rask (1988) suggests that when 20% of workers suffer from irritations the structure is suffering from sick building syndrome (SBS). Obtaining a zero concentration of all toxic airborne contaminants present in any workplace is generally not feasible. Workers can normally assimilate a small amount of various toxic materials without injury.

Important Aspects

Important aspects inherent in the above stated general areas of industrial hygiene are (ASHRAE Handbook (Fundamentals), 2001);

- identification of toxic contaminants
- evaluate particulate size as it pertains to lung absorption
- evaluate importance of skin absorption and ingestion
- determination of air collection methods
- identify analytic methods

- development of control measures

Identification of all types of toxic airborne contaminants/irritants is essential in order to develop and implement an effective capture and removal method. It should be noted here that an irritant is an agent which causes various physical discomforts but does not evoke an immunologic response such as crab allergenic proteins which are classified as sensitizers. Particulate normally found in the workplace is generated as a result of various work related activities whereby each individual workplace evokes a different and unique set of circumstances. However, all particulates normally fall into one of two general classes, chemical and biological. Snow crab processing involves a number of individual processes, all of which could be potential antigen generation sources. One of the major protein groups speculated to be involved in allergic responses to crab and other crustacea are the tropomyosins. This particular group consists of heat-stable highly homologous proteins, some of which have allergenic properties (Ortega and Berardinelli, 1998).

Raw crab is also processed from time to time which involves the crab being lowered into a vat containing a sulfite solution, mainly for preservation purposes. The sulfates used in raw crab production fall into the chemical type of hazard, specifically a bio-aerosol category. Sulfite fumes that result from a chemical reaction disperse into the atmosphere and can be potentially dangerous if inhaled in appreciable amounts. Various types of cleaners can also act as contaminant sources and are used in crab plants to clean and sanitize the floor, equipment, and the workers themselves. Knoeppel and Schauenburg (1989), Black and Bayer (1986), and Tichenor (1989) report data on the release of volatile organic compounds contained in various cleaning detergents. Field studies have shown that in other contexts such products contribute significantly to indoor pollution. Each cleaner has associated with it a Material Safety Data Sheet (MSDS) which outlines the toxicological properties, preventative measures, first aid, preparation information, and other miscellaneous information.

Ammonia (NH_3) is used as a refrigerant in the brine and chill tanks in crab plants to maintain the required water temperature. Although there was no ammonia sampling done in any of the four plants and no history of ammonia leaks was sought or available to our knowledge, it should be considered for future reference to ensure that there is not a contamination issue present that has been overlooked. Carbon monoxide (CO) can also be present in instances where machinery is used, in particular when the crab is offloaded from the boat and placed in the holding rooms using gas powered forklifts. Again, no specific carbon monoxide sampling was completed in this study but if carbon monoxide contamination is suspected the necessary precautions should be taken to validate any suspicions or concerns.

Although it is overlooked, more often than not the production of metabolic carbon dioxide can result in high concentrations of the gas. In general, a sedentary person takes about 15-40 breaths a minute and at each breath 1 litre of air is replaced (Etheridge et al, 1996). Exhaled air from the lungs contains about 4% carbon dioxide (Meyer, 1983). The production rate of carbon dioxide depends on the activity and as a result Norback et al (1992) have compiled data for the production rates of carbon dioxide:

- Active pre-school children (12 litres per hour)
- Sedentary office work (18 litres per hour)
- Light industrial or domestic work (36 litres per hour)

Based on these values it may be reasonable to assume that crab processing would fall into a moderate-heavy industrial work category if such a category existed. It would then be reasonable to assume that carbon dioxide would be produced at a rate greater than 36 litres per hour and could reach levels of 72 litres per hour or higher depending on the person and specific process. Carbon dioxide concentration is used as an indicator of whether or not the air is fresh or stale (Etheridge et al, 1996), however it was not assessed in this study.

In addition, endotoxins could also be a contributing factor to airborne contamination. Research into endotoxins in crab plants is planned but has not yet been carried out. Endotoxins are a gram-negative bacteria found in the outer membrane of the cell wall and may be important in crab plants. Previous studies have shown large quantities of gram-negative bacteria in bulk samples of plant processing tanks while personal levels of endotoxin were generally very low (Ortega and Berardinelli, 1998). More research into endotoxins and their potential effects on workers needs to be carried out.

Airborne particles usually enter the atmosphere as a result of either a primary or a secondary process. Primary processes involve actions which physically force the particles into the air such as brushing and butchering. Secondary or passive types of processes differ from primary processes in that the particles are released into the air via a chemical reaction or as a result of a condensible vapor, as in the passive evaporation of allergens in an open air fish market (Taylor et al, 2000). The size of particulate matter is directly proportional to the effect it has on the respiratory system of exposed workers. Particulate matter can be made up of either solids, liquids, or a combination of the two. Solid particles consist of dusts, fumes, smokes, and bio-aerosols as opposed to liquid particles which consist of mists, fogs, and smokes. In crab processing the main aerosolized particulates are the protein antigens. A particulate must be ingested in order to be considered a health risk.

Respirable particles vary in size from less than 1 μm to about 10 μm (Alpaugh and Hogan, 1988) depending on the source of the particulate. If particle size is an important practical consideration then the particle size spectra should be measured.

Particle sizes range from sub-micron to 20 microns or greater. The particulates associated with allergens include the entire range of sizes where some will be liquid aerosol and some will be in a solid dispersion. Allergen piggybacking will occur to a certain extent with otherwise inert particles. According to (Morrow, 1964) particles smaller than about 2 μm will be retained in the lungs and particles ranging from 8 μm to 10 μm will be retained in the upper respiratory tract. As a side note, particles in the 1 to 10 μm range will settle in still air at a constant velocity but will remain suspended for extended periods of time just by interaction with normal room air currents. Figure 2.1 shows the relative deposition efficiencies of various sizes of airborne particles in the human respiratory system (Task Group on Lung Dynamics, 1966).

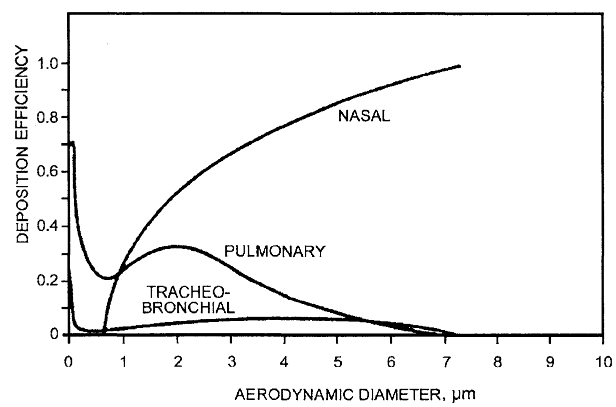

Fig. 2 Relative Deposition Efficiencies of Different Sized Particles in the Three Main Regions of the Human Respiratory System, Calculated for Moderate Activity Level
(Task Group on Lung Dynamics 1966)

Figure 2.1: Relative deposition efficiencies of different sized particles in the three major regions of the human respiratory system

The x-axis is plotted as an aerodynamic diameter and is defined as the diameter of a unit-density sphere having the same gravitational settling velocity as the particle in question (Willeke and Baron, 1993). It can be seen that particles seem to become lodged in the nasal region with a considerably higher degree of efficiency than the other two regions. However, since the allergen and sulfite particles fall somewhere between 0 and 1 μm it is reasonable to assume that all three regions of the respiratory system will be affected with particular problems occurring with particles of 0.1 μm in size. Figure 2.2 shows a plot of typical particle size fraction values versus their diameter and differentiates between fine and coarse particles.

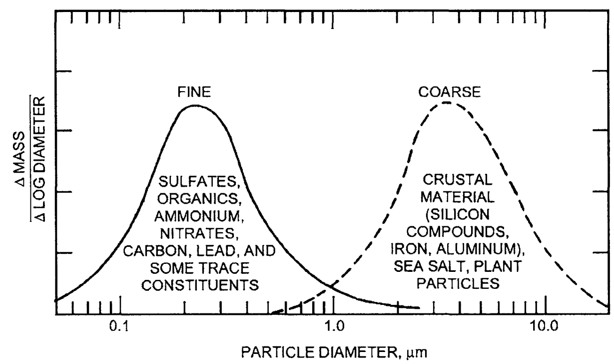

Fig. 1 Typical Urban Aerosol Composition by Particle Size Fraction
(EPA 1982, Willeke and Baron 1993)

Figure 2.2: Typical urban aerosol composition by particle size fraction

It is easy to see that the sulfites and biological particles present in crab plants could fall in both the fine or coarse particle designation. Allergic reactions not only occur in the respiratory tract but also in the eyes and on the skin causing itching, irritation, dryness and rashes. Although particle size is related to the severity of the allergic reactions in the skin and eyes it is not of the same order of magnitude as it is with the respiratory system.

2.2 HVAC Systems

All residential and industrial enclosures need some sort of air handling unit installed that is capable of controlling the environment. In particular, industrial environment ventilation systems need to be designed to handle various individual conditions and simultaneous exposures to heat, cold, humidity fluctuations, pressure imbalances, airflow variations, and stagnant or mobile toxic airborne substances. Ventilation can be effectively provided by mechanical systems such as local supply/exhaust or general supply/exhaust, by natural draft methods, or a combination of the two.

Mechanical systems are used in a majority of cases as they usually are able to provide the best environmental control in the workplace. A mechanical system generally consists of the following elements;

- inlet section
- filter
- heating or cooling coils
- return and supply air fans
- ductwork
- diffusers

Figure 2.3 depicts a general system with the above major system elements. This figure is only a basic schematic of a typical HVAC type of system and says nothing about the specific location of air intakes/exhausts, layout of ductwork, nature of supply air and exhaust, fan power and location, or building schematics.

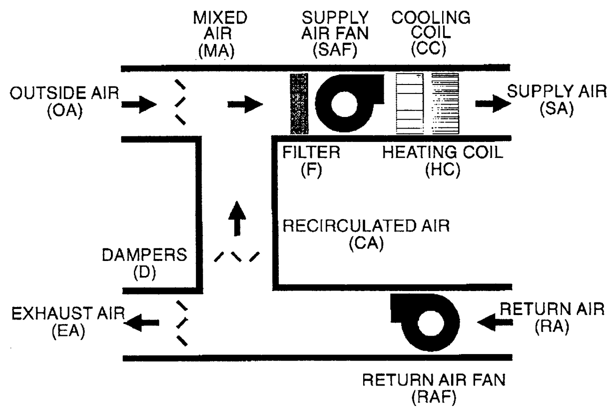

Figure 2.3: Typical air-handling unit (Fundamentals 2001)

This type of general system can be used to locally supply and exhaust air from a specific location of interest or applied generally to the whole enclosure. Both local air supply/exhaust as well as general air supply/exhaust will be considered in attempting to ascertain their effects on produced airflow patterns and possible movement of airborne particles that could be contained within these airflows.

Localized supply and exhaust systems are normally the most cost effective method of controlling air pollutants and are most effective in situations in which the degree of toxicity of the air due to the presence of airborne contaminants is the primary concern. Local air supply and exhausts are installed near the source of the contamination both to prevent mixing with the rest of the building air and optimize ventilation airflow. Local ventilation systems may or may not recirculate any of the air depending on the degree of pollutant. If the levels are too high and exceed the predetermined threshold limit value (TLV) for the particular contaminant and zone then the air will be totally exhausted to the outside. It should be noted here that there is currently no TLV value for crab. The capturing efficiency of local ventilation systems depends on the hood design, positioning near the source of contamination, and exhaust airflow. In addition the selection and layout of the hood has a significant influence on the initial and operating costs of both local and general ventilation systems (Applications 1999). Local systems do very little for the overall comfort of the workplace due to the fact that they concentrate on individual locations and not the building as a whole.

When the installation of a local system is impossible or undesirable for whatever reason, a general ventilation system can be used to provide comfortable working conditions and dilute airborne contaminants to an acceptable level. In these, supply air is mixed with a certain percentage of the recirculated air and sent through filters and heating/cooling coils before it is released into the workspace. The percentage of recirculated air, type of filters, heating/cooling of the air and fan power will be determined by factors such as the level of aerosolized pollutant, physical size of the building, basic layout of the system, and associated ductwork. Room air movement affects the distribution of both ventilation air and suspended airborne particulate within the workplace enclosure. It is worth noting here that if insufficient replacement air is provided in situations where significant amounts of air is being exhausted, then the pressure of the building will become negative with respect to the atmospheric pressure outside the building envelope. This could cause infiltration of outdoor air and possibly bring back in the contaminant that was previously exhausted. In crab processing food quality issues can become important when bringing in outside air and recirculating existing plant air. A clean supply of air needs to be maintained at all times to avoid any contamination of plant air from outside contaminants and also to avoid any cross contamination within the plant itself.

Natural ventilation is also used as a means of ventilating buildings by allowing the flow of air through open windows, doors, grilles, or any other type of opening in the building envelope. Natural ventilation systems make use of natural and/or artificially produced pressure differentials between the outside of the building and the inside to drive the air. Infiltration and exfiltration are natural ventilation methods whereby the flow of outdoor air into and out of a building is allowed through cracks and other unintentional openings in the building envelope. These methods are also driven by natural and/or artificially produced pressure differentials. Air within a building that moves from one space to another is denoted as transfer air, which can either occur naturally or intentionally. Figure 2.4 depicts the ventilation methods described above.

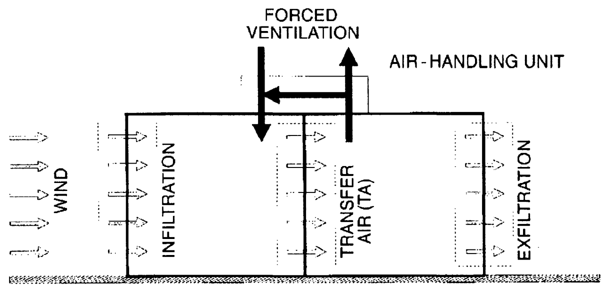

Figure 2.4: Ventilation methods (ASHRAE Handbook (Fundamentals), 2001)

2.3 CFD Theory and Implementation

The purpose of this section is to give a brief overview of the main areas of computational fluid dynamics that are inherent in the simulations presented in this thesis. It should be noted that the information discussed here is general in nature as the intent is not to analyze a commercial CFD package but merely to apply the principles in an efficient and logical manner.

2.3.1 Governing Equations

Commercial CFD packages available today have codes structured around a number of numerical algorithms which are capable of approximating various fluid flow problems. Commercially available codes such as Fluent are based on finite volume formulation techniques, however finite difference, finite element, and spectral methods are also viable solution techniques. Each of these have been used in the past to solve the governing Navier-Stokes equations due to the lack of exact analytical solutions. Only a few simplified and somewhat impractical situations such as laminar flow over an infinitely long plate have exact analytical solutions. Since these equations are normally unsolvable analytically, they are approximated using one of the numerical methods described above and explained in the following section. The equations governing fluid flow are continuity (conservation of mass), the Navier-Stokes (conservation of momentum), and the energy equations. These equations are classified as a set of coupled, nonlinear, mixed, elliptic-parabolic system of partial differential equations (PDE's)(Keller, 1978).

Examining the conservation of mass equation:

$$\dot{m}_{stored} = \dot{m}_{in} - \dot{m}_{out} \tag{2.1}$$

After application of the conservation law and numerous expansions and substitutions we have:

$$\frac{\partial \rho}{\partial t} + u\frac{\partial \rho}{\partial x} + v\frac{\partial \rho}{\partial y} + w\frac{\partial \rho}{\partial z} = -\rho\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z}\right) \tag{2.2}$$

Finally, we may write the equation more compactly in the following form:

$$\frac{D\rho}{Dt} = -\rho\nabla \cdot \vec{V} \tag{2.3}$$

Next, we examine the momentum equations. The momentum equations may be easily derived if we consider the following conservation law for a control volume $dV = dx\, dy\, dz$, in each of the three flow directions:

$$\dot{M}_{stored} = \dot{M}_{in} - \dot{M}_{out} + \Sigma F_{external} \tag{2.4}$$

Again, using the conservation law and various substitutions yields the momentum equations in the x,y, and z directions:

$$\rho\left(\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z}\right) = \rho g_x - \frac{\partial p}{\partial x} - \left(\frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z}\right) \tag{2.5}$$

$$\rho\left(\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z}\right) = \rho g_y - \frac{\partial p}{\partial y} - \left(\frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{zy}}{\partial z}\right) \tag{2.6}$$

$$\rho\left(\frac{\partial w}{\partial t} + u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z}\right) = \rho g_z - \frac{\partial p}{\partial z} - \left(\frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z}\right) \tag{2.7}$$

In vector notation, the momentum equations may be written as:

$$\rho\frac{D\vec{V}}{Dt} = \rho\vec{g} - \nabla p - \nabla\tau_{ij} \tag{2.8}$$

where τ_{ij} is the stress tensor denoted:

$$\tau_{ij} = \begin{pmatrix} \tau_{xx} & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \tau_{yy} & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \tau_{zz} \end{pmatrix} \tag{2.9}$$

The above equations are valid for any type of fluid provided the appropriate constitutive relationships are used for the stresses. This research deals with fluids of the incompressible type which now transforms the above momentum equation in the three principal directions into the following:

$$\rho\left(\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z}\right) = \rho g_x - \frac{\partial p}{\partial x} + \mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right) \tag{2.10}$$

$$\rho\left(\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z}\right) = \rho g_y - \frac{\partial p}{\partial y} + \mu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2}\right) \tag{2.11}$$

$$\rho\left(\frac{\partial w}{\partial t} + u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z}\right) = \rho g_z - \frac{\partial p}{\partial z} + \mu\left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2}\right) \tag{2.12}$$

Finally, we may generalize the above equations and present them in vector form using the following compact notation:

$$\underbrace{\rho\frac{D\vec{V}}{Dt}}_{inertia} = \underbrace{\rho\vec{g}}_{bodyforce} - \underbrace{\nabla p}_{pressure} + \underbrace{\mu\nabla^2\vec{V}}_{friction} \tag{2.13}$$

Due to the presence of the non-linear terms in these PDE's, analytical methods can yield very few solutions. If these PDE's can be made linear then closed form analytical solutions are possible. These PDE's become linear when the non-linear terms drop out (i.e. fully developed flow in ducts, inviscid and irrotational flows) or when the non-linear terms are very small compared to the other terms (i.e creeping flows). Since most engineering flows cannot be made linear, numerical methods are needed to obtain accurate solutions.

2.3.2 Geometry Definition and Grid Generation

Computational fluid dynamic packages such as Fluent have the ability to solve complex fluid flow problems with relative ease without performing any physical testing. The process begins with the geometry, which has to be either created internally within the CFD package (Gambit) or imported from an external CAD/CAE package such as AutoCAD. Figure 2.5 shows the basic program structure followed.

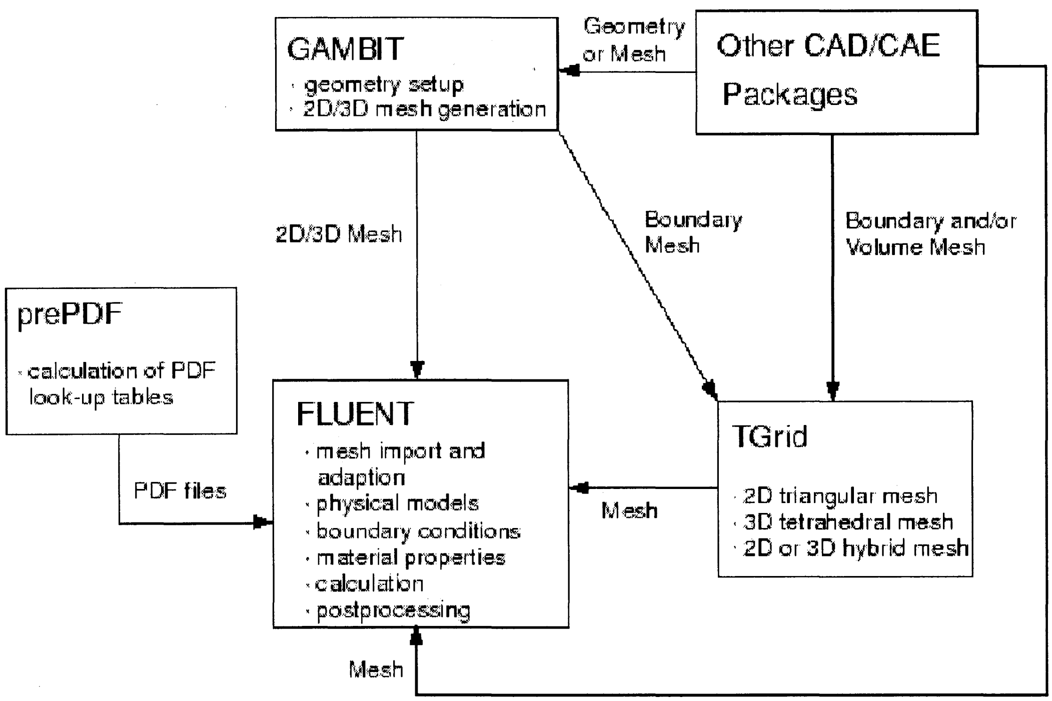

Figure 2.5: Basic program structure (Fluent Website)

In order to be able to develop solutions to various flow problems by applying the governing equations of fluid flow, the region of interest on the geometry, or computational domain must first be constructed and discretized, or meshed into geometrically similar cells. The term 'discretized' implies that the computational domain is divided, or meshed into a non-overlapping series of cells (or control volumes) whereby their size, shape, and number is directly proportional to the accuracy of the solution. The discretization process can also be described as the art of replacing the differential equations with a set of algebraic equations to obtain an approximate solution. A mesh is basically a set of small blocks which fill the volume through which the fluid flows, the finer the mesh the more accurate the solution will become. A mesh normally consists of element types ranging from triangles or quadrilaterals in two dimensions and tetrahedra, hexahedra, prisms, or pyramids in three dimensions. They should be generated such that the surfaces of the geometry are as smooth as possible and any abrupt changes in the volume of the mesh cells are avoided (Blazek 2001). Figures 2.6 and 2.7 show the basic element types used to define meshes.

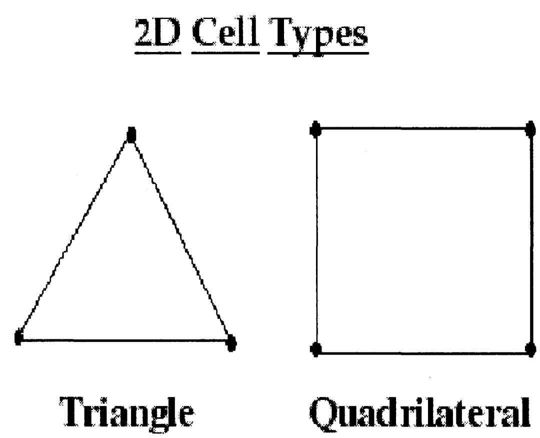

Figure 2.6: 2-D cell types (Fluent Website)

At each node in the mesh there are a variety of variables associated with it such as velocities, temperatures, pressures, etc. The governing equations at each of these mesh nodes must be satisfied in order to produce an accurate solution. Knowledge of fluid flow properties and characteristics are key factors in determining where to design and refine the mesh and nodes to obtain the best solution. In general, optimal meshes are often non-uniform: finer in areas where large property variations occur

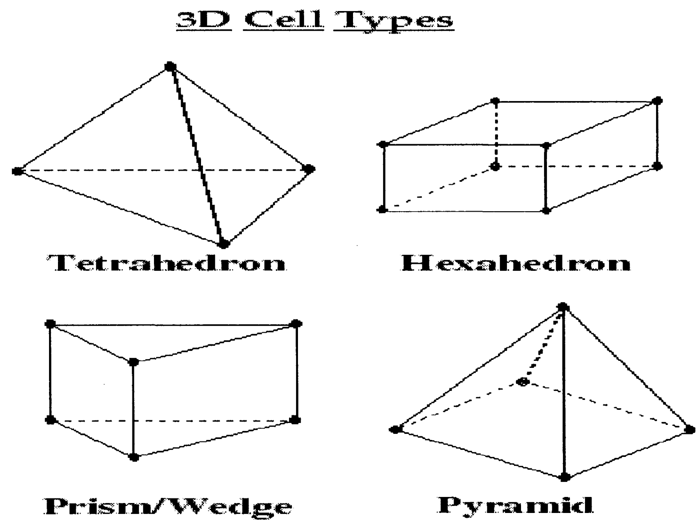

Figure 2.7: 3-D cell types (Fluent Website)

from point to point and coarser in regions with relatively little property change.

Fluent 6.0 has been chosen for the analysis and uses a Finite Volume Method solver. FVM, or finite volume methods are based on a numerical algorithm consisting of the following steps (Versteeg et al, 1995);

- Formal integration of the governing equations of fluid flow over all the (finite) control volumes of the solution domain
- Discretization involving the substitution of a variety of finite-difference-type approximations for the terms in the integrated equation representing flow processes such as convection, diffusion and sources. This converts the integral equations into a system of algebraic equations.
- Solving the algebraic equations using an iterative method

The control volume integration is a key feature of the FVM which results in the conservation of all relevant properties in each finite size cell generated in the mesh. In simpler terms, there is a clear relationship between the numerical algorithm and the physical principles of fluid flow. The main mathematical concept that determines the success of this algorithm is convergence. Convergence is the property of a numerical method to produce a solution which approaches the exact solution as the grid spacing, control volume size or element size is reduced to zero. The number of iterations required to achieve convergence depends on the complexity and nature of the grid.

There are many different forms that meshes can assume but they generally fall into two main categories, namely;

- structured
- unstructured

Structured grids are the more difficult of the two mesh forms to generate due to the systematic manner in which the computational domain is segmented into similar cell types. When the geometry that needs to be meshed is complex it becomes difficult to discretize each computational domain into similar topological regions and then map them with separate structured grids. It can become very tedious to keep the grids orthogonal to the surfaces when 3-D geometries are meshed with structured grids. However due to the increased efficiency in the generation of a solution, structured grids are sometimes chosen over unstructured ones. The element types chosen are used throughout the entire domain whereby only their size and general shape varies. Normally these solutions are slightly more accurate than those obtained using unstructured meshes. An example of structured 2-D and 3-D meshes are shown in Figures 2.8 and 2.9.

Figure 2.8 depicts a 2-D structured quadrilateral grid around an airfoil and Figure 2.9

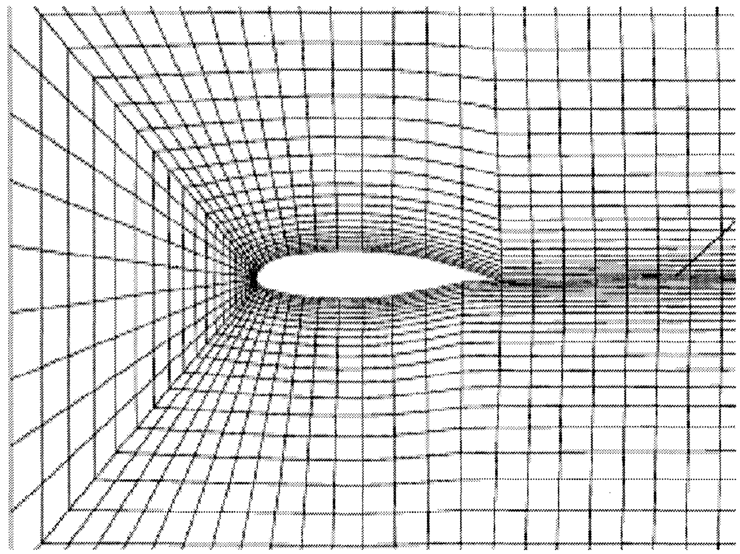

Figure 2.8: 2-D structured grid mesh (Fluent Website)

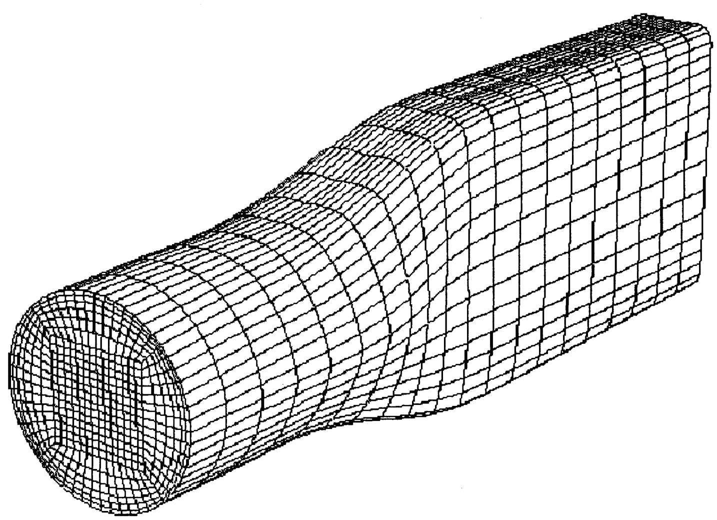

Figure 2.9: 3-D multi-structured grid mesh (Fluent Website)

depicts a 3-D multi-structured quadrilateral grid of a flat head screwdriver. The main disadvantage of structured grids is the fact that they require a longer time to define the block topology, once this is determined the generation of the grid is usually very straightforward. Another main disadvantage occurs in areas where the flow variables are drastically changing and thus a finer and/or custom designed mesh would be required to produce more accurate results. However, when the geometry is fairly simplistic the difference between results obtained from structured or unstructured grids is negligible.

On the other hand unstructured grids require much less effort by the user as they can be generated about complex 2-D and 3-D geometries with relative ease. The cells are no longer arranged or ordered in any particular way but do, however, define the domain boundaries completely as any gaps in the computational domain will result in errors. These types of meshes are used when the domain is divided into many regions and are reduced to a minuscule size whereby there is no need for any local meshing within the block. Unstructured grids are flexible in that they can have combinations of elements from both structured and unstructured meshes and are termed 'hybrid' meshes. An example of unstructured 2-D and 3-D meshes are shown in Figures 2.10 and 2.11.

Figure 2.10 depicts a 2-D unstructured quadrilateral grid around an airfoil and figure 2.11 depicts a 3-D unstructured tetrahedral quadrilateral grid of a petroleum pressure vessel. A main advantage of unstructured meshing is the ease with which the meshing techniques can be customized to meet the designer's needs. Certain areas of the meshed domain may require a finer or coarser grid depending on the degree of accuracy required or variations in physical parameters. The structure of the mesh will not be compromised as the mesh has no real order to begin with. This type of adaptation will only result in local refinements to the connectivity of the mesh and not affect the mesh globally.

In the following chapters, local exhaust hoods will be modeled to determine the

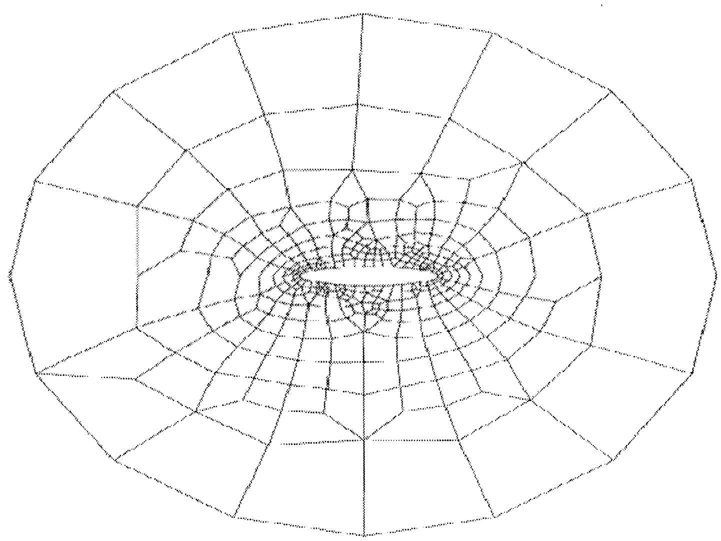

Figure 2.10: 2-D unstructured quadrilateral grid mesh (Fluent Website)

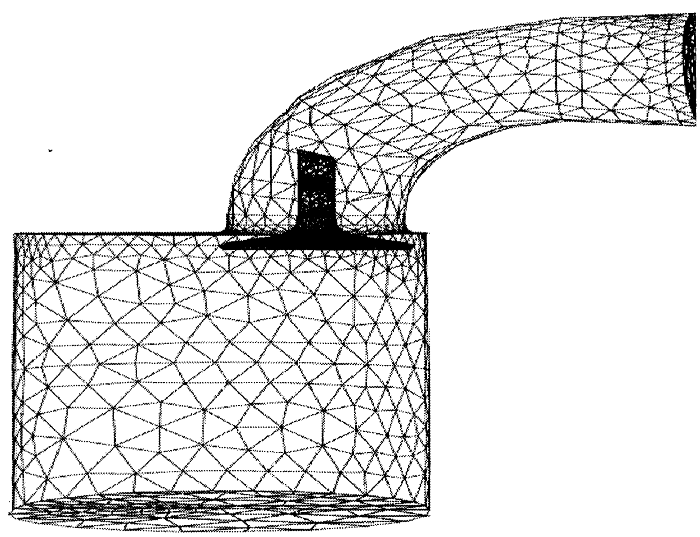

Figure 2.11: 3-D unstructured tetrahedral grid mesh (Fluent Website)

velocity profiles in the vicinity of the hood face and to ascertain the effects of nearby turbulent structures such as people and processing equipment. An example of the typical meshing that will be used is shown in Figure 2.12 which depicts a simulation of empirical and theoretical relationships.

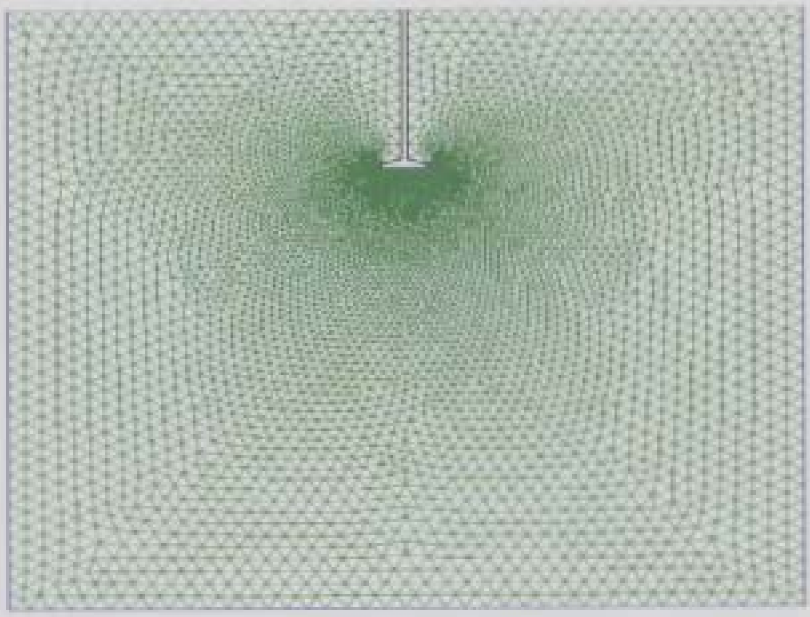

Figure 2.12: 2-D Tri-gridded mesh around a local exhaust hood

The basic boundary conditions applied have set the hood face as a velocity inlet using a negative velocity value to essentially create a velocity outlet and the walls of the domain as pressure inlets to allow air to be drawn into the hood from all directions. The only area that required a finer grid was the face and sides of the hood as velocity and pressure varied in those areas and required a more robust grid to ensure solution convergence.

Whenever any CFD simulation is undertaken, great care must be taken when formulating an appropriate meshing strategy. If a structured grid is used, then the solution process is efficient but the grids themselves are normally difficult to implement, especially in 3-D. If the unstructured approach is taken, then the solution process is a little less efficient but has the advantage of easier grid implementation. In many situations the efficiency of the solution process is sacrificed for a more accurate solution due to the relatively small difference in computational time. For the purpose of the work presented here an unstructured hybrid type of grid will be chosen simply due to the ease in which the meshing could be completed and due to the fact that there are areas where the mesh will need to be refined.

Chapter 3

Field Research & Raw Data Collection

Originally it was proposed that five Newfoundland and Labrador plants with differing histories of involvement in snow crab processing would be studied. The intent was to try to approximate a representative sample of the industry and of the general crab processing labour force as a basis for the development of a provincial prevalence estimate of the incidence of allergy and OA to snow crab. At the start of the study, with help from the Department of Labour and the Department of Fisheries and Aquaculture, all of the existing Newfoundland plants were grouped into five different categories based on age, size (amount of crab processed), production process, ventilation and enclosure of the cooking area, and products produced. The 32 plants that actively processed crab in 2000 were broken into three categories based on amount produced.

- less than 1 million pounds (13 plants)
- 1-4 million pounds (12 plants)
- grater than 4 million pounds (7 plants)

Within these categories a distinction was made between plants that processed meat products and those that did not and between those with ventilation systems and those without. Plants were approached in each of 5 categories and eventually signed a memoranda of understanding with representative plants from four of the five categories. Unfortunately it was not possible to obtain a representative large, old plant (10-30 years of crab processing) that produced more than 10 million pounds per year, and with poor ventilation willing to participate in the study.

Over the course of the 3-year crab asthma project a variety of different types of data have been collected during numerous visits to crab processing facilities. These data include plant layouts, processing procedures, plant histories, PBZ and Area air samples, temperature and humidity measurements, processing quotas, prevalence, beliefs and concerns, and socioeconomic and quality of life issues (Neis at al, 2003). Air collection methods consisted of sampling with personal breathing zone (PBZ) samplers and area samplers. Sampling was carried out in each of the four participating crab plants. Details of the sampling methods, analytical treatment and raw data results are described in this chapter. The collected data has been used to aid the research team to pursue a variety of research avenues in an attempt to collectively reach individual research goals.

3.1 Plant Overviews and Collected Data

Processing methods vary from plant to plant due to changes in the physical layout of the plant and the particular species being produced at any given time. The physical layout of each individual plant influences the location of the processing equipment. Sometimes plants are used for a variety of other fish related processes such as shrimp, caplin, redfish, mussels, as well as lumpfish, and therefore contain all the specific equipment needed for production of each of these different species. As a result there is sometimes limited room with which to work leaving little choice in the placement of equipment. More often than not processes are located in close proximity to one another and confined in spaces that are ideally too small. Processing crab in the raw state and then cooking it or cooking first and then processing can also affect processing methods and flow of production. Since layout and processing procedures can vary from plant to plant it is both necessary and beneficial to provide an overview of these in each of the four participating plants. Plant histories will also be included to give a sense of the changes that each plant may or may not have experienced.

Temperature and humidity will also be included as the data can provide an indication of the effectiveness of existing ventilation systems and, because allergens can be found in steam from cooking areas and possibly in moisture evaporation, they may provide an indirect indication of allergen levels. In all four plants, temperature and humidity was measured using portable data loggers placed in different areas of the plants and data recorded. Ventilation data taken at the time of air sampling in each of the participating plants will also be presented here. Over the 3-year span of the project some plants made ventilation changes of some sort from one year to the next, some did not. Where appropriate, the ventilation at both instances is described below.

Finally, PBZ and area sample results will be presented here as well as the results obtained from the raw crab experiment.

3.1.1 Plant 1

Plant History

Plant 1 began processing crab in 1997 and is the largest plant in the study with the highest production levels. A former groundfish plant, the plant was renovated to its current layout and ventilation standards in the year 2000. The main crab processing area has a volume of 4983 m^3 which includes the butchering and cooking areas. The holding room is an additional 492 m^3. Plant D has processed an average of 6 million pounds of raw crab per year since it began processing. In most years, virtually 100% of production has gone to sections. However, during two processing years, about 2% of production involved whole cooked crab for the Japanese market.

Processing Overview

Consider the schematic of plant 1 shown in Figure 3.1

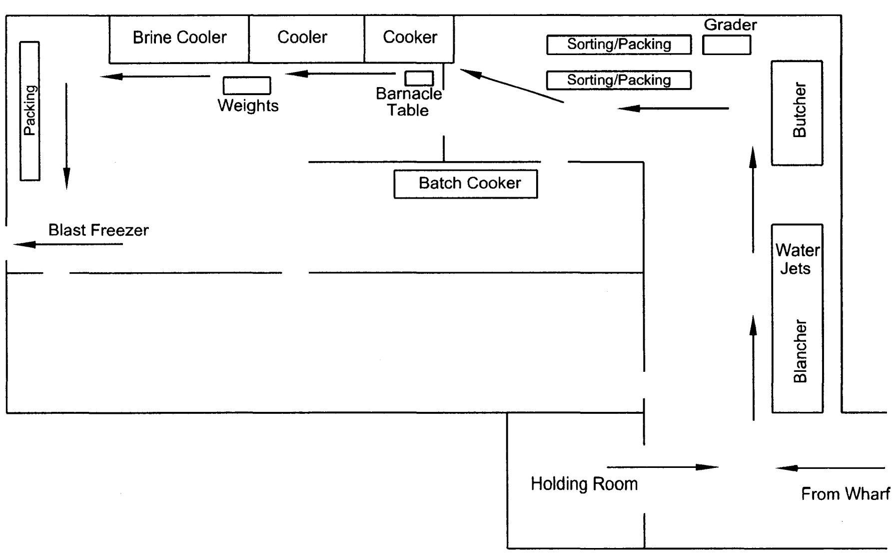

Figure 3.1: Plant 1 process flow

Production begins at plant 1 with the offloading of the live crab with a forklift from boats docked at the nearby wharf and placing it in the holding room. The live crab is piled in the holding room in bins and iced until it is ready to be transported to the blanching area. This is the only plant of the four participating plants that treated the crab before it was butchered. When the crab leaves the holding room, it is first placed in a bath of water at 30 degrees C. There is an enclosing hood situated above the water bath that is exhausted to the outside. The bath stuns the crab before it gets fed via, a plastic conveyor belt, through a hooded and ducted area containing high pressure water jets. These jets clean the crab before it gets transported to the butchering table. The butchering station is fed with the same conveyor belt that moves the crab through the blancher and high pressure water jet area. After the crab is butchered , it is transferred to the packing and grading lines where it is graded according to size and packed into plastic cooking containers. Uncooked crab clusters with barnacles attached to them are taken from the packing and grading lines and sent to a table where barnacles are chipped off with a rectangular piece of metal. Once all the crab is clean it is sent to the continuous cooker and loaded into metal cooking cages and lowered into the cooking water, which is kept at 100 degrees C. It then automatically proceeds through the cooker and into the cooling tank before getting removed and weighed. After it is weighed, the crab is brine frozen and then glazed. After glazing, the crab is packed in cardboard boxes and taken to the cold storage.

Ventilation

Plant 1 was the only plant in this study with a professionally installed mechanical ventilation system. In this plant, the crab processing production line is connected to other processing areas by means of windows and doorways. During air sampling, some crab processing (batch cooking) was taking place on a separate production line set up away from the hooded and ventilated regular line in one of the other adjacent rooms. An attempt had been made to ventilate this production line and cooker but the system was less satisfactory than the one associated with the main production line. The entire plant is connected via two air handling units, a 8000 cfm unit and a 9000 cfm unit. The 9000 cfm unit was connected to the processing plant while the 8000 cfm unit was connected to an old upstairs plant. The unit is thought to be configured to mix 25% of the used plant air with 75% new outside intake air and distribute this mix to the plant during processing. However due to a problem with the automated controls the actual percentages of new and used air were unknown at the time of air sampling. Supply and return dampers are located in the ceiling throughout the entire plant. Some noticeable problems were that the supply dampers were not oriented so as to ensure that air was supplied correctly and some supply dampers were supplying a considerable amount of air while others were not supplying air at all. In plant 1, the cooking area is 132 m^3 and is basically enclosed except for the opening where the worker loads the cooker with crab crates. The cooker is separately ventilated and the room also has a wall mounted exhaust fan.

Temperature and Humidity

In plant 1, the butcher area had an average temperature reading of 15 degrees C and an average of 65% humidity. Humidity was slightly higher (5%) in the sorting table area. In the cooking area, the temperature was 25 degrees C and there was a humidity reading of 45%.

3.1.2 Plant 2

Plant History

Plant 2 is a medium-sized plant that began processing crab in 1991. In this plant, the holding room/butcher areas are adjacent to each other with the volume of space in the butchering area equaling 201 m^3, the small cooking room has a volume of 71.6 m^3 and the main processing area is approximately 1600 m^3. It processes approximately 2 million pounds of raw crab per year.

Processing Overview

Consider the schematic of plant 2 shown below in Figure 3.2

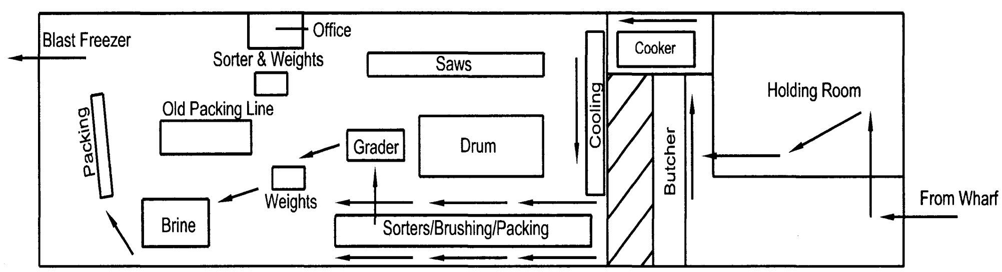

Figure 3.2: Plant 2 process flow

The process in plant 2 begins with the offloading of live crab from the commercial crab boats at the adjacent wharf using forklifts and moving it to the chilled holding room. The crab is iced and held in crates inside the holding room until it is moved to the butchering line. The butchers hold the crab by its legs, one set in one hand and one set in the other. The abdomen of the crab is then pushed against a vertical steel plate causing the body to split, thus separating the body from the legs. The body and other debris are discarded via a water filled trough under the butchering table and washed outside to a open barge next to the wharf. The separated leg clusters are thrown onto a moving conveyor belt in front of the butchers and transported through a small window into as small room where they fall into an opening in the top of the hooded cooker.

Depending on the number of butchers working at any given time, the clusters sometimes pile up in the cooker before the mechanized conveyor in the cooker has a chance to move the clusters through and complete the cooking process. Due to this common occurrence there is sometimes a worker stationed inside the enclosed cooking room who has the sole responsibility of making sure that the crab stays submerged in the cooking water. The clusters are carried though the cooker and up through a window into the main processing area. A conveyor belt drops the crab into a cooling tank from the cooking room through this hooded window.

Large amounts of steam escape into the cooking room as the crab emerges from the 100 degree temperature water. The steam escaping at both the entrance and exit of the cooker causes the cooking room to fill with steam. Ice is added to the cooling tank to keep the temperature of the water at 3-4 degrees C. The crab is removed from the cooling tank, put into crates, and stacked near the sorting/cleaning table where it will be cleaned of any excess dirt, barnacles, or bits of shell and packed into crates according to size. Any undersized crab are graded at a separate table and packed into similar crates. Approximately 20% of the crab is trimmed and packed in smaller, grade A packages. The remainder is sent to the cleaning table which is located along the north wall of the plant and has workers along each side. These workers hold the crab leg clusters against brushes to clean them and then pack them in crates. The crates of crab clusters are then weighed and sent to the brine freeze tank where they receive a glaze and are pre-frozen. The clusters are then boxed in cardboard boxes and moved to the blast freezer where they are frozen and await shipping to various markets worldwide.

In addition to the processes described above there are additional processing technologies present in the plant that were not in use at the time of the air sampling. There are sawing stations that make use of table saws with an open spinning blade to score crab clusters before packaging. This is done to facilitate removal of the crab meat from its shell by the consumer. During some periods, meat products are produced where legs are sawed into sections, leg meat is removed using rollers, knuckles go through a crusher and eventually pass through a revolving drum. The drum is perforated and contains water jets. As it revolves, the meat is washed out of the knuckles, falls through the drum and is separated from the water in a ripple board. This drum was not in use in either phase of air sampling at this plant so any comments on the degree to which this drum would contribute to allergen levels cannot be made at this time.

Ventilation

In plant 2 there is a fresh air intake in the butchering area and doors are often open as crab is brought into the adjacent holding room from the nearby wharf. There are no exhaust fans in this area. There is a fan on the roof that is linked via square ducting to the butcher room and to an area located over the brushing/packing table. This system was operational during air sampling in 2001 but the duct intake located in the butcher room was closed off during air sampling in 2002. Management made this change to prevent steam from the brushing/packing table area being circulated back into the butcher room through this opening. When the intake in the butchering room was open, instead of the roof fan actually drawing steam up through the ducting from both the butchering room and brushing/packing table and exhausting it to the outside, the steam was being drawn in through the ducting from the brushing/packing table. Knowledge of basic physics indicates that there was a greater negative pressure at the butchering room intake opening than was created by the roof fan thus causing the steam to bypass the fan and be drawn back down into the butchering room. There is also a 12 inch diameter, 1/4 hp, 1725 rpm wall fan located between the production office and the blast freezer

The cooking room area in plant 2 is largely enclosed with only two small open windows linking it to the butchering area and to the main processing room. A hood located over the opening between the cooking room and main processing room was reported to have reduced the leakage of steam from the cooking area into the main processing room. The cooker itself is also partially hooded, with openings for the entry and exit of the crab. During the time of the research there was a lot of steam in the cooking room. However, no steam was visibly leaking from the cooking room into other areas. The cooking room area of plant 2 has four exhaust fans (one was not in operation during either sampling period) to remove steam during the cooking process. One fan is attached to the cooker hood and vented directly from the cooker and the other two are ceiling exhaust fans. The fan attached to the cooker is a 12 in diameter, 1500 rpm fan. One of the ceiling fans is a 16 inch diameter, 1/4 hp, 1625 rpm fan, the other a 24 inch diameter, 1/2 hp, 1075 rpm fan. There are no active fresh air intakes into the cooking room to replace the exhausted air. This probably causes the exhaust hoods to draw air from other areas of the crab facility such as the butchering room or main processing area to maintain a balance.

In plant 2 the main processing area is walled off from the cooking room and butcher area and consists of a single large room where cooling, cleaning, sawing, meat removal, brine freezing and packing are carried out. The volume of this processing area is approximately 1600 m^3. In general, ventilation in the processing area is poor, particularly in the brushing/packing area. There are two fresh air intakes in this section of the plant, one behind the sorting table and one behind the saws table. There are exhaust fans located over the brushing/packing area, sawing area, and in the box assembly area. Except for the fan above the brushing/packing area, these fans were not in operation during air sampling. There were also large quantities of cooked crab stacked around the brushing/packing area that could be sources of allergen contamination. Since the allergen concentrations are high in this area it would be reasonable to assume that either the stacked crab, the cleaning process, airflow problems, or a combination of all three are causing the elevated allergen concentrations. The drum and crusher used for separating the crab meat from the shell could be another source of allergens when in operation, however this cannot be confirmed as they were not in use.

The existing ventilation system in plant 2 would tend to move the air throughout the processing area exposing plant workers to any air borne contaminants along the way rather than venting allergens directly out of the plant from their sources. The temperature and relative humidity data indicate that the cooking process causes the relative humidity in the cooking room to be at saturation concentrations, indicated by the presence of steam. This also supports the premise that the ventilation system is not working properly. When humidity is high in the cooking room, it is high in the butchering area as well as in the main processing area. This may be caused by the damp outside air, the butchering process or may indicate that steam from the cooker is migrating to the butchering area. The same could be true for the cooker/cooler situation. It is reasonable to assume that relative humidity levels would probably be higher when the drum is in operation.

Temperature and Humidity

Plant 2 generally had higher humidity levels than the other plants. Temperatures of approximately 14 degrees C and humidity values of 85% were obtained in the butchering area. Temperatures in the cooking room were variable during the sampling period, averaging about 34 degrees C, with relative humidity values of 90-100% most of the time. Relative humidity values indicate humidity concentrations in this room are close to saturation concentrations while the cooker is in operation. Temperatures in the main processing area during air sampling were relatively low, approximately 16 degrees C with 90% relative humidity in the area around the end of the cooling tank. Towards the other end of the processing room, adjacent to the brine freezer, temperatures averaged 18 degress C and relative humidity was somewhat lower, between 60-70%. In the processing area of the plant, adjacent to the section cleaning and packing area, are the crusher and the revolving drum used to remove meat from crab knuckles. The drum was not in operation during the air-sampling period. Adjacent to the drum are the size graders where temperatures hovered in the 14 degress C range with humidity values of 85%. Temperatures and humidity readings in this area were 17 degrees C and 70% respectively.

3.1.3 Plant 3

Plant History

Plant 3 is a small plant with the volume of space in the butchering area being 228 m^3 and the volume of the main processing area being approximately 1100 m^3. This plant has been processing crab since 1997 but relatively little crab was processed in the first season. Between 1998 and 2002 the plant processed an average of 1.2 million pounds of raw crab per year, almost exclusively sectioned products. Snow crab in this area generally requires little cleaning thus removing the need for brushing and scraping.

Processing Overview

Consider the schematic of plant 3 shown below in Figure 3.3

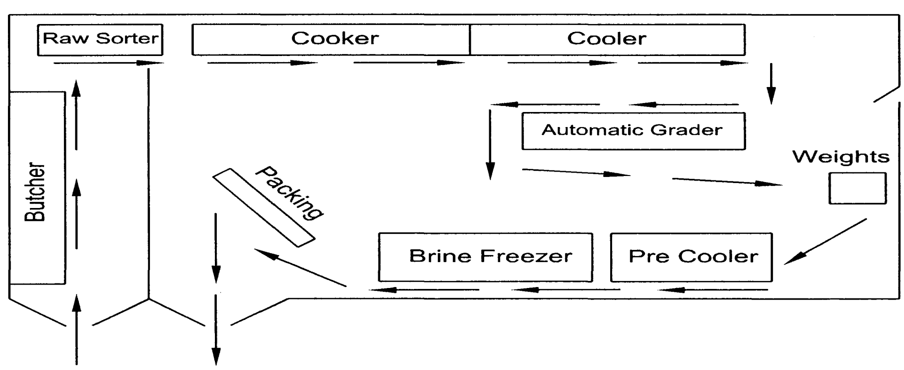

Figure 3.3: Plant 3 process flow

The process at plant 3 begins in a similar manner as in plant 2 with the offloading of the live crab from the commercial crab boats at the adjacent wharf using forklifts and moving it to a holding room. The holding room here is in a different building than the main processing plant. The crab is then carried to the butchering room to be butchered. Once butchered, it is sent through some high pressure water jets and placed into bins to be sent to the automatic cooker. The bins proceed through the continuous hooded cooker and into a cooler filled with ice at a temperature of approximately 4 degrees C. From there it is put through an automatic grader where each cluster is sorted according to weight. Once the grader has successfully sized the clusters, they are stacked next to the brine tank to await weighing. The automatic grader was not installed in year 1 of the study but was in operation during year 2. The crab crates are then loaded into the brine tanks where they are glazed and frozen. They are then removed, boxed, and taken to cold storage in an adjacent building.

Ventilation

In plant 3, butchering takes place adjacent to the grading, cleaning and sorting area and is partially walled off from the main production area with the continuous cooker being located in the main processing area. The only fresh air intake in the butchering area comes from the open double doors which were open approximately 80% of the time during sampling. Other than these open doors there is no other feasible means present by which air can be forced toward the raw grading/sorting area and then toward the cooker. This airflow direction may change in response to changes in the wind direction and magnitude which would cause a higher negative pressure boundary at the double doors to occur and effectively introduce a suction effect that could possibly draw allergens from the main processing area of the plant to the butchering room.

There are now three exhaust fans attached to the continuous cooker. A second fan was added in the summer of 2000 and a third fan was added in the summer of 2001 prior to air sampling. All three fans are connected directly to the enclosing cooker hood and ducted out of the plant. These are in fact the only exhaust fans in use in the main processing area, with the exception of a small wall fan located above the weights, which was not in use during the actual time of air sampling. Other than the butchering and packing area doors there does not appear to be any fresh air supply for the plant other than possible infiltration and cracks under doors. Apparently there was a wall fan near the entrance to the cooker but this was removed in the spring of 2001 when an extension was added to the plant. An additional hood was added to the cooker and there appears to be little steam escaping from the cooker. Preventing the escape of steam from the cooker would be particularly important in this plant since the cooker is in the main production area and not separated from the rest of the plant. In the main production area the air is most likely stagnant, particularly when doors are closed, with air quality undoubtedly diminishing as the day goes on.

Temperature and Humidity

In plant 3, temperatures in the butchering area were about 14 degrees C during the period of sampling with relative humidity averaging 90%. Temperatures in the cooking area ranged between 16 degrees C and 23 degrees C during the sampling period. Relative humidity varied between 65% and 90%. Temperature and relative humidity concentrations were similar in the area of the cooler and in the brine tank areas due to the fact that the processes are extremely close to one another.

3.1.4 Plant 4

Plant History

Plant 4 is the smallest operation studied, both in terms of volume of raw crab processed each year and the size of the main processing area. The total area of the holding room is 826 m^3 and the butchering area 106 m^3. The area of the cooking room is 79 m^3 and the main processing room where the crab is sorted, cleaned, scored and frozen is only 532 m^3. This plant is licensed to produce snap and eat products. These products are cooked sections that are cleaned and scored once across the legs using table saws. The plant has a maximum quota of one million pounds a year and has been processing snow crab since 1999. Between 2000 and 2003 this plant processed an average of approximately 400,000 pounds of raw crab per year.

Processing Overview

Consider the schematic of plant 4 shown below in Figure 3.4.

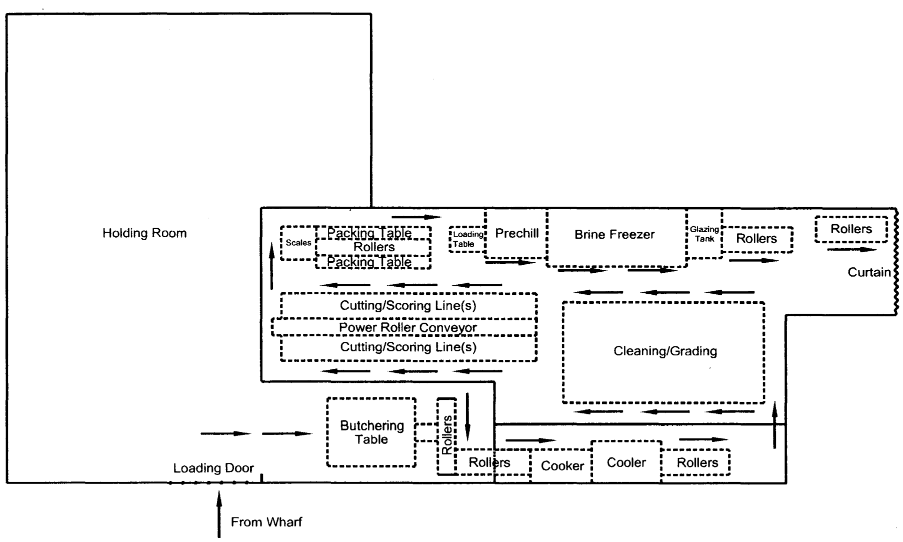

Figure 3.4: Plant 4 process flow

Production begins at plant 4 with the offloading of the live crab with a forklift from boats docked at the nearby wharf and placing it in the holding room. The live crab is piled in the holding room in bins and iced until it is ready to be transported to the butchering room. Once the crab is butchered it is loaded onto a metal pallet that carries a number of crates of raw, butchered crab and pushed through an opening in the wall connecting the butchering room to the cooking room. Inside the cooking room the pallet is lifted and lowered into a hooded batch cooker and then into an adjacent batch cooler by a hydraulic lifting assembly. The crab is then removed from the cooler and stacked next to the wall in the far end of the cooking room where it awaits a short trip through another access hole in the cooking room wall linking it to the main processing area. The crab is then processed at the sorting and cleaning table where it is cleaned of any dirt and barnacles using mechanical brushes and manual scraping techniques, and then sorted according to size. Troughs built into the table distribute the sized crab clusters into separate crates located on the floor underneath the troughs. After the crab is removed from this area it is taken to the sawing tables where the clusters are scored using table saws. Scoring enables the consumer to easily break the legs and remove the crab meat contained inside. The crab is then repacked into crates, weighed, and sent to wait to be loaded into the brine freezer to be frozen. Once removed from the brine freezer it is packaged, boxed, and transported to a blast freezer for cold storage until shipment.

Ventilation

In plant 4 the butchering area is adjacent and open to the holding room, which is open to the wharf. The cooking area is a small enclosed room except for a small hatch in the wall to allow transfer pallets of butchered crab. This plant was the only one of the four to use only a batch cooker to cook all crab. The cooking room was temporarily full of visible steam when the crab was transferred from the batch cooker and placed in the cooking tank. The exhaust fan in the cooking room seemed to remove some of the steam but without a fresh air intake the fan could not possibly maintain a negative pressure with respect to the adjoining areas. A hole had been cut at some point in the venting pipe from the batch cooker to relieve some of the pressure inside the cooker so that the lid would not be sucked shut and difficult to remove. This hole inadvertently served two purposes as it relieved the pressure on the cooker cover and exhausted some of the steam that escaped into the cooking room. The main processing area where the sorters, saws, brine freezer, packers, and box washers are located had no ventilation during air sampling in year 1.

During year one of air sampling there were no fresh air intakes and no exhaust fans in this area. At the time of the year 1 air sampling it was noted that the only way that air could possibly circulate was through the movement of the workers, sporadic opening and closing of doors, possible infiltration, or temperature changes within the room, causing a convection effect, which is highly unlikely. It was noted that the air had a heavy feel as the working day progressed and a slight haze could be seen in the air in the corner where the saws and weights were located. Year two air sampling was carried out after changes had been made to the main processing area in the form of ten overhead exhaust hoods, one over each of the ten table saws. However, no fresh air intakes was introduced to replace any exhausted air. The hoods measured 2.5 ft long by 1.5 ft wide and were connected to a header in the attic via 3 inch diameter plastic hoses. A 3 hp exhaust fan located in the attic was connected to the header and served to exhaust the air through a rooftop vent.

Temperature and Humidity

In plant 4, humidity readings in the range of 50-75% were obtained at an average temperature of 18 degrees C in the sawing area. Readings obtained in the same area when the plant was not in operation yielded humidity readings in the range of 60-

65% at an average temperature of 14 degrees C. Humidity readings of 80-90% were obtained in the cooking room with a temperature of about 15 degrees C in this area. Again, readings taken when the plant was not in operation yielded humidity readings of 60-70% with a temperature of about 12 degrees C, thus showing a clear drop in values when the cooker was not operating.

3.2 Air Sampling Results and Analysis

The following detailed air sampling results were compiled from sections contained in the final draft report (Neis et al, 2003) generated specifically for the crab asthma project.

In all four plants, confidential draft reports summarizing the results of air sampling in the plants were distributed to management and worker representatives, reviewed with them during teleconferences and then amended and finalized. These confidential reports contained general recommendations related to possible ventilation specifics. In three of the four study plants, management indicated that they had made some changes to their ventilation in response to the recommendations so the plant was re-sampled the following season. In two of the three cases, the actual changes were very minor or nonexistent and, not surprisingly, air sampling results were similar in the second season to those in the first season. In the third case, a ventilation system was developed by an outside contractor and implemented for the main processing area that had no formal mechanical ventilation during the first season of air sampling. Despite considerable investment, allergen levels did not change significantly.

Allergen levels in different plants and in particular areas in the plants can be affected by overall production levels, production processes, job tasks of the worker wearing the samplers, as well as by air flows, dilution and natural and mechanical ventilation. Approximate average production levels per shift at the time of the air sampling in each of the study plants were as follows:

- Plant 1: 61,500 pounds
- Plant 2: 32,500 pounds
- Plant 3: 18,000 pounds

- Plant 4: 17,350 pounds

Production levels in plant 1 were approximately 3.5 times larger than those in plants 3 and 4. Production levels in plant 2 were approximately half the level of those in plant 1 but almost twice as high as those in plants 2 and 3 during the air sampling periods. Production levels did not vary substantially from year to year in plants that were re-sampled a second time. Due to the fact that some production processes are more automated and less labour intensive than others, the ratio of pounds of crab processed to the number of workers on a shift varied between plants with workers in plant 1 processing more crab per worker than in the other plants. However, as indicated by the PBZ sample results, this did not mean higher exposures for these workers. Differences in the raw material, the actual process, and end product would also have affected the nature and extent of their interaction with each pound of crab they handled and ultimately their allergen exposures. In addition, because of complex airflows and production processes like cooking, cleaning, etc., individual allergen exposures would be affected not only by the amount of crab being manipulated by individual workers and the nature of their manipulation but also by indirect exposures related to their proximity to other workers, to processes responsible for aerosolizing the allergen, and to local and general airflow patterns.

In plant 2, products consisted of approximately 80% industrial cluster and 20% trimmed grade A products. In plant 3, production consisted of sections where limited cleaning using water jets took place prior to cooking. The cooker was in the main production area but hooded and vented. Sections were automatically graded in the second year and the product was brine frozen with no post-cooked crab cleaning. Meat products are not processed in this plant. In plant 4, production was 100% snap and eat crab sections that were cooked, cleaned with rotating brushes, graded, scored using table saws and brine frozen. In all participating plants the crab is butchered raw. However, in plant 1, butchering takes place in the main production area and occurs after blanching and cleaning whereas in three of the plants, butchering takes place in a room partially or almost completely separated from the main processing area. Products consisted primarily of sections with some whole crab production. Butchering, cleaning, sorting and grading occurred after blanching and cleaning using water jets but prior to cooking. All cleaning was done manually on the raw product only and did not involve the use of mechanical rotating brushes. Mechanical ventilation was in place along with some enclosed and nonenclosed hooding for particular processes like blanching, water jet cleaning and cooking.

In order to determine the amount of aerosolized crab protein that may be present it was necessary to sample the air using both area samplers and personal breathing zone (PBZ) samplers. PBZ samplers were voluntarily worn by workers at each process of the processing line in each of the four plants. In addition to the normal processes that were common to all plants, PBZ's were also worn by workers at plant specific locations comprising a variety of specialized tasks. The area samplers were placed in strategic locations throughout the plant so as to not disturb the natural production flow and at the same time obtain the most representative samples possible. In all cases, area samples were based on samples of two hours duration. There was some variability, however, in the duration of PBZ air samples with most, except those in plants 4 and 1 lasting the length of a full normal shift (approximately 8 hours). In plants 4 and 1, pumps were worn for an entire shift if possible, however the average sampling duration for the PBZ's was about 250-300 minutes (4-5 hours). Sampling took place whenever the workers were processing crab. In all four plants, the pumps ran at a constant flow rate of 3.0 l/min.

Filters in both type of air samplers were polytetrafluoroethylene (PTFE) and were 99.9 % efficient for 0.3 micron size particulates. For the analysis of the allergen samples themselves, a pool of reactive sera from snow-crab sensitized individuals was assembled. Snow crab cooking water proteins were immobilized on the surface of Immulon IV (Dynex Corp., Chantilly VA, USA) plastic μl wells. The cooking water protein was diluted to a concentration of 10 μl/ml in 200 mM carbonate buffer, pH 9.2, and 100 μl was added to each well and the mixture incubated at room temperature overnight. After washing the wells, 50 μl of the filter extract or dilutions of the snow crab cooking water protein reference standard containing defined mass units, along with 50 μl of the serum pool. This reaction mixture was incubated overnight at room temperature. Rabbit I-labeled anti IgE was added to each well (100 μl) and again incubated and washed the mixture as before, prior to gamma-scintillation counting. A total of 237 air samples were obtained for allergen sampling, 108 were PBZ samples and 129 were area samples. Fourteen PBZ and 37 area samples were collected in plant 1 (the only plant for which we have air samples for only one season), 43 PBZ and 38 area samples were collected in plant 2, 35 PBZ and 37 area samples were collected in plant 3, and 16 PBZ and 17 area samples were collected in plant 4. These figures do not include the 10 air samples done for the raw crab experiment.

In general plants 2 and 4 had substantially higher levels than the other two plants indicating that there was no close relationship between allergen levels and the overall volume of crab processed. This suggests that production processes and ventilation play a key role in dictating allergen levels.

As indicated in Figures 3.5 and 3.6, a comparison of allergen levels in samples from the four study plants by job task indicate that high allergen levels are associated with particular job tasks including in particular sawing and sorting and brushing. The pattern is generally similar for PBZ and area samples.

Figures 3.7 and 3.8 compare allergen levels associated with areas where workers are handling raw versus cooked crab. Cooking areas refer to the areas adjacent to the

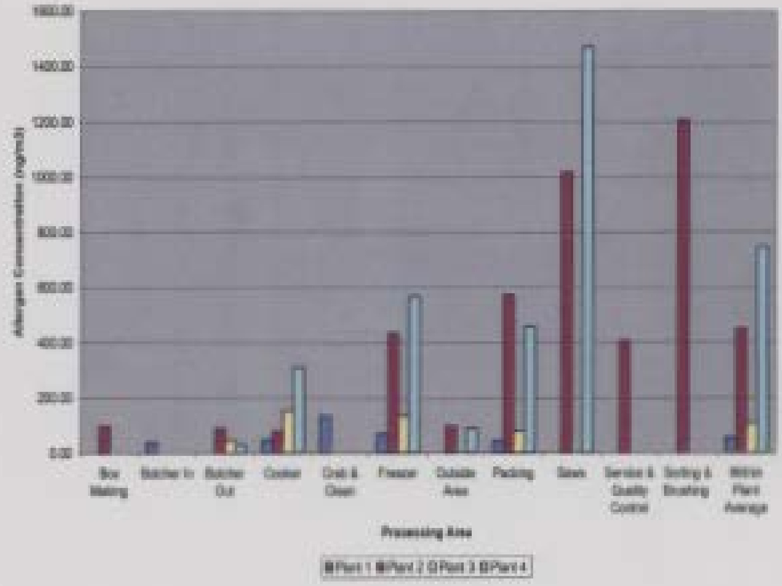

Figure 3.5: PBZ sample allergen levels

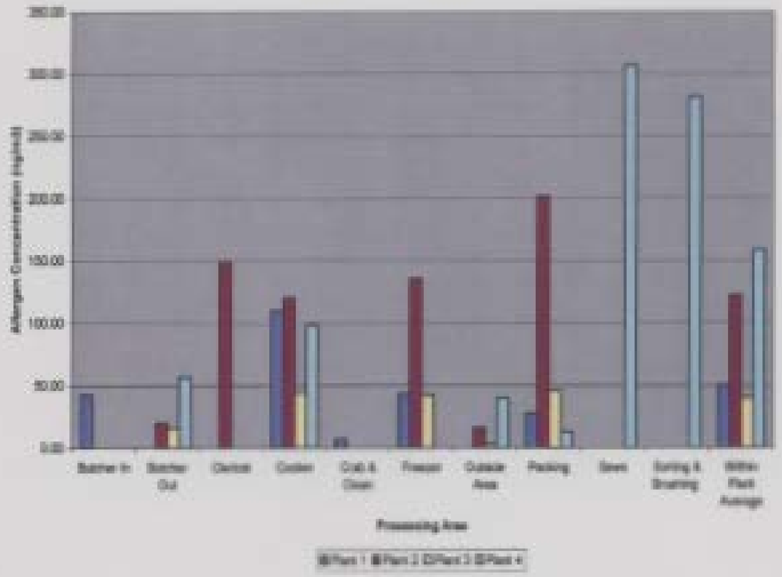

Figure 3.6: Area sample allergen levels

cooker. These show that high allergens levels are generally associated with manipulation of cooked crab.

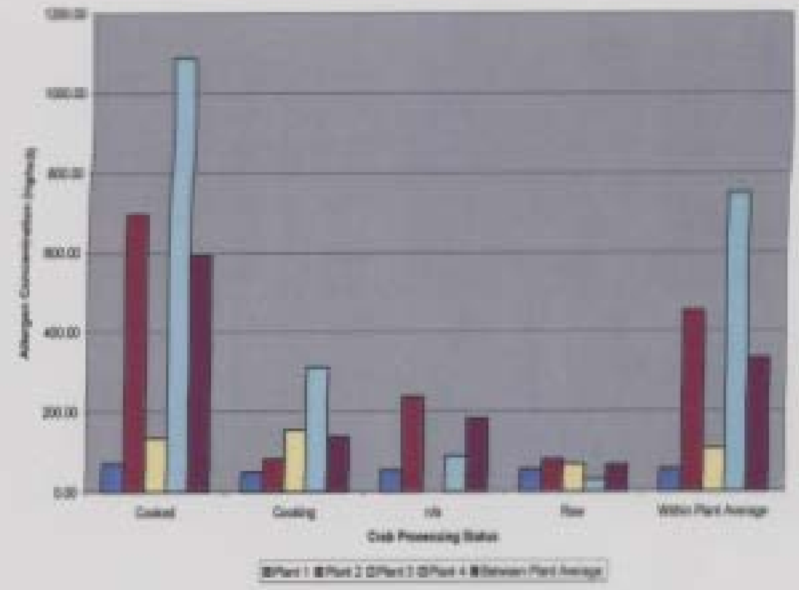

Figure 3.7: PBZ allergen levels by crab processing status

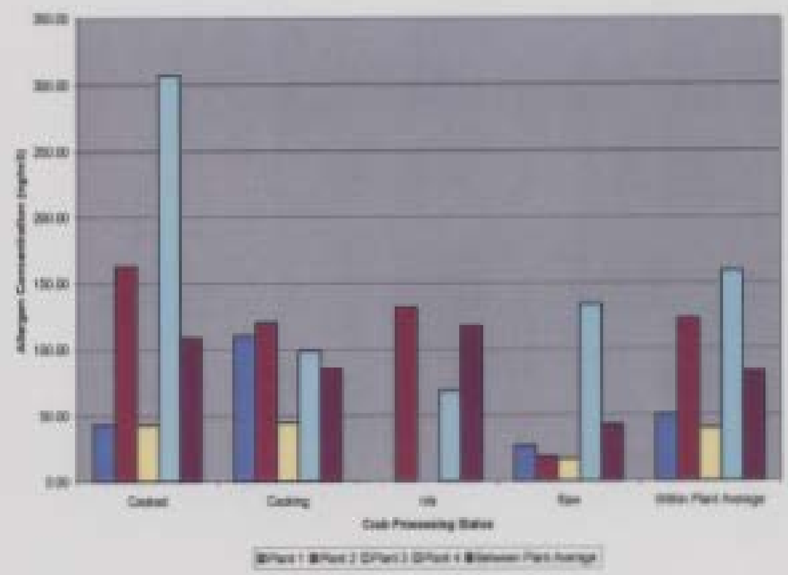

Figure 3.8: Area allergen levels by crab processing status

Interpreting Air Sampling Results

During recent interviews with workers in plant 1, it was discovered that conditions in the plant may not have been entirely typical during the air sampling visits. Several workers noted that there were virtually no boil-overs during air sampling. It was also reported that the plant was producing mainly raw crab during that time. It is likely that allergen levels in this plant are higher than those reported when crab is being cooked and the cooker is boiling over. The research team was hoping to re-sample the air in this plant during the 2003 processing season but the plant owners could not be contacted to arrange a time. Interviews with plant workers indicated that plant 2 processes some meat products from any damaged crab that is obtained, however no meat production was taking place when air sampling was done during the 2002 season. Given that the air sampling results indicate that cleaning, washing and sawing cooked crab is associated with high allergen levels in the absence of effective ventilation, it is likely that allergen levels in this plant are higher than those reported when meat is being produced.

All PBZ and area air sampling results have been tabulated for each plant in each of the years that air sampling was carried out. They have been included in appendices A, B, C, and D.

3.3 Allergen Levels

The crab asthma study is, in general, essentially comparing allergen levels and ventilation systems in four plants that have different production processes in addition to processing differing volumes of crab. Production volumes in these four study plants range from less than 500,000 pounds per year of raw crab up to 6 million pounds per year. Concentrations of airborne snow crab allergen in the 4 participating Newfoundland and Labrador plants ranged from less than 10 ng/m^3 to greater than 1000 ng/m^3. Two of the four plants demonstrated maximum measured airborne concentrations in the 100's of nanograms while the other two had maximum concentrations in the 1,000's. In instances where bio-aerosol concentrations of asthmagenic agents were observed to vary by orders of magnitude of this kind, a significant risk exists for sensitization to occur. High concentrations have been observed more often in certain areas of the processing plants and have also been associated with discrete tasks. Recent Quebec research has identified plants with allergen levels in all areas below 100 ng/m^3, similar to two of the four plants in this study which have been identified to also have levels close to this limit.

It has been recommended that permissible maximum exposure limits not exceed 100 ng/m^3 from PBZ samplers with this threshold being lower for area samples. Plants have been identified in Quebec and in Newfoundland as having concentrations considerably below 100 ng/m^3 suggesting that this is an achievable goal. While it is true that some workers who are already sensitized may react to lower concentrations (i.e. less than 100 ng/m^3) it seems most prudent to recommend target concentrations which are achievable and most likely to prevent or minimize sensitization. If the maximum is set at 100, there will be many areas in the plants with substantially lower levels where sensitized workers could be relocated, although this will have to be done with close monitoring and understanding that levels may still be too high for highly sensitized individuals.

This maximum upper limit of 100 seems appropriate for the short term, however it can be reviewed and adjusted on the basis of future research. Based on the fluidity of crab processing and related changes in final products that occur within individual plants, a design that will completely rid the plant of allergens will be difficult to achieve but by no means impossible. Fluidity of the workers and the equipment are just two of the many design parameters that have to be taken into account in the design process. If it becomes possible to accurately determine the locations of the allergen concentrations within the plant then safely removing them is indeed feasible.

3.4 Allergen Identification

The most abundant, airborne protein sampled in the crab plants has been identified as tropomyosin. This protein was found on an air sample collected during the study. It was also found in steam produced while cooking snow crab. Although only one of the airborne proteins in crab plant atmospheres to which workers are reacting, tropomyosin is an excellent quantitative marker for allergen levels. If tropomyosin levels go up, so do the levels of the other proteins. Prior to the crab asthma study, no information was available about the proteins that are allergenic in snow crab, particularly in occupational settings.

The pool of IgE-positive snow crab worker sera reacted to several proteins present in a filter from an air sample taken during this study. The molecular weight of these proteins were found to be 50.1 kD, 43.2 kD, 34 kD, 18.5 kD, and 14.4 kD where the 34 kD protein elicited the greatest intensity of IgE-reactivity in the sera sample. These findings are consistent with a previous report by (Leung et al, 1998) that describes the molecular characteristics of the major IgE-reactive molecule in crab as having a molecular weight of 34 kD. This investigation was based on the sera reactivity (IgE) of individuals who have an allergic reaction to crab after it has been ingested into the system. The molecular mass of the protein tropomyosin has been determined to be around 50 kD. However, in general, high molecular weight sensitizers (proteins or glycoproteins) are in the 5-70 kilo daltons range and can provoke a specific IgE response in workers exposed to these agents (Houba et al, 1996). For example, sensitization to a high molecular weight antigen liberated during the crushing of shells, the boiling of whole crab, and the separation of legs and claws has been demonstrated (Cartier et al, 1986).

The presence of IgE-reactivity in the snow crab worker sera to the proteins in the filter extract provides evidence of a direct link between occupational exposure and the risk of sensitization, as opposed to other routes of exposure such as ingestion of the proteins. The presence of snow crab proteins in the air filters indicates that numerous snow crab proteins are aerosolized during processing indicating a potential source of worker sensitization that may be especially important in occupational asthma and rhinitis. Evidence from mass spectrometry suggests that one of the important proteins to which workers are becoming sensitized is in fact tropomyosin. Known to be an important crustacean allergen, tropomyosin was found in both the analysis of the contents of an air sample filters and in condensate made from the steam produced during cooking of snow crab. This work also indicated reactivity to some other proteins and indicated that cooking may in fact alter these proteins.

3.5 Cleaning Chemicals

Interviews with workers and management in all four plants has led to monitoring more closely the potential role played by cleaning chemicals and cleaning processes in contributing to breathing problems among plant workers. It was discovered that in plants 2, 3, and 4 some of the regular crab processing workers also do clean-up. It is therefore possible that some workers may be experiencing breathing problems as a result of a reaction to some or all of the cleaners rather than a reaction to the crab. This is important because some of the breathing problems identified in worker histories could be caused by exposure to cleaning chemicals. Unfortunately all of the MSDS's (Material Safety Data Sheets) for the cleaning chemicals used in some of the plants were not obtained. According to the MSDS's received, however, the chemicals being used can indeed cause serious respiratory problems. The obtained MSDS's for cleaning chemicals used in crab plants generally do not indicate that workers need to wear masks. However, they assume the presence of an adequate and appropriate ventilation system. Minimizing exposures to cleaning chemicals as well as crab allergens might also reduce the risk of breathing problems.

3.6 Raw Crab Experiment

Research to date has led to an hypothesis that processing the crab prior to cooking results in lower levels of aerosolized allergens. An experimental study has been designed and carried out to test this hypothesis. The main question that needed to be answered was would processing the crab before cooking it reduce allergen levels by a minimal or significant amount. Research to date has also suggested that processing (cleaning, brushing, etc.) crab prior to cooking results in less aerosolization of allergens than when the same processes are executed after the crab is cooked. The relatively low allergen level results obtained in this study associated with work areas where raw crab is being handled would tend to support this hypothesis. Looking more closely at this question in the last year of the study we designed an experiment to test this hypothesis in one of our cooperating plants.

The experiment was carried out in plant 4 on August 18th, 2003. The experiment was conducted by sampling the air using personal breathing zone samplers (PBZ's) at the beginning of the shift until a quota of 500 pounds of raw crab was processed. The cassettes containing the samples were then removed from the PBZ's and replaced with new ones and then same process was repeated with cooked crab instead of raw crab. The raw crab part of the experiment required a reorganization of the normal production process at this plant for the period of time needed to process the crab prior to cooking. This meant that the crab was butchered as per normal and then proceeded to the main processing area instead of heading to the cooking room to be cooked. Once in the main processing area the normal processes were carried out in the same manner as if the crab were cooked. Finally the crab was sent to the cooking room and then to the brine freezer, packed, and stored in the blast freezer. The work area was then cleaned in preparation for the cooked crab part of the experiment. This part of the experiment was carried out with the plant processing crab as per usual, with samples being taken until the 500 pound quota had again been reached. It should be noted here that since there were only 5 PBZ's in operation during this experiment and due to the fact that there are only about 7-8 workers involved in the experiment, workers had to move from process to process throughout the duration of the experiment to maintain the flow of crab. Results from this experiment are shown in Table 3.1.

Table 3.1: Raw/Cooked crab experiment results

Plant 4, Raw Crab Experiment Allergen Personal Samplers July 21st, 2003. Sampler: Brad Pelley

Calibrated by: Brad Pelley **On:** July 21st, 2003

Sample #	Pump #	Sample Type	Time On	Time Off	Elapsed Time (min)	Flow Rate (lpm)	Area	ng/m^3 Results	Operations Monitored	Remarks/Conditions
1	1	Allergen PBZ	7:30am	8:20am	50	3.00	Packing and Cleaning	<50	Grading and cleaning crab and packing into crates	Processing raw crab.
2	2	Allergen PBZ	7:30am	8:20am	50	3.00	Saws/Packing	<50	Grading and cleaning sections as well as scoring clusters	Processing raw crab.
3	3	Allergen PBZ	7:30am	8:15am	45	3.00	Saws	<50	Scores (Saws) the sections	Processing raw crab
4	4	Allergen PBZ	7:30am	8:10am	40	3.00	Saws/Packing and Weights	<50	Grading and cleaning crab sections as well as scoring clusters	Processing raw crab.
5	5	Allergen PBZ	7:30am	8:05am	35	3.00	Saws	514	Scores (Saws) the sections	Processing raw crab.
6	1	Allergen PBZ	8:30am	9:15am	45	3.00	Packing	1052	Grading and cleaning sections	Processing cooked crab.
7	2	Allergen PBZ	8:30am	9:10am	40	3.00	Saws	550	Scores (Saws) the sections	Processing cooked crab.
8	3	Allergen PBZ	8:30am	???	N/A	3.00	Saws	N/A	Scores (Saws) the sections	Processing cooked crab. Pump was off when returned.
9	4	Allergen PBZ	8:30am	9:10am	40	3.00	Saws	508	Scores (Saws) the sections	Processing cooked crab.
10	5	Allergen PBZ	8:30am	9:05am	35	3.00	Saws	619	Scores (Saws) the sections	Processing cooked crab.

From this experiment it can be seen that the allergen concentration levels when crab was being processed in the raw state were consistently lower than the levels observed during cooked crab production. There was however one curious reading occurring from the raw crab portion of this experiment, namely the 514 ng/m^3 sample. An explanation for the probable cause for this reading is not known at this time.

This simple experiment seems to validate the hypothesis that processing the crab raw seems to be somehow linked to a consistently lower release of crab proteins that have been linked to instances of crab asthma. The hypothesis also holds true in plant 1 where they do all their processing raw prior to cooking which seems to account (along with the ventilation system) for the relatively low levels of measured aerosolized allergens. These preliminary results may be perceived as an indication to all plants that currently process in the cooked state that they may want to re-evaluate their production methods to reflect the findings of this experiment and this research in general. However, because it is now known that allergens differ somewhat between raw and cooked crab there is a need to re-analyze the raw crab air samples using sera from workers reactive to raw crab to ensure that the results have not underestimated allergen levels associated with raw processing. In addition, the differences in allergen concentrations between raw and cooked crab processing are not large, something that is not surprising given the relatively small amount of crab (500 pounds cooked and 500 pounds raw) and the level of sensitivity of the PBZ air sample results (less than 50 minimum levels). It is important to verify these results further before making a recommendation to industry that they consider switching from cooked to raw crab processing. In addition, it is promising that the experiment found that raw processing resulted in higher yields, thus verifying anecdotal information received from researchers working in other provinces.

3.7 Result Summary and Discussion

The primary goal of the research presented in this thesis is to examine interactions of possible aerosolized contaminants with simulated airflow patterns and velocity distributions within the crab plants involved in the study. Various ventilation methods will be examined to determine which ones prove to be the most effective in containing and eliminating aerosolized contaminants. In summary, the basic exposure control strategies that will be addressed are:

- reduction/elimination of contaminant sources
- local hooding with exhaust
- general ventilation
- other exposure control techniques

Reduction or elimination of the contaminants at the source is probably the most effective control method. Variations in processing techniques are currently being investigated and may prove to significantly lower the amount of antigen being aerosolized. Isolating various processes such that the aerosolized particulate can be denied access to the rest of the workplace will undoubtedly lower overall contamination levels.

Local source control is more effective than control by general ventilation methods due to the fact that the particulate, namely proteins, are generated in large volumes and in some instances with high velocities (brushing, sawing processes). Air movement through local hoods is vented at high velocities and exhausted directly to the exterior of the enclosure. The downfall in using this type of control strategy is that for all the air that is exhausted there needs to be at least equal amounts of makeup air brought back inside. This may be undesirable as new air may need to be filtered and conditioned again before it enters the workplace which wastes valuable heating and cooling energy. Using general ventilation whereby the contaminant concentration levels are diluted to acceptable levels is normally not the primary exposure control strategy implemented. The ideal situation would be to avoid having contaminants mix throughout the workplace if at all possible. Due to the fact that the quantities of contaminants released are unknown, exhaust air may need to be cleaned before being released into the community environment (McDermott, 1977). Another possibility is the recirculation of indoor air through various filters without having to exhaust any indoor air or bring in any new outdoor air. The lack of even a small percentage of fresh air may cause problems if the filters become plugged or fail to capture the airborne particles.

Other exposure control methods can be implemented other than introducing ventilation systems. Contamination that originates from crab protein antigens, cleaning agent fumes, or other miscellaneous sources can be controlled by a variety of other methods. In the case of the cleaning agents, substitution of less hazardous substances may drastically reduce harmful substances in the workplace. Changing the production processes to reduce the amount of contaminant released into the workplace is also a viable exposure control method. Air cleaning strategies have not been considered as a practical exposure control technique, mainly due to the fact that in general the air is cleaned after the contaminants are fully dispersed and are therefore at their lowest concentration. Regardless of the particular control strategy chosen the means by which the toxic contaminants are generated and eventually distributed throughout the workplace needs to be determined.

At this point in the study, the assessment of any existing ventilation systems that were present has provided a better sense of how the air may or may not be moving inside the plant. Lack of ventilation in many areas of the plants will most likely contribute to the buildup of allergens over the course of the day as there are no means by which allergens can be exhausted. Areas of high allergen concentrations that may coincide with areas with little or no means of ventilation is an important correlation. Identification of high exposure areas will aid in the improvement of ventilation methods in those areas. However, due to the fluidity of the crab industry and the constant movement of workers and equipment to meet the needs of the industry, ventilation design is a formidable task. Therefore a need exists to develop numerical simulations in order to obtain a better understanding of the airflow characteristics in a typical processing environment with the intent on providing feasible and viable solutions that can be examined and possibly implemented.

From the plant histories we have learned that most plants differ from one another and no two are exactly the same. Work histories are important in the attempt to correlate instances of OA to specific workers. The location in which they worked, how long they worked there, what the ventilation systems were like during that time, what type of crab they were processing, and how much of it they were processing are all examples of important issues provided by individual plant histories. In addition, background information on previous processing techniques and ventilation methods are helpful in identifying areas that have been altered over time as well as areas that could be improved.

Along with the plant histories, processing overviews are essential in attempting to link high allergen concentrations to specific crab processes. The proximity of processes to each other is common in crab plants, which makes it difficult to determine which process is responsible for the allergen concentrations measured in the air. Each process is unique in that they each can provide distinctive methods of allergen production. It was important to understand the ways in which the workers complete their tasks as it provides insight into the probable locations of allergen generation, magnitude and direction of allergen projection, and a basis for preliminary exhaust hood design. Since crab processing environments differ from other industrial environments, ventilation methods have to be designed with this in mind to ensure both an effective contaminant capturing and ergonomically feasible design. Knowledge of each process and how they function together is also important in identifying areas that may be changed or improved. Changing and reorganizing processing methods may have an appreciable effect on resulting allergen levels. Preliminary experiments have shown that by processing crab in the raw state instead of cooked without actually changing the actual processing methods has produced lower allergen levels.

Temperature and relative humidity values were collected during the air sampling periods to attempt to develop a correlation between high allergen readings and high temperature and/or humidity readings. Identifying areas where temperature and humidity values are high is important for a couple of reasons. Areas where the temperature and humidity are high in addition to having high allergen levels can cause a very unhealthy working environment. The air tends to have a 'heavy' feeling and breathing may become difficult, as is normally the case in any area experiencing high temperature and humidity values. Also, areas of high humidity, especially in the cooking areas can indicate the presence of steam that suggests that the cooker may be leaking steam into the working environment and thus the venting of the cooker may need to be examined. Steam leakage can also cause the walls and ceilings of the workplace to become damp and moldy, thus introducing another contamination source. Raw data shown in appendices E, F, G, and H was collected using data loggers which were activated and deactivated via computer software. The data loggers were placed in selected areas and run for a variety of times from a couple of hours up to twenty four hours.

Air sampling results obtained from the PBZ and area samplers have identified areas in the crab plants producing a variety of allergen concentration levels. The concentration levels range from less that 10 nanograms per cubic meter to levels in the thousands of nanograms per cubic meter. From this, we have learned that different processes seem to be responsible for the different allergen levels. When allergen levels at certain processes are compared across plants, the results are similar suggesting that some processes are indeed more likely to produce allergens than others.

Chapter 4

Local Ventilation Conceptual Design

Ventilation is undoubtedly one of the key methods for reducing worker exposure to airborne contaminants resulting from crab production processes such as butchering, cooking, cleaning, sawing, sorting, grading, weighing, brine freezing, and packing. Due to the fact that air is virtually invisible it is often difficult to visualize its movement through an enclosure such as a room, into a ventilation system, through the connecting ductwork, and exhausted to the outside. Since the laws of fluid dynamics must always be adhered to, a system must be designed in accordance with these laws to ensure that the system works properly. In most cases, ventilation systems that do not work properly are deficient because one or more airflow principles are violated in their design or operation (McDermott, 1977). The ideal situation is to be able to design a system that will capture or contain all airborne contaminants emanating from a particular process or operation. A local hood design needs to be designed such that it minimizes airflow requirements, protects worker breathing zones, follows design recommendations, and makes it usable by workers to avoid all common hood selection fallacies.

Designing local or general ventilation systems for existing plant structures that were not designed to incorporate any required ventilation is difficult and sometimes proves to be virtually impossible. In each of the four participating crab processing plants in this study, all but one had little or no formal ventilation system installed able to effectively remove harmful airborne contaminants from the occupied spaces. As a result, the design options are limited and the best case design may not be feasible mainly due to lack of space for installation. Processes are sometimes laid out in such a way that inhibits installation of a system.

4.1 Local Exhaust Ventilation Systems

A simple exhaust system can be said to exist of a fan, ducting, and an array of air inlets and exhaust outlets based on individual design specifications. The fan is the energy source that causes the air to move by transferring air molecules from the downstream duct to the upstream duct. The act of physically removing air particles from the downstream duct causes a partial vacuum to be created inside the duct. Air molecules move from outside the duct to fill this partial vacuum, and it is this motion that constitutes the airflow into the hood (Burgess et al, 1989). In general, air is therefore being moved from an area of high pressure to an area of lower pressure by a fan. The fan has to produce enough negative pressure to draw in the required amount of air into the exhaust hoods such that airborne contaminants are exhausted from the workplace.

Local exhaust ventilation (LEV) systems are designed to collect and remove airborne contaminants consisting of particulates (dust, fumes, smokes, fibers), vapors, and gases that can create an unsafe, unhealthy, or undesirable atmosphere (ASHRAE Handbook (Applications), 1999). LEV systems are normally used in situations where the control of air pollutants, is desired and the capture and exhausting of these pollutants is of the utmost importance. Local exhaust systems can be classified by contaminant source type, by hood type, and by system mobility (ASHRAE Handbook (Applications), 1999). These three classifications have been used to differentiate between the exhaust system types investigated here.

A process or operation needs to be fully understood before an effective exhaust hood design can be conceived and implemented. The size and type of hood must match the type and geometry of the contaminant source or sources such that the contaminant can be effectively removed. Posokhin (1984) classified sources as either buoyant (heat), non-buoyant (diffusive), or dynamic. The main source of appreciable heat generation present in crab plants capable of forcing allergen into the air would probably come from cooked crab, cookers and cooling tanks. Buoyant sources have not been examined in this thesis as they could not be modeled at this time. The focus is therefore directed toward non-buoyant and dynamic sources. As a result, it will be assumed that any surrounding air patterns will ultimately determine dispersion rates and facilitate particle transportation to adjacent areas instead of any temperature induced movement. Non-buoyant sources are present in crab plants at locations where crates of cooked (and possibly raw) crab are stockpiled to be brushed, sawed, cleaned, packed, etc. Dynamic sources are present in areas where the allergen is forced into the air by a high velocity particle flow, as is the case with the rotary cleaning brushes at the cleaning/sorting table or the table saws at the scoring tables. Both of these tables include a mixture of these two source types as crab is also piled near and on top of these tables. An alternative source of allergen production could originate from crab waste collected in plastic crates underneath the sorting/cleaning table. The waste generally consists of bits of shell, dirt, and broken legs. This crab waste is normally removed from the table via a conveyor belt with the majority of it being collected by the crates but some is wasted over the side and onto the plant floor.

Exhaust systems can be further classified by hood types, which basically consist of either the enclosing type or the non-enclosing type. Enclosing hoods are capable of better contaminant control and removal due to the fact that any air movements within the workplace do not affect the removal process making the subsequent exhaust rate of the hood minimal. The main problem with using totally enclosing hoods is the ensuing lack of access to the process, thus resulting in their use being restricted to the most hazardous of exposures. In the snow crab industry the workers must have access to most processes in the processing line, especially the cleaning/sorting and sawing tables in addition to any batch cooking or cooling. The main exception to this are the continuous cookers and coolers that only need a worker to load the crab at one end and a worker to remove the crab from the other end.

Non-enclosing hoods are normally used if the process being exhausted needs to be accessible to the workers, as is the case with many of the processes in the snow crab industry. With these hoods, contaminants released outside the hood must be captured by the hood rather than allowed to escape to the general workspace. Since totally enclosing a sorting or scoring table was not a feasible option, non-enclosing types of exhaust hoods were examined for methods to effectively control and exhaust pollutants. Unfortunately, from the time the contaminant is released to the time it is captured by the exhaust system it can undergo numerous adverse effects from external sources such as extraneous air movements due to nearby structures and moving machinery. It is therefore important to note that airflow patterns that surround processes must be paid close attention to in order to allow a non-enclosing hood to function at its maximum capacity. Figure 4.1 depicts the two general hood types.

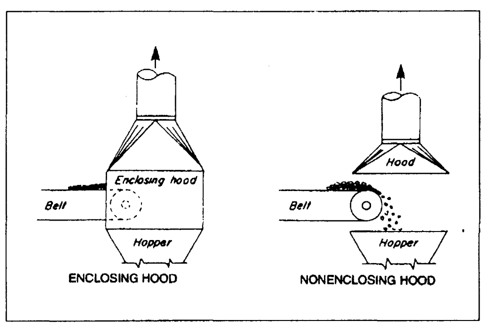

Figure 4.1: Enclosing and nonenclosing hoods (ASHRAE Handbook (Fundamentals), 2001)

Non-enclosing hoods are further classified as updraft coaxial, side draft (or slotted), and downdraft types, depending on the mechanism by which they remove the plume generated by the contamination source, as can be seen in Figure 4.2. All three hood types are examined in this thesis, but due to various limitations that become evident later, only updraft coaxial and slotted draft hoods have been presented and numerically modeled.

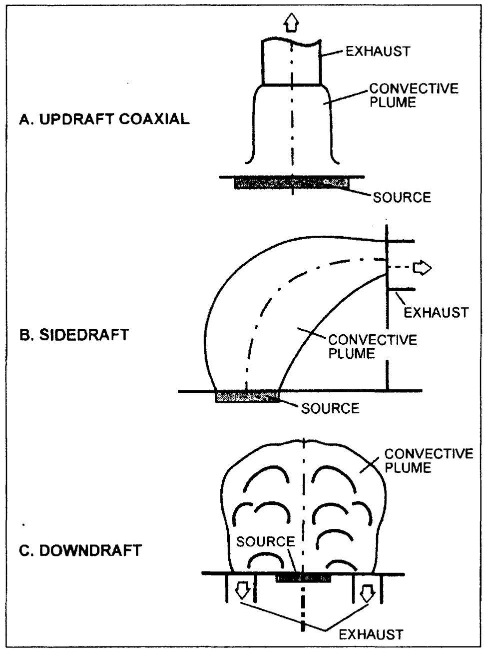

Figure 4.2: Fundamental exhausting methodologies (ASHRAE Handbook (Fundamentals), 2001)

As a final note, in addition to classifying systems by contaminant source type and by hood type we can also classify by system mobility. Local exhaust systems with non-enclosing hoods, such as the ones analyzed here, can be either stationary, movable, portable, or built-in. Since cleaning/sorting tables, sawing/scoring tables and cooking/cooling tanks remain at a fixed location during production, only stationary types of hoods have been applied.

4.2 Non-buoyant and Dynamic Contaminant Sources

There are a number of non-buoyant allergen sources in a typical crab processing plant capable of releasing harmful allergens into the workplace. Some of the obvious sources occur from stockpiled crab awaiting further production (weighing, sorting, etc.), crab waste located throughout the plant, dirty equipment, as well as worker clothing and apparel. Crab at plant 3 was witnessed to be piled neat the brine tank waiting to be weighed before heading to the brine tank, thus constituting a non-buoyant source. This crab sitting in the main processing area could come in contact with an airflow and result in allergens being transported to different areas of the plant, depending on the strength and direction of the air flow patterns.

In this particular case, the crab is iced, which will probably reduce the possibility of allergen being released into the workplace. However, in many cases the cooked crab is not iced thus increasing the risk of air contamination. Another possible contamination source is located at the sorting/cleaning tables in the form of crab waste collection crates. When the workers clean the crab the waste usually gets removed from the table via a water filled trough or conveyor belt located underneath the brushes. In plant 2, crab waste was partially collected in a crate placed in an area underneath the cleaning table ensuring that the majority of the waste was contained.

A fair portion of the crab waste actually ends up on the plant floor which is most likely transported around the plant via worker movement. Better control of the crab waste troughs could possibly be achieved simply by using bigger crates or better placement of the existing crates. At any rate, this collection of cooked crab waste would seem to be an ideal location for allergen generation. This forced impact caused both by machinery coming in contact with the crab and the crab falling from the table to the floor can be a catalyst for the aerosolization of allergens. Since the cleaning/sorting tables, scoring tables, and batch cooling tanks are being considered in this thesis as the main contaminant sources, correctly designed overhead hood or slotted hoods may be the ideal solution. Normally workers are partially leaning in over the cleaning/sorting tables when they use the rotary brushes to clean the crab. A similar situation occurs at the sawing/scoring table with the workers partially leaning over the table saws. Caution should be exercised when designing hoods for these areas, in particular overhead hoods, as they may draw in air from outside the hood area and further contaminate the breathing zone of the workers, as can be seen in Figure 4.3.

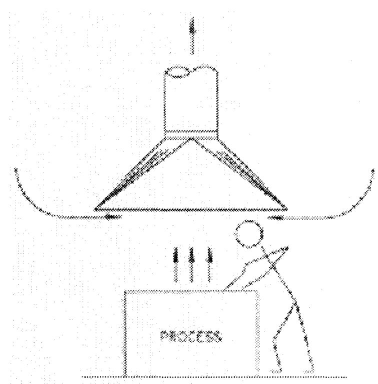

Figure 4.3: Influence of hood location on contamination of air in the operator's breathing zone (ASHRAE Handbook (Fundamentals), 2001)

Since the contamination sources are generally located at the different processing locations the probability of drawing in contaminants from other processing areas could be reduced if the exhaust rates and hoods configurations are specified correctly. The close proximity of the processes in most of the plants could cause an incorrectly designed hood to draw in contaminants from nearby locations.

Rotary brushes and table saws pose a different problem due to the dynamic nature with which the particulate is being released into the air. The brushes are 8 inches in diameter and 4 inches wide and are made of a hard, abrasive plastic material. They rotate away from the worker and are used to remove any dirt, barnacles, leech eggs, or any other material that needs to be removed before weighing, grading, freezing, etc.. The brushes are partially housed within the table in a small metal trough located underneath which attempts to collect the released particulate from the brushes. Only the bottom three quarters of the brushes are actually housed by the metal trough with the top portion exposed. The particulate being released into the air as a result of the crab being held against the brushes departs within a certain angular velocity range with respect to the table surface. Figure 4.4 below shows a possible approximate angular range of particulate release into the breathing zone of the worker. These detailed particle trajectories around typical grinding operations were observed by Bastress et al (1974).

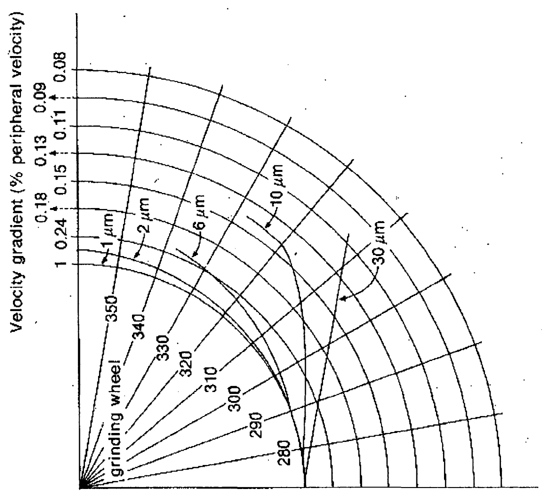

Figure 4.4: Possible direction of rotation and particulate release angle from rotary brushes (Bastress et al, 1974)

Larger particles do not remain airborne, but intermediate size particles remain airborne after they are released into the air from the brushes. From Figure 4.4, it can be seen that fine particles will usually follow the brush and are dispersed when they meet the next portion of crab being cleaned, thus making their path hard to predict.

The particulates associated with allergen will be represented by the entire range of sizes ranging from sub-micron to 20 microns or greater. Some will be liquid aerosol and some will be in a solid dispersion. If it is imagined that Figure 4.4 is the top quarter of the brush closest to the worker then it can be seen that particles in the range of 10-30 microns will be projected back into the worker breathing zone while particles in the 0-6 micron range will tend to travel around the periphery of the brush and be released away from the worker.

Similarly, the table saws at the scoring table also release particulate into the worker breathing zone. However, the fine particulate from these most likely in the range of 0-1 μm. In both cases, a hood correctly designed and installed should reduce the accumulation of particulates in the worker breathing zone.

4.3 Airflow Patterns

Understanding the nature of airflow patterns in general is essential in order to realize that a non-enclosing hood must reach out and capture the contaminated air beyond the boundaries of the hood. A poorly designed hood will invariably ensure that contaminants will escape in significant quantities into the workplace and cause increased worker exposure. Elements of critical importance in designing non-enclosing hoods for contaminant capture are;

- capture velocity required at the point of contaminant release and the surrounding environment
- airflow through the hood required to obtain the desired capture velocity outside the hood
- hood geometry

The proper determination of the capture velocity is critical in the design of a non-enclosing hood. Capture velocity (V_c) is defined as the minimum hood-induced air velocity necessary at the point of contaminant generation to capture and direct the contaminant into the hood (Industrial Ventilation, 1988). Capture velocity depends on distance from the hood, with increased distances evoking turbulence effects from various structures. The capture velocity must therefore be able to overcome any additional velocity disturbances present at the point of contaminant release. Once the necessary capture velocity is specified it is then used to determine a volumetric flow rate (Q_f) for the exhaust hood, keeping in mind that the selection of a capture velocity is by no means a straightforward task. To illustrate the importance of air patterns in the vicinity of a hood, consider the following situation depicted by a simple overhead hood in Figure 4.5.

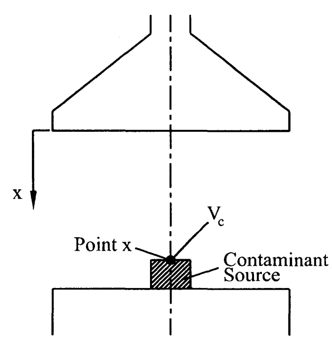

Figure 4.5: Overhead hood with contaminant source at location x

If it is assumed that all contaminant release processes occur in still air, then the value for the capture velocity V_c at point x could take on an easily determined numerical value. This still air situation would cause the determination of the magnitude of V_c to be trivial since all of the air passing point x will eventually enter the hood. However this assumption of a still air situation is unrealistic in a typical workplace environment and in particular the fast paced crab industry.

Air velocities created by a non-enclosing hood are imposed on a complex airflow pattern which is always present due to other sources of air movement, such as perimeter infiltration and process-induced airflows (Burgess et al, 1989). When a hood is introduced to real world conditions, competing airflows will distort the generated velocity contours. Distortions can arise from upward/downward convective flows, moving people, drafts from doors and windows, variations in hood design such as adding flanges and vanes, flow separation around a person or object in front or near the hood, and drafts created by equipment operation. Due to the difficulty in quantifying these various airflow patterns, for demonstration purposes, a constant and uniform cross-draft parallel to the hood face has been assumed as is shown in Figure 4.6.

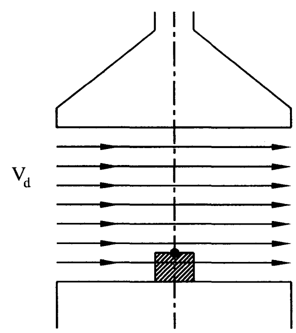

Figure 4.6: Uniform cross draft

If the general cross draft has a velocity of V_d at point x then the total velocity at point x is the vector sum of the two

$$V_{Total} = V_c + V_d \tag{4.1}$$

Whether or not the contaminant is drawn into the hood will depend on the relative magnitudes of V_c and V_d, as well as the distance between the release point of the contaminant and the hood face opening. This illustrates the importance of cross-drafts and how they can affect the performance of non-enclosing hoods, especially when the nature of the surrounding environment can produce complex flow patterns. In theory, were there no cross-drafts present then all of the contaminants in the hood capturing vicinity would be captured by the hood and exhausted from the workplace, however this is not likely to be the case. Each process/operation must be treated individually in that a specific capture velocity may be required whilst taking into account specific airflow patterns in the hood vicinity due to the nature of the workplace and its daily operation.

The inability to quantify both the existing airflow patterns and the effect of exhaust systems on those patterns limits the estimation of hood performance to an approximation. Given this, current design procedures result in capture velocities specified in a manner that acknowledges, either implicitly or explicitly the uncertainties in the design process (Burgess et al, 1989). Table 4.1 shows the typical ranges of capture velocities for different contaminant dispersion characteristics (Alden and Kane, 1982).

Table 4.1: Range of capture velocities

Condition of Contaminant Dispersion	Examples	Capture Velocity (m/s)
Released with essentially no velocity into still air	Evaporation from tanks, degreasing, plating	0.25 to 0.5
Released at slow velocity into moderately still air	Container filling, low-speed conveyor transfers, welding	0.5 to 1.0
Active generation into zone of rapid air motion	Barrel filling, chute loading of conveyors, crushing, cool shakeout	1.0 to 2.5
Released at high velocity into zone of very rapid air motion	Grinding, abrasive blasting, tumbling, hot shakeout	2.5 to 10

The main problem with this table is the range of capture velocities presented is large and the selection criteria are very qualitative at best. Some of the reasons for selecting velocities that fall within the high or low end of the velocity ranges are based on whether or not the hood is large or small and whether or not the contaminants are released into quiet air, moderately still air, or rapid air. All of these terms are undefined and unquantified, which makes it very difficult to choose a representative velocity. The lower end of the given ranges should be used in instances where room air currents are minimal or favorable to capture, contaminants are of low toxicity, production volume is low or intermittent, and if there are large hoods moving large masses of air. Likewise, the upper end should be used if there are disturbing room air currents, high toxicity contaminants, high production volumes, or if there are small hoods controlling local areas (Industrial Ventilation, 1988). In light of this, to overcome any error in choosing suitable capture velocities, a series of velocity values encompassing the whole range of velocities presented in the table has been used in the analysis. A range of velocity values is needed to account for the dynamic release mechanism caused by the rotary brushes and saws due to the fact that particulate, and therefore allergen, is released into the air at much greater speeds (ACGIH, 1988). As a result, a relationship for the velocity field needs to be either obtained from experimental data or from existing theoretical relationships.

Hood geometry is crucial in determining the amount of airflow needed for a specific application. The volume of airflow required to generate the necessary capture velocities will depend on the distance from the hood face and will vary greatly with hood geometry and adjacent turbulent structures such as equipment and people. Centerline velocities decrease rapidly with distance from the hood face in that the velocity reaches 10% of the hood face velocity within the distance equal to the square root of the hood face area, or one duct diameter. This assumes that there is no interference from the previously mentioned turbulent structures which would result in a different percentage. The addition of a properly sized flange has been shown to reduce the required velocity. Empirically, based on centerline air velocities only, the capture velocity at any distance x is increased by a factor of 1.33 (Dalla Valle, 1952) after flange addition. Typically, velocity distribution in the vicinity of the hood face area is not uniform but may assume a parabolic or even inverse parabolic profile. Wakes formed close to the hood sides, or vena contracta, reduce the effective suction area of the hood. The size of the wakes and how uniform the velocity will be, will depend on hood design. The formation of wakes and their magnitude will become evident in upcoming numerical simulations.

Determination of the velocity contours and pressure distribution near the hood face and surrounding environment has been accomplished by numerical modeling where a variety of centerline velocity relationships and velocity profiles for overhead exhaust and slotted hoods have been examined. Specific models have been chosen to bridge the gap between the theoretical relationships presented and the real-world situations encountered in the crab processing plants. Unfortunately, the problem with using these velocity centerline models is that they ignore the effects of turbulent structures on contaminant capture and transport (Varely et al, 1997) and do not describe any sort of velocity profile at the hood face or in the immediate vicinity, both of which will be discussed more in a later section and numerically modeled in chapter 5. In addition, due to their inadequacy in describing velocity profiles, a variety of experimental profiles should be imposed on the hood face boundary to determine which one will produce the desired capture velocities. Uniform, parabolic, and inverse parabolic velocity profiles are therefore applied.

4.4 Point and Line Sources

The installation of either an overhead or slotted hood will undoubtedly reduce the amount of aerosolized allergens entering the breathing zone of the workers. An induced vertical or horizontal airflow will most likely exhaust the contaminants and not force them into the worker breathing zones. Aerosolized allergens will naturally become weaker in concentration as they move away from their source. Theoretically, if the goal was to capture contaminants produced from a point source along the centerline of the hood then as long as the specified capture velocities along the centerline at that point were attained then it could be surmised that most if not all contaminants would be exhausted. Unfortunately this is not the case due to the fact that the contaminants are not released from point sources but rather from sources having an appreciable and definite area.

A point source can approximate airflow near a round or square/rectangular hood, and the linear source approximates the airflow near a slot hood (ASHRAE Handbook (Applications), 1999). A point source will draw air equally from all directions. If the exhaust flow rate is known, the velocity at any location x can be calculated by;

$$V_x = \left[\frac{Q}{4\pi x^2}\right] \tag{4.2}$$

This shows that the point source is taken as a small sphere with a surface area of $4\pi x^2$. Thus, in theory the velocity is shown to be inversely proportional to the square root of the distance from the hood. A slot hood can be modeled by a line source of suction whereby the velocity diminishes with distance as a function of the surface area of a cylinder instead of a sphere. Ignoring the cylinder ends gives;

$$V_x = \left[\frac{Q}{2\pi L x}\right] \tag{4.3}$$

Here the velocity is shown to be inversely proportional to distance (L) instead of the square root of the distance, which is an improvement. These relationships are valid only for hypothetical point and linear sources of suction. In reality, the suction is applied over a finite hood face area, and the hood and ducting take up a portion of the physical space surrounding the point of suction. Thus the assumption of these sources of suction for overhead hoods and slotted hoods is not exactly applicable in real life and thus must be modified to satisfy realistic situations. To determine how the contaminants behave as they move away from their specific source is of interest because if their path can be determined, then the airflow patterns present will dictate their motion and how they will be affected by the exhaust air stream. It may also lend an insight into alternative methods by which the pollutants can be removed.

4.5 Overhead and Slotted Exhaust Hoods

It is desirable to create an appropriate capture velocity at predetermined locations in front of the hood opening depending on the nature of the contamination. Unfortunately in overhead exhaust operations, air drawn into the hood opening is taken from all directions and even from behind the hood face itself, thus rapidly reducing the capture velocity with increased distance from the hood face. The addition of a simple flange will reduce the amount of air being drawn into the hood from locations behind the hood face and thus increase the capturing efficiency. Overhead and slotted hoods have been considered as mechanisms by which the airborne allergens will be removed. These hoods have been analyzed and compared with each other in order to determine the best hood design for the individual processes being modeled. Relationships proposed by Dalla Valle, Fletcher, and Conroy provide values for capture velocities at specified distances from the hood face along its centerline. An attempt will be made to mimic the values and trends produced by these relationships by imposing linear, parabolic, and inverse parabolic profiles on the hood face boundary. It is necessary to determine the velocity profile that will best represent the actual exhaust hood scenarios encountered in a typical crab processing facility. The relationships will be applied to both unflanged and flanged hoods in the following sections to provide centerline velocity information to further guide the velocity profiles mentioned here and included in chapter 5.

4.5.1 Unflanged Overhead Hoods

Since the hoods being considered are for typical cleaning/sorting, saw tables, and open cooking/cooling tanks which are typically rectangular in nature, one such expression for the centerline velocity for an unflanged rectangular hood has been proposed as follows by (Dalla Valle, 1952).

$$V_x = \left[\frac{V_f}{10(x^2/wL)}\right] \tag{4.4}$$

where V_x and V_f are the velocities at a location x along the centerline of the hood and at the hood face respectively. The hood area is denoted as A_f and the x term is the distance from the hood area to the location of the contaminant source. It should be stressed here that this is an empirical formula rather than one developed from theory. The applicable ranges on the variables used in the above equations are as follows, where w and L represent the width and length of the hood face.

$$0 < \frac{x}{w} < \infty \tag{4.5}$$

Since this is a centerline velocity function, the co-ordinate convention has been assumed to be x in the vertical downward direction and y in the horizontal left-right direction. Based on this relationship between the velocity, airflow, and distance from the source we can prescribe capture velocities at the point of contamination that will result in the required velocity at the hood face. It should be noted here that the capture velocity is analogous to the V_x term in all of the centerline velocity models presented. This makes sense because this is the velocity needed at a point x in order to ensure that the contaminant is captured by the hood air flow. Q_f at the hood face is calculated simply by multiplying the hood face velocity by the hood face area in the following manner;

$$Q_f = V_f A_f \tag{4.6}$$

Another centerline velocity model has been proposed by Fletcher (1977, 1978, 1982; Fletcher and Johnson, 1982) and is given by;

$$V_x = \left[\frac{V_f}{8.58\alpha^2 + 0.93}\right] \tag{4.7}$$

where V_x, V_f, A_f and x are as before. Again, this is an empirical formula that accounts for hood shape rather than a formula developed from theory. The applicable ranges on the variables used in the above equations are as follows, where w and L represent the width and length of the hood face respectively.

$$\alpha = \left[\frac{x}{(wL)^{1/2}}\right]\left[\frac{w}{L}\right]^{-\beta} \tag{4.8}$$

$$\beta = 0.2\left[\frac{x}{(wL)^{1/2}}\right]^{1/3} \tag{4.9}$$

These models will predict the required flow rate Q_f at the hood face using predetermined capture velocity values or vice versa. The hood area A_f for the cleaning/sorting table has been chosen to be 23ft x 8ft and 3ft x 1.5ft for the individual saw hoods. Rationale for choosing the areas was based on the typical sizes of the individual processes observed in plant 4. However, since the numerical modeling was completed in 2-D the length of the hood was taken to be 1 (i.e. unity) and all calculations for all hood cases (slotted and overhead) were completed using a length of unity. Flow rates required to produce the specified capture velocities at varying vertical distances x from the hood face while keeping the hood face area A_f constant have been plotted below in Figures 4.7, 4.8, 4.9, and 4.10. An overhead hood, unflanged or flanged, is classified as such if the aspect ratio (width/length) is greater than 0.2.

These plots just basically provide a visual representation of the relationships so that the flow rates and distances can be more readily determined and understood. It can be seen that the flow rates required are much greater as the required capture velocity

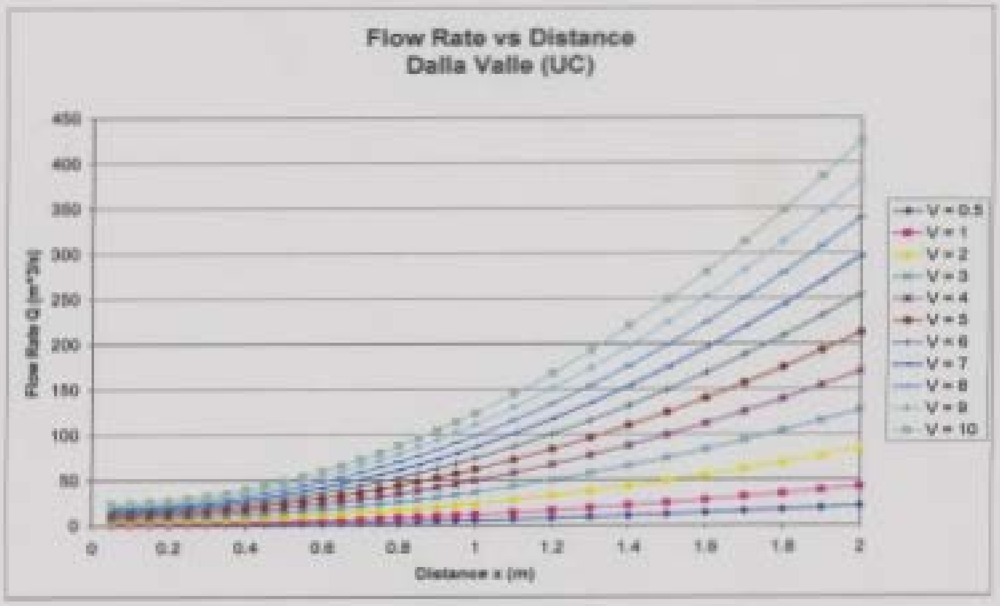

Figure 4.7: Dalla Valle predicted flow rates along the centerline of the unflanged cleaning hood

value increases.

A cooling tank hood has taken on an arbitrary area of fifteen feet long by eight feet wide to be used with the canopy hood relationship for an overhead hood for a batch cooking or cooling tank given below by (ACGIH, 1988).

$$V_z = \left[\frac{V_f A_f}{1.4PD}\right] \tag{4.10}$$

Where P is the perimeter of the tank/process and D is the height of the canopy hood above the tank/process. As a rule this type of canopy hood is not recommended if workers must bend over the source (ACGIH, 1988). As a result this type of hooding will only be applied to an open batch cooker or open cooling tank. The hood is required to extend out over the limits of the process by 0.4D in order to ensure capture. Since this type of hooding may not be possible in crab processing due to required worker interaction with most processes it has only been briefly examined here

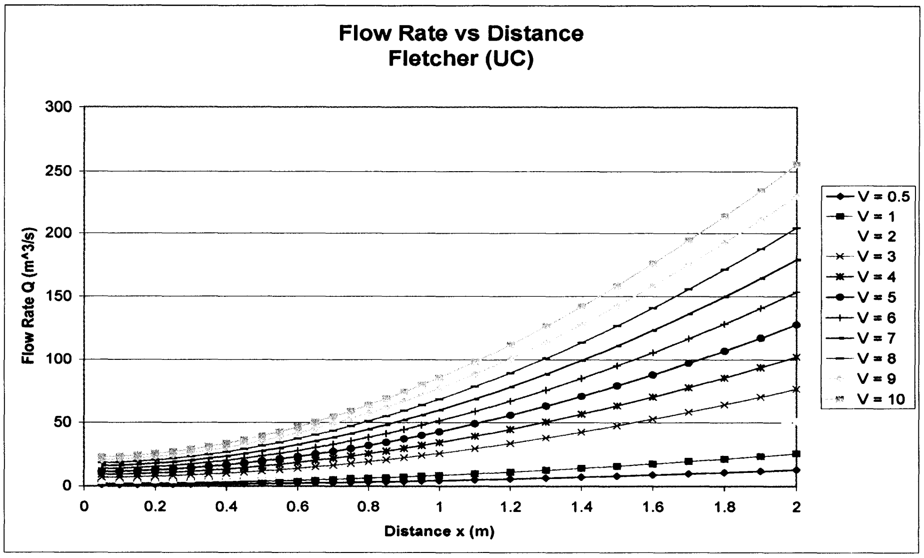

Figure 4.8: Fletcher predicted flow rates along the centerline of the unflanged cleaning hood

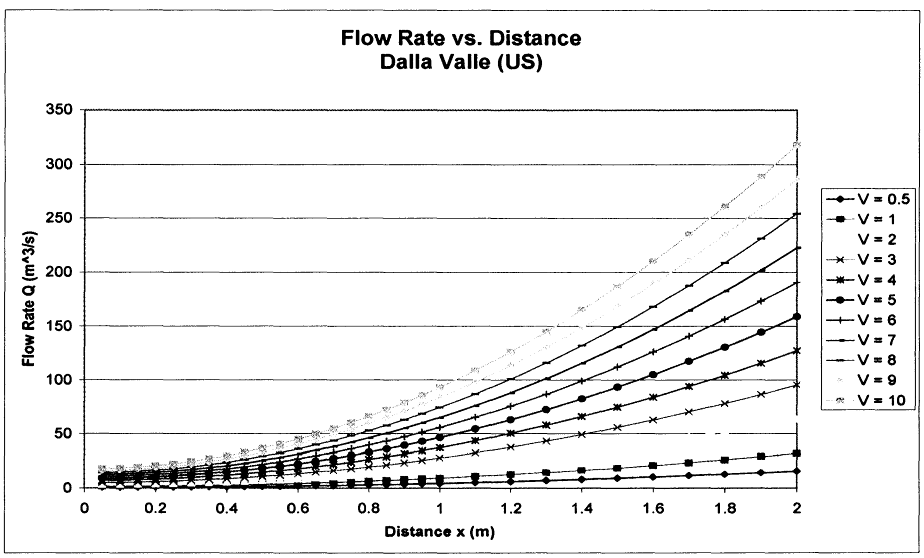

Figure 4.9: Dalla Valle predicted flow rates along the centerline of the unflanged saw hood

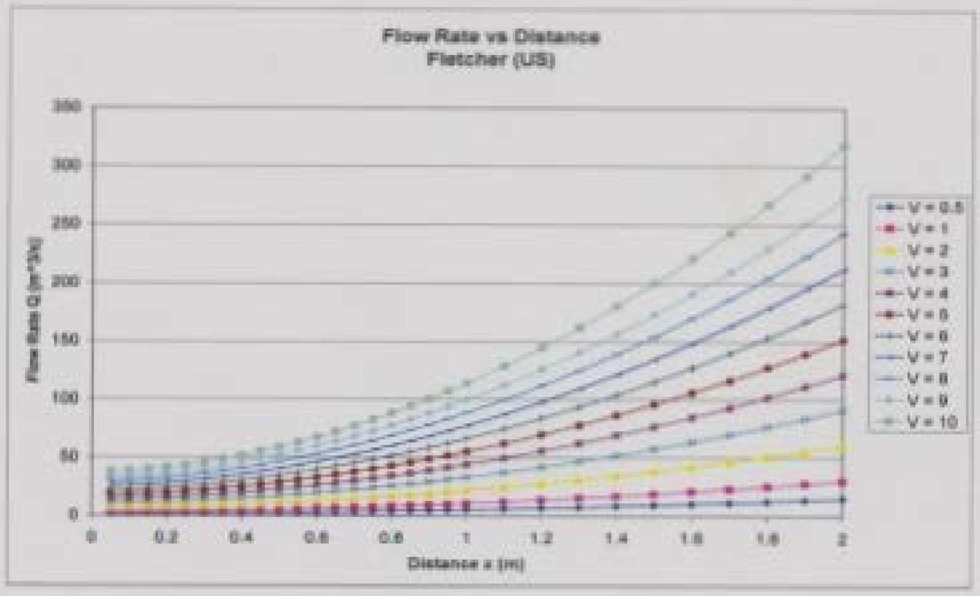

Figure 4.10: Fletcher predicted flow rates along the centerline of the unflanged saw hood

for completeness and comparison purposes. Capture velocity data has been plotted and shown below in Figure 4.11.

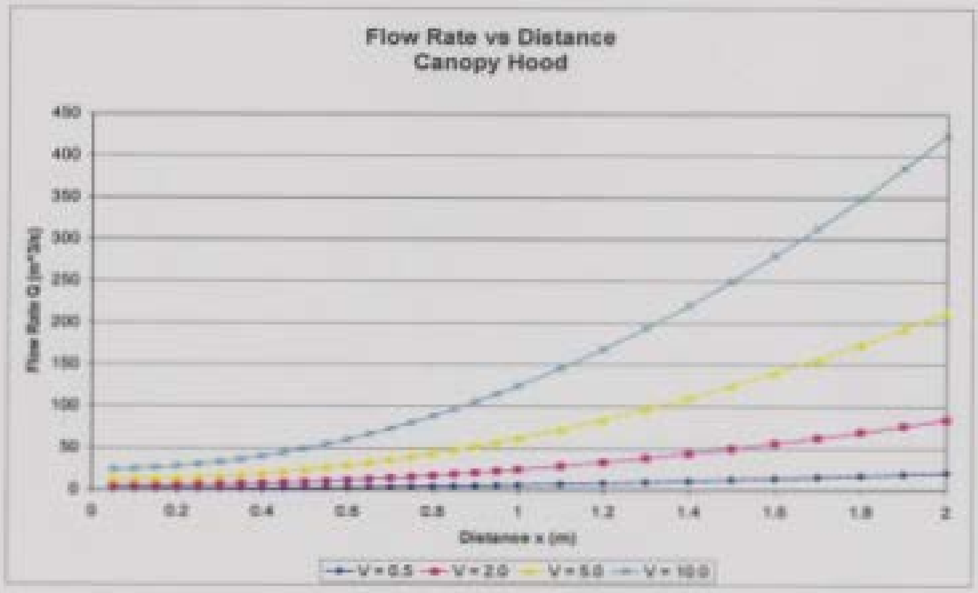

Figure 4.11: Flow rates for selected capture velocities

These flow rates can be used to both provide the basis for a exhaust system design and to provide a visual representation of the flow rates, velocities, and distances to be used in the upcoming numerical analysis.

As was previously mentioned, the obvious problem with the relationships proposed above by Dalla Valle, Fletcher, and Conroy is that they refer only to the air velocity along a line extending out from the center of the hood and do not define the velocity distribution across the hood face (McDermott, 1977). The airflow rates given above apply only to capture velocities specified along the centerline of the hood face assuming that there are no significant cross drafts present or any other type of interferences. In reality this is not normally the case and as a result these models provide a sound base from which to work. Based on this, it is necessary to be able to predict how the airflow patterns are distributed in the entire exhaust area such that a feasible and realistic hood flow rate can be chosen to exhaust the contaminants at a specific point of capture. This will be accomplished in the numerical simulations of the previously mentioned velocity profiles presented in the next chapter.

4.5.2 Flanged Overhead Hoods

In general an unflanged hood is sometimes inefficient due to the fact that air is also drawn in from behind the hood outside the contamination zone and from other sources in the plant, which unnecessarily increases the exhaust flow rates and energy costs. The addition of a simple flange has been shown to reduce the air that is being drawn from behind the hood and decrease the airflow needed to develop the same capture velocity, as can be observed by the slightly altered equation shown below (Dalla Valle, 1952).

$$V_x = \left[\frac{V_f}{7.5(x^2/wL)}\right] \tag{4.11}$$

where V_x and V_f are the velocities as before. The applicable range is as follows

$$0 < \frac{x}{w} < \infty \tag{4.12}$$

Conroy et al. (1988) also predicted the flow rate using the following relationship;

$$V_x = \frac{V_f}{2\pi\left[0.25 + (x/w)^2\right]^{1/2}\left[0.25 + (x/L)^2\right]^{1/2}} \tag{4.13}$$

where V_x and V_f are again the velocities as before. Similarly the applicable range is as follows

$$0 < \frac{x}{w} < \infty \tag{4.14}$$

These two models will again predict the required flow rate Q_f at the hood face using predetermined capture velocity values or vice versa. The hood areas A_f are the same as was specified for the unflanged cases. A flange of width equal to the square root of the hood face area has been used. Flow rates required to produce the specified capture velocities at varying vertical distances x from the hood face while keeping the hood face area A_f constant have been plotted in Figures 4.12, 4.13, 4.14, and 4.15.

Again, these plots provide a visual representation of the empirical data presented by Dalla Valle and Conroy as it pertains to flanged overhead exhaust hoods.

Capture velocities increase as flow rates increase, as can be seen above. The overhead hood should be positioned such that the contaminant is not allowed to deviate from

Figure 4.12: Dalla Valle predicted flow rates along the centerline of the flanged cleaning hood

its natural path and as many of the contaminants as possible are removed from the worker's breathing zone. It is important to avoid one of the most common fallacies with regard to hood design, namely the belief that hoods draw air from a significant distance away from the hood opening and can therefore capture and control contaminants released at varying distances from the hood. Inlet air velocity decreases sharply within a single duct diameter from the hood opening. Even a well-designed capturing hood usually can generate an adequate capture velocity no more than two feet from the hood opening, as will become apparent in upcoming numerical simulations. Beyond this distance, random drafts and other air currents can disperse the contaminants in the room (McDermott, 1977). With this in mind it should be also pointed out that excessive exhaust airflow rate can be just as ineffective as a deficit in airflow rate. If the airflow rate is too high it causes the hood to draw in air from outside the contaminant zone, whereas incomplete contaminant capture will result if the airflow is too low due to the fact that the hood will not be able to exhaust the

Figure 4.13: Conroy predicted flow rates along the centerline of the flanged cleaning hood

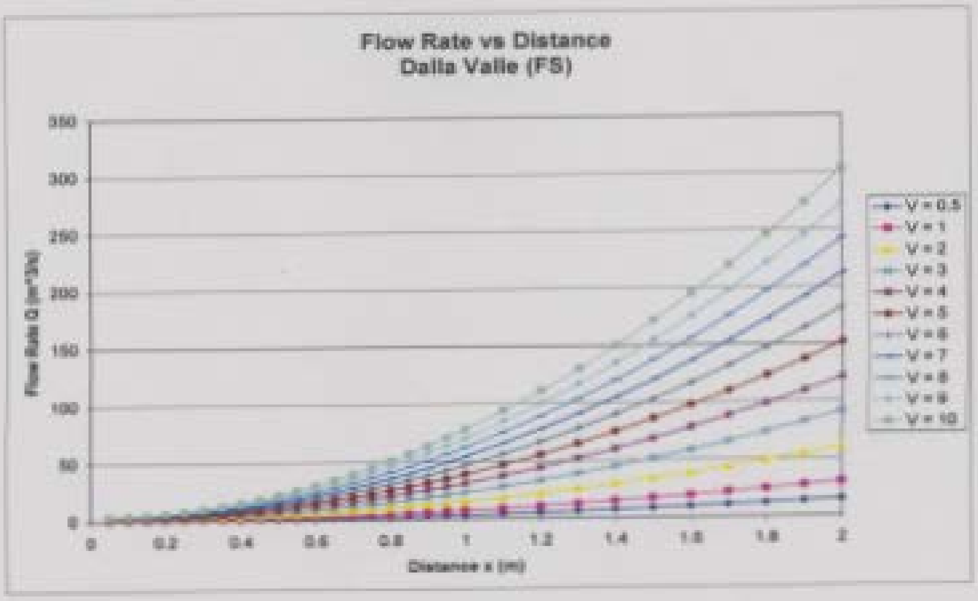

Figure 4.14: Dalla Valle predicted flow rates along the centerline of the flanged saw hood

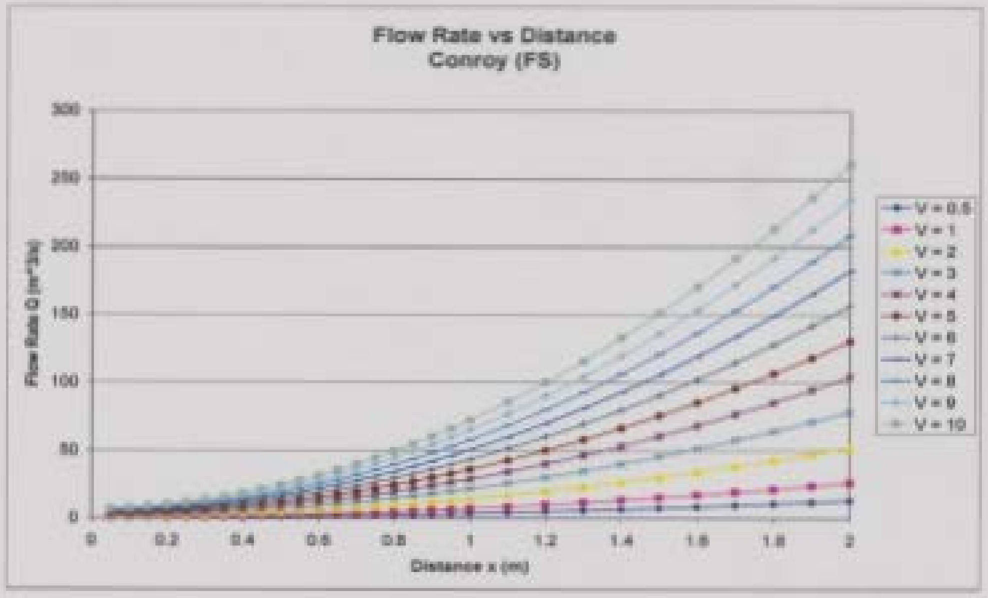

Figure 4.15: Conroy predicted flow rates along the centerline of the flanged saw hood

contaminant effectively.

4.6 Side Draft and Slot Hoods

Side draft hoods are essentially overhead hoods that have been placed in a horizontal orientation rather than a vertical one. They are typically placed as close to the source of contamination as possible such that the contaminant is drawn away from the breathing zone of the worker. When this distance has been determined and the face area (A_f) of the hood is selected based on source size, the airflow is calculated to provide the required capture velocity at the farthest point of contaminant generation. Side draft hoods change classification to slot hoods when the aspect ratio (width/length) drops to 0.2 or less and were studied extensively by Silverman (1941, 1942a, 1942b, 1943) as a follow up to Dalla Valle's work. Silverman (1943) measured centerline velocities in front of a number of different configurations of slot hoods and developed empirical formulas relating capture velocity to airflow and distance.

Slot hoods are normally used to ventilate narrow opening surface tanks but may have applications for the snow crab processing industry. The slot provides resistance to distribute air along the length of the tank and may allow the hood to reach out farther with a lower airflow than a hood without a slot. However, as a rule of thumb, two feet is the maximum reach of a slot hood (McDermott, 1977). In lieu of this, the maximum distance that has been examined is up to one meter from the hood face. Since the numerical modeling is completed in 2-D the length of the slotted hoods presented here were taken to be 1 (i.e. unity) for all calculations.

When designing a slot hood it is desirable to use a slot that is narrow enough to allow the entering airflow to distribute itself evenly over the slot length. If the slot is too wide the air will only enter the hood through the center of the slot. If the slot is too narrow then there will be an excessive pressure drop which will also cause the air to enter the hood poorly. In the following sections slotted hoods will be examined to produce centerline velocities to guide numerical simulations in the next chapter. The relationships proposed by Fletcher and Conroy for unflanged and flanged overhead hoods as well as unflanged and flanged slotted hoods are identical. The only difference is the aspect ratios associated with each case.

4.6.1 Unflanged Slotted Hoods

For unflanged hoods Silverman (1942b) found that the data was best represented by;

$$V_x = \left[\frac{Q}{3.7Lx}\right] \tag{4.15}$$

where Q is the flow rate into the hood, L is the hood length, and x is the distance to the contaminant source from the hood face. This equation is similar to the one predicted by potential flow theory differing only by the value of the constant(3.7 vs. 2π).

Fletcher's relationship mentioned in the overhead hood section is also used here for slotted hoods as long as the aspect ratio is 0.2 or less. These two models will also predict a required flow rate Q_f at the slotted hood face using predetermined capture velocity values or vice versa. The hood area A_f for the cleaning/sorting table and saw table is now drastically different due to the reduction in aspect ratio and the horizontal rather than vertical orientation of the hoods. According to Industrial Ventilation (1988), practical experience has shown that a slot velocity of 1000 to 2000 fpm (approximately 5 to 10 m/s) will provide good airflow distribution while avoiding excessive pressure drop. Data for an aspect ratio of 0.13 has been plotted and shown below in Figures 4.16, 4.17, 4.18, and 4.19. Only one aspect ratio has been used for demonstration purposes as the trends are the same for any aspect ratio with only their magnitudes subject to change.

Figure 4.16: Silverman predicted flow rates along the centerline of the unflanged slotted cleaning hood

The trends produced by Silverman's relationship are linear rather than the quadratic trends produced by Dalla Valle, Fletcher, and Conroy. Capture velocities ranging from 0.5 to 10 m/s have been used to provide the necessary flow rates required at the hood face to produce these velocities at the point of capture. Also, the noticeable increase in Q at the start of every trend is due to the fact that the calculations are done per unit length. This will also be evident for the flanged hoods as well.

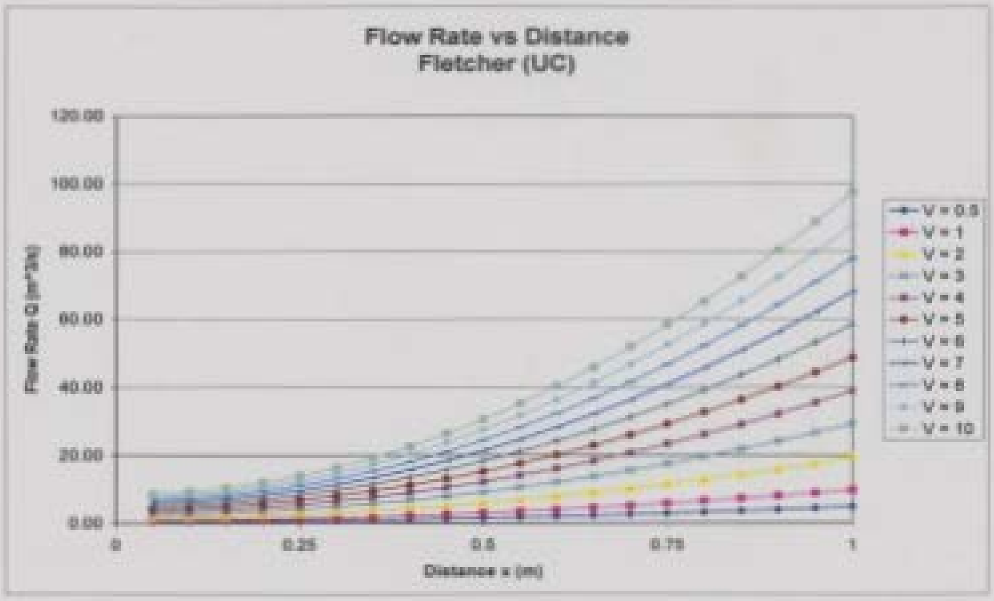

Figure 4.17: Fletcher predicted flow rates along the centerline of the unflanged slotted cleaning hood

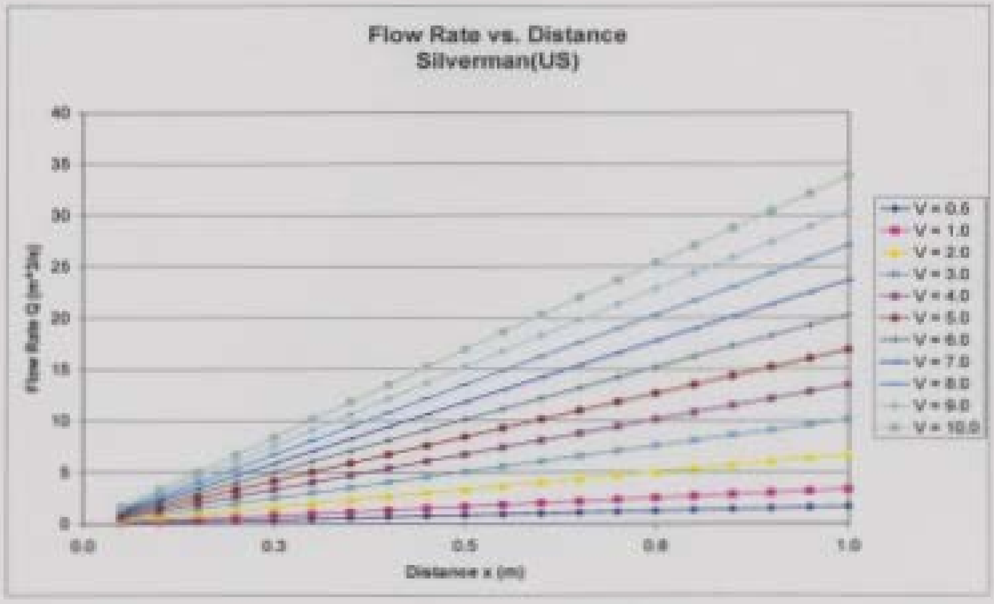

Figure 4.18: Silverman predicted flow rates along the centerline of the unflanged slotted cleaning hood

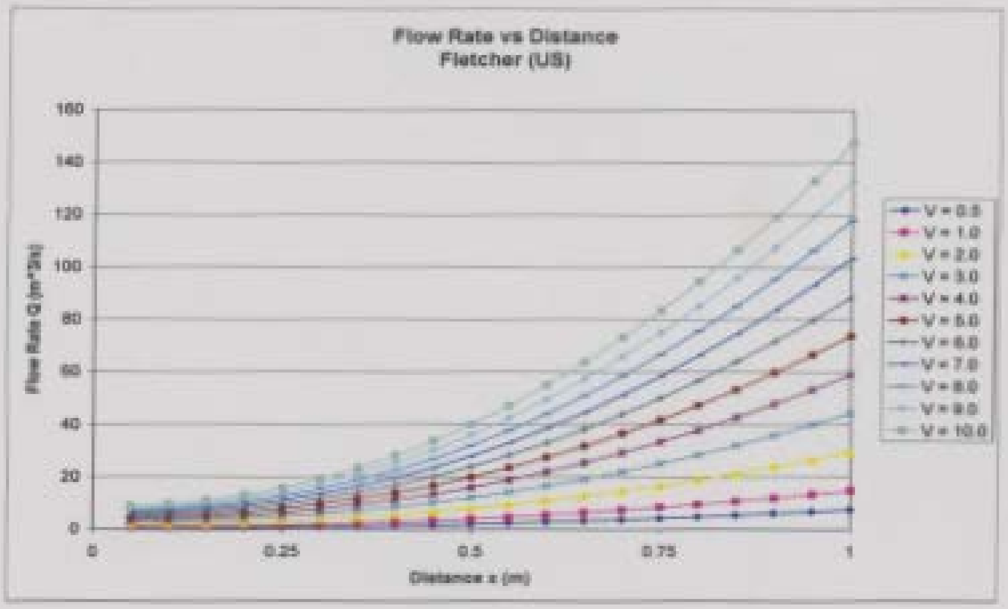

Figure 4.19: Fletcher predicted flow rates along the centerline of the unflanged slotted cleaning hood

4.6.2 Flanged Slotted Hoods

For flanged hoods, Silverman (1942b) also found that the data was best represented by

$$V_x = \left[\frac{Q}{2.8Lx}\right] \tag{4.16}$$

where Q is the flow rate into the hood, L is the hood length, and x is the distance to the contaminant source from the hood face. This equation is again similar to the one predicted by potential flow theory differing only by the value of the constant(2.8 vs. 2π).

Conroy's relationship, also mentioned in the overhead hood section is also used here for slotted hoods as long as the aspect ratio is still 0.2 or less. Similarly, data for an aspect ratio of 0.13 has been plotted and shown below in Figures 4.20, 4.21, 4.22, and

4.23. Only one has been used for demonstration purposes as the trends are the same for any aspect ratio with only their magnitudes subject to change.

Figure 4.20: Dalle Valle predicted flow rates along the centerline of the flanged slotted cleaning hood

Figure 4.21: Fletcher predicted flow rates along the centerline of the flanged slotted cleaning hood

Figure 4.22: Dalle Valle predicted flow rates along the centerline of the flanged slotted saw hood

Figure 4.23: Conroy predicted flow rates along the centerline of the flanged slotted saw hood

Note again the linear behavior of the trends produced by Silverman. Capture velocities ranging from 0.5 to 10 m/s have again been used to provide the necessary flow rates required at the hood face to produce these velocities at the point of capture. Also it can be seen that the flow rate required to obtain the same capture velocity is reduced up on the addition of a flange.

4.7 Potential Flow

The hood capturing vicinity, or zone of influence of a hood can be defined by a distinct pattern of streamlines. Any contaminants that are produced and fall into the zone of influence will be removed by the exhaust airflow described by the streamlines. With all things being equal, any contaminants that fall outside this zone will most likely not be exhausted by the hood. A streamline by definition is a line in the flow field that is everywhere tangent to the velocity vector at any point and is in the same direction as the flow at that point at any given instant in time. Since streamlines are convenient to calculate mathematically and likewise convenient to produce using computational fluid dynamic software, both have been done to ensure that the streamlines are represented correctly and to provide additional insight into the underlying fluid flow principles.

The primary obstacle to overcome in hood design is to identify the influences on the velocity fields created by the hood. These influences normally consist of competing airflows and turbulent structures. Studies in recent years have focused on the application of potential flow theory to the empirical information gathered by previous research. As a result these efforts have provided a sound mathematical model to be used by system designers to quantify the contaminant capabilities of hoods before having them constructed and installed.

It is known that airflow near a hood can be described using the incompressible, irrotational (i.e. potential flow) model (Applications 1999). Potential flows are special types of flows that are assumed to be incompressible (ρ = constant), inviscid ($\mu = 0$), and irrotational ($\omega = \nabla \text{ x } \vec{V} = 0$). Inviscid flows produce the following continuity and x, y, and z momentum equations in vector notation

$$\nabla \cdot \vec{V} = 0 \tag{4.17}$$

$$\rho \frac{D\vec{V}}{Dt} = \rho \vec{g} - \nabla p \tag{4.18}$$

or

$$\rho \left(\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} \right) = \rho g_x - \frac{\partial p}{\partial x} \tag{4.19}$$

$$\rho \left(\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} \right) = \rho g_y - \frac{\partial p}{\partial y} \tag{4.20}$$

$$\rho \left(\frac{\partial w}{\partial t} + u \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z} \right) = \rho g_z - \frac{\partial p}{\partial z} \tag{4.21}$$

These are commonly referred to as Euler's equations. The vector momentum equation may also be written as:

$$\frac{\partial \vec{V}}{\partial t} + \nabla \left(\frac{p}{\rho} + \frac{1}{2} \vec{V} \cdot \vec{V} + \Psi \right) = (\vec{V} \times \vec{\omega}) - \nu (\nabla \times \vec{\omega}) \tag{4.22}$$

where $\vec{g} = -\nabla \Psi$, is the gradient of the gravitational potential and $\vec{\omega} = \nabla \times \vec{V}$ is the vorticity. The vorticity vector may be written as:

$$\vec{\omega} = \omega_x \mathbf{i} + \omega_y \mathbf{j} + \omega_z \mathbf{k} \tag{4.23}$$

or in terms of $[u, v, w]$

$$\vec{\omega} = \left(\frac{\partial w}{\partial y} - \frac{\partial v}{\partial z}\right)\mathbf{i} + \left(\frac{\partial u}{\partial z} - \frac{\partial w}{\partial x}\right)\mathbf{j} + \left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}\right)\mathbf{k} \tag{4.24}$$

If the flow is assumed to be both inviscid and irrotational then neglecting the right hand side of equation (1.6) yields

$$\frac{\partial \vec{V}}{\partial t} + \nabla\left(\frac{p}{\rho} + \frac{1}{2}\vec{V}\cdot\vec{V} + \Psi\right) = 0 \tag{4.25}$$

which is Bernoulli's equation for unsteady flow. If steady flow is assumed then the term in brackets is equal to a constant, i.e.

$$\frac{p}{\rho} + \frac{1}{2}\vec{V}\cdot\vec{V} + \Psi = \text{Constant} \tag{4.26}$$

If a particular flow is irrotational then a velocity potential ϕ can be defined as

$$\vec{V} = \nabla\phi \tag{4.27}$$

which upon substitution into the equation of continuity yields Laplace's equation

$$\nabla^2\phi = 0 \tag{4.28}$$

or

$$\frac{\partial^2\phi}{\partial x^2} + \frac{\partial^2\phi}{\partial y^2} + \frac{\partial^2\phi}{\partial z^2} = 0 \tag{4.29}$$

Since 3-D problems are much more difficult to solve than 2-D ones the attention here has been focused on plane 2-D flows whereby the velocity components u and v will depend only on x and y. Laplace's equation now becomes

$$\nabla^2\phi = \frac{\partial^2\phi}{\partial x^2} + \frac{\partial^2\phi}{\partial y^2} = 0 \tag{4.30}$$

Assuming steady incompressible flow the 2-D continuity equation is

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{4.31}$$

Since the continuity equation has now been reduced into two terms the stream function ψ can be introduced as

$$u = \frac{\partial\psi}{\partial y} \tag{4.32}$$

and

$$v = -\frac{\partial\psi}{\partial x} \tag{4.33}$$

or in cylindrical coordinates we have

$$v_r = \frac{1}{r}\frac{\partial\psi}{\partial\theta} \tag{4.34}$$

and

$$v_\theta = -\frac{\partial\psi}{\partial r} \tag{4.35}$$

Therefore both the stream function ψ and the potential function ϕ satisfy Laplace's equation for 2-D plane flow. In addition, some additional relationships between ϕ and ψ are required in order to effectively determine the streamlines, namely

$$u = \frac{\partial\phi}{\partial x} = \frac{\partial\psi}{\partial y} \tag{4.36}$$

and

$$v = \frac{\partial \phi}{\partial y} = -\frac{\partial \psi}{\partial x} \tag{4.37}$$

These relationships between the derivatives of the harmonic functions ϕ and ψ are the famous Cauchy-Riemann equations from the theory of complex variables (Potter et al, 1997). These relationships are fundamental in obtaining the stream function ψ.

4.7.1 Potential Flow Predictions and Approximations

Potential flow theory has been used by many authors who have applied it to airflow in front of hoods for a variety of specific configurations. Using this approach is warranted due to the elliptical nature of the velocity contours being coincident with equipotential surfaces as can be seen in Figure 4.24.

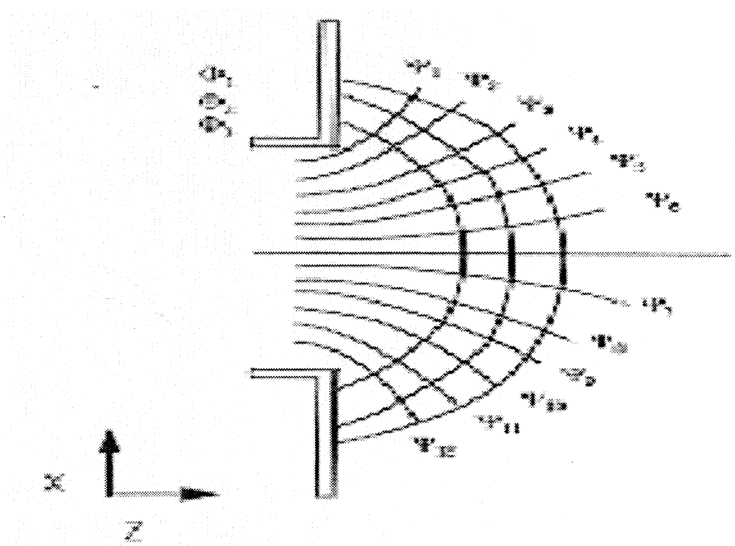

Figure 4.24: Equipotential lines ϕ and streamlines ψ

Flynn and Ellenbecker (1985) examined the air flow into a flanged circular hood using potential flow theory using two velocity models. In addition, Flynn and Ellenbecker (1987) applied a uniform cross draft perpendicular to the hood centerline by simple vector addition to generate a third model, with the results comparing favorably to Dalla Valle's emperical data (Varely et al, 1997). Validation of all three models produced good correlation, in particular the model with cross draft.

Conroy et al (1989) also evaluated capture efficiency of hoods except his research leaned toward flanged slot hoods. A potential model initially developed for an elliptical opening had been used to represent a rectangular slotted opening which could also be used with cross drafts. Streamlines were generated again by using the assumption that they were perpendicular to lines of potential. Conroy also showed that contaminant transport in the presence of a cross draft could be modeled if it was assumed that the contaminant was released with no velocity into this cross draft. It was then assumed, as was stated earlier, that one hundred percent efficiency would be achieved for streamlines entering the hood and zero efficiency otherwise. Validations showed that experimental data suggested that an inscribed ellipse potential flow model provided good correlation, and that contaminant transport can also use potential flow theory (Varley et al, 1997). This revelation has provided the basis for the contaminant transport theory and properties used in this study.

To better visualize the streamlines generated in the overall vicinity of the hood they have been approximated and plotted using relationships that describe basic potential flows governed by Laplace's equation. Due to the fact that Laplace's equation is a linear partial differential equation it permits various basic velocity stream functions to be combined to form new stream functions (Munson et al, 1998). The potential flow model used for the unflanged hood simply a superposition of two basic flows given in Currie (1995) and White (1999).

- Flow in a Corner of Arbitrary Angle

- Uniform Rectilinear Flow

described by the following stream functions

$$\begin{aligned} \psi_{Unflanged} &= \psi_{CornerFlow} + \psi_{UniformFlow} \\ &= UR^n sin\left[(n)\theta\right] + Uy \end{aligned} \tag{4.38}$$

in cartesian coordinates we have

$$\begin{aligned} \psi_{Unflanged} &= \psi_{CornerFlow} + \psi_{UniformFlow} \\ &= U\sqrt{(x^2+y^2)}^n sin\left[(n)\arctan(y/x)\right] + Uy \end{aligned} \tag{4.39}$$

Corner flow is an example of a pattern that cannot be conveniently produced by superimposing sources, sinks, and vortices (White 1999). The streamlines produced by corner flow can be plotted however for different values of the constant n which defines the angle. At a value of $n = 2$ the corner produced is at an angle of $\pi/2$ and the associated streamlines are plotted in Figure 4.25.

Here the streamlines $\psi = 0 - 15$ have been plotted for two 90 degree corners, symmetrically placed back to back such that the symmetric flow could be visualized and used to represent the flow that would occur in the vicinity of the hood intake. The centerline of the plot shown by the x-axis represents the centerline of the hood face with the scale on both axes in feet.

A uniform flow normal to the centerline of the hood face has also been included as well to simulate any cross flows that may be present. A conservative value of 1.0 m/s has been used for the velocity and has been assumed to be constant. The streamlines produced by a uniform flow are plotted in Figure 4.26. The uniform flow produced streamlines are obviously horizontal in nature at constant values of x with a constant velocity U of 1.0 m/s.

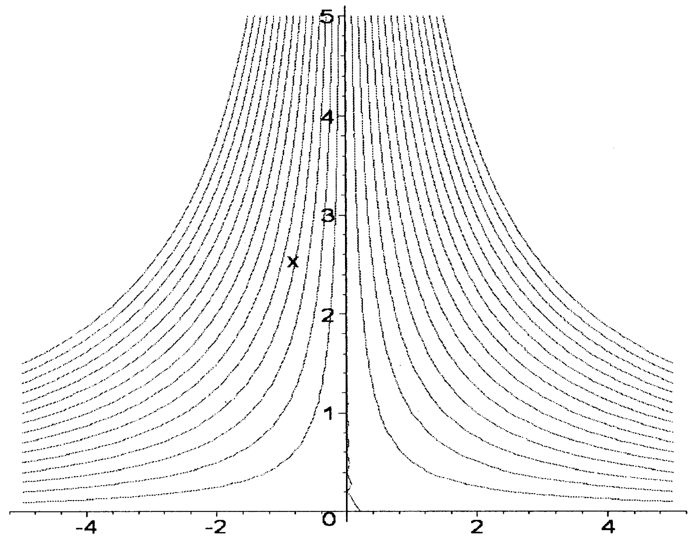

Figure 4.25: Streamlines for flow into two 90 degree corners (Unflanged)

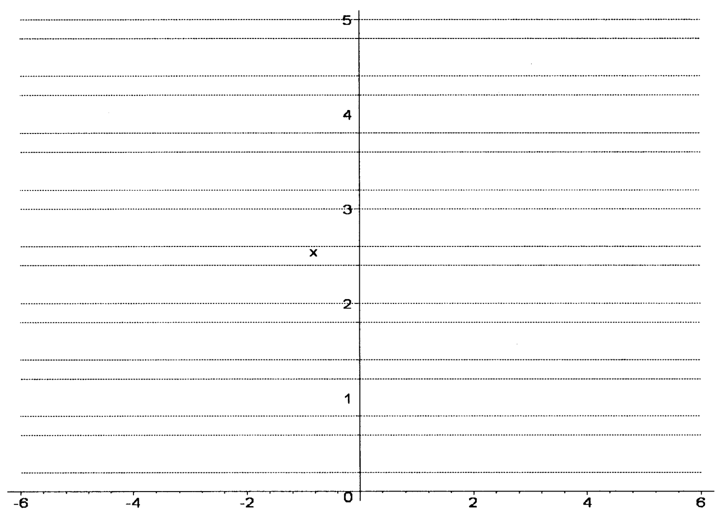

Figure 4.26: Streamlines for a uniform flow (Unflanged)

All of the streamlines shown above are plotted in 2-D and are assumed to be constant over the length of the hood. They do not account for the end effects of the hood and as a result are not quite correct, although a very good approximation.

The fact that the relationship for the flanged case is again valid only along the centerline poses an identical problem in determining the flow field in the vicinity of the hood face at varying distances from the centerline. Since a flange has now been incorporated the streamlines produced will change and will be modeled by superimposing the following potential flow models (Currie, 1995).

- Flow in a Corner of Arbitrary Angle
- Flow around a sharp edge
- Uniform Rectilinear Flow

described by the following stream functions

$$\begin{aligned} \psi_{Flanged} &= \psi_{CornerFlow} + \psi_{SharpEdge} + \psi_{UniformFlow} \\ &= UR^n sin\left[(n)\theta\right] + UR^n sin\left[(n)\theta\right] + Uy \end{aligned} \tag{4.40}$$

in cartesian coordinates we have

$$\begin{aligned} \psi_{Flanged} &= \psi_{CornerFlow} + \psi_{SharpEdge} + \psi_{UniformFlow} \\ &= U\sqrt{(x^2+y^2)}^n sin\left[(n)\arctan(y/x)\right] + \\ &\quad U\sqrt{(x^2+y^2)}^n sin\left[(n)\arctan(y/x)\right] + Uy \end{aligned} \tag{4.41}$$

Again the streamlines $\psi = 0 - 15$ have been plotted in Figure 4.27 for two 90 degree corners using a value of $n = 2$ which again defines the angle as having the value of $\pi/2$.

An identical uniform flow normal to the centerline of the hood face has also been included and plotted in Figure 4.28.

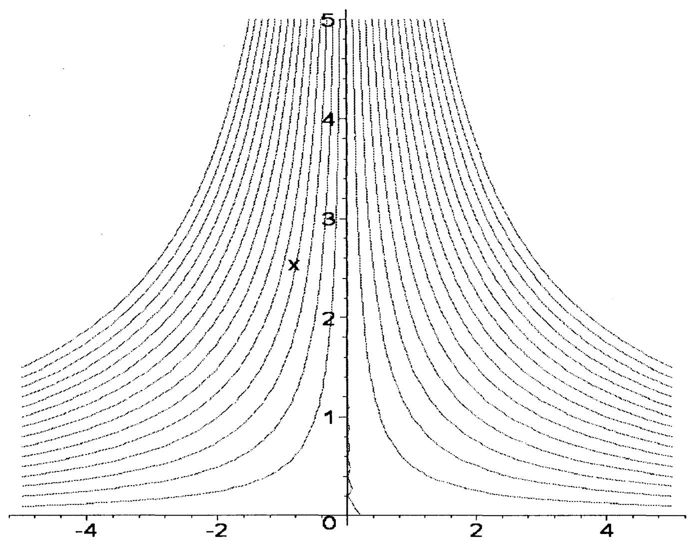

Figure 4.27: Streamlines for flow into two 90 degree corners (Flanged)

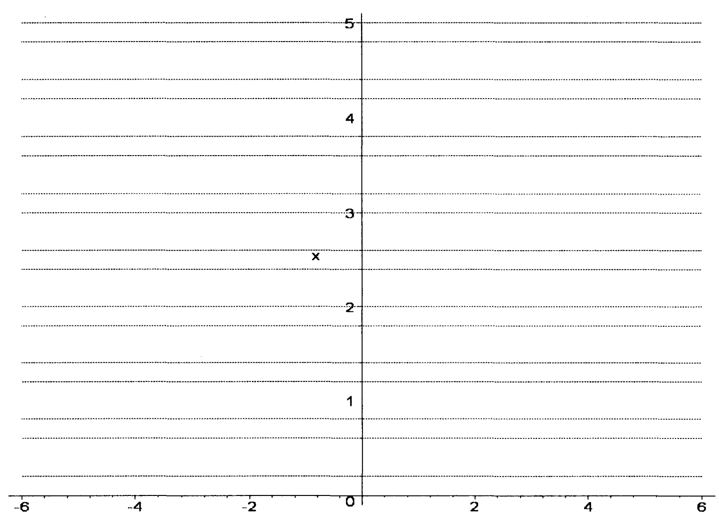

Figure 4.28: Streamlines for a uniform flow (Flanged)

In addition to these two flows there is an additional potential flow considered that is identical to the potential flow model described by flow in a corner of arbitrary angle.

The only difference is that now the angle is equal to 2π instead of $\pi/2$. This results from having $n = 1/2$ and thus produces the streamlines produced around a sharp edge which have been plotted and shown in Figure 4.29.

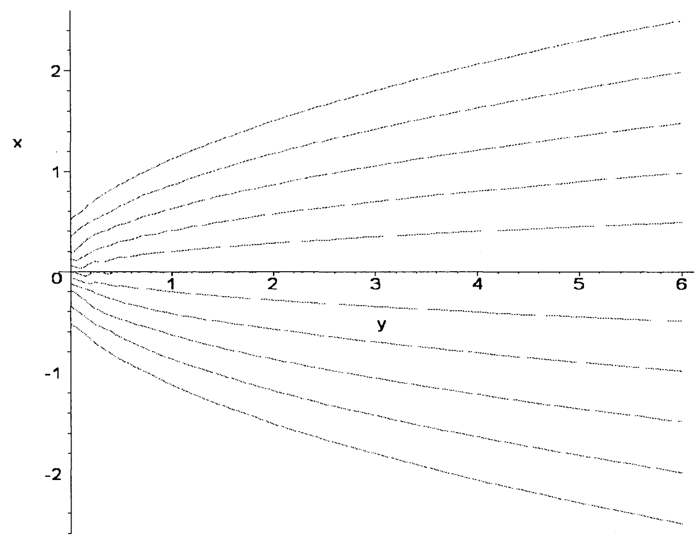

Figure 4.29: Streamlines around a sharp corner (Flanged)

This plot shows how the flow would wrap around a flange represented by the horizontal y-axis if it were attached to the hood face. Again, this flow is assumed to be free from any other possible airflow patterns. To superimpose these three flows in the hope of accurately representing the flow field at the face of the hood would be an approximation at best due to many assumed idealizations. Since all of the streamlines have been plotted in 2-D, the assumed idealizations alluded to above prevent accurate results when combining potential flows in this manner due to the fact that in reality the exhaust hood represents a 3-D situation.

Research in the area of potential theory has assumed ideal conditions but nonetheless it provided an important relationship between classic fluids theory and the empirical research and work completed by Dalla Valle. The application of a cross draft to the model adds a real world consideration as it represents the problem of impinging airflows created by the surrounding environment. While the potential flow approach allows designers to model hoods in situations where the surrounding environment has an appreciable impact, it ignores any turbulence of viscous effects and most times contaminant dispersive forces are considered unimportant. In reality these situations are often present and cannot be ignored, which indicates that a potential flow approach must be applied with due caution.

4.7.2 Turbulent Structures

The practice of sizing exhaust hoods based on velocity contours neglects the existence of events that would inevitably influence the exhaust hood performance. Turbulent structures created by the presence of cross drafts, room air turbulence, and flow separation around objects within the vicinity of the hood are all but ignored when relying solely on the velocity contour technique. Drafts generated by thermal gradients suggesting heat generation have been neglected due to the assumption of a well mixed room in addition to the assumption that thermal buoyancy is negligible when compared with fluid movement generated by pressure gradients (Varley et al, 1997). Separation of airflow streamlines will occur when the air flow approaches an object, causing a boundary layer (indicative of a pressure increase and velocity decrease) to appear on the upstream side of the object. This phenomena causes the streamlines to become detached from the surface of the object, as can be seen in Figure 4.30 depicting a cylinder in a laminar flow field.

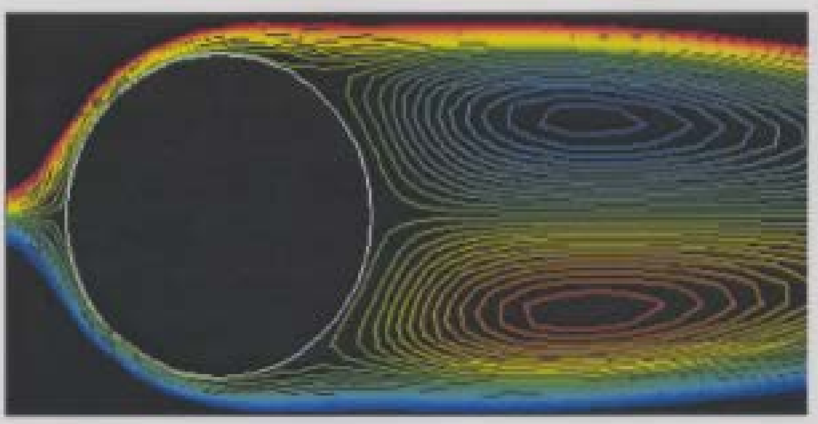

Figure 4.30: Stream function contours in the wake of a cylinder placed in a laminar flow field

The effect that this phenomenon has on the flow streamlines around a cylinder are obvious. While this is a simple example, similar effects will result when airflow attempts to move around various turbulent structures in the vicinity of the hood face in crab processing plants. In particular, a vertical cylinder will be inserted in the domain to simulate a worker such that the effect on the surrounding airflow patterns can be observed.

4.8 Makeup Air

A ventilation system will not work properly if there is not enough or too much air in the room to exhaust. If the static pressure of the room becomes negative then the fan may not work properly due to this additional resistance. For example, a negative pressure of 0.05 to 0.1 inches of water (12.5 to 25 Pa) will make doors difficult to open. A negative pressure situation was witnessed in plant 4 during air sampling when the cooking room door was difficult to open indicating a lack of supply air. In severe negative pressure cases, condensation is apparent on ceilings and walls in cold areas and is sometimes indicative of rain being drawn in through cracks that will run down inside walls. As a result make-up air needs to be supplied in a controlled and methodical manner rather than relying on random infiltration from various open windows, doors, cracks, etc..

Air supply to any industrial space can be facilitated by mechanical or natural means. The supply rate should exceed the exhaust rate by about 10% and will also serve to induce a slightly positive pressure and help keep out drafts and other harmful contaminants (McDermott, 1977). Natural ventilation is generally inefficient in large buildings as it may cause drafts and cannot solve air pollution problems (ASHRAE Handbook (Applications), 1999). The air supply methods considered here have been modified for the simulations but are basically derived from the following;

- Displacement Flows
- Entrainment Flows

Displacement flow is the movement of air within a space in such a way that the flow emulates a piston or plug-type flow, as can been seen in Figure 4.31

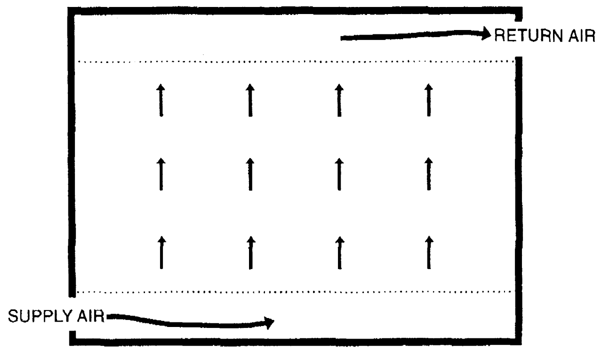

Figure 4.31: Displacement flow within a space (ASHRAE Handbook (Fundamentals), 2001)

Entrainment flow is attained by introducing and removing air at the ceiling level, as can be seen in Figure 4.32

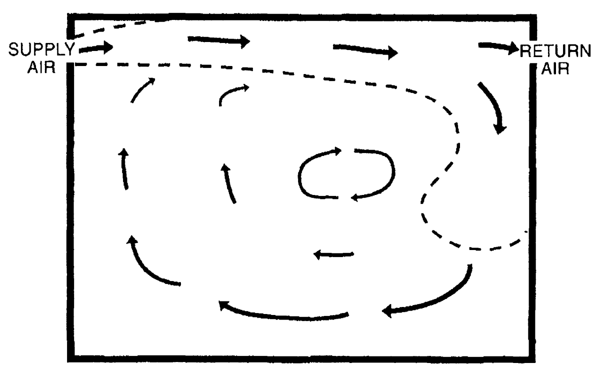

Figure 4.32: Entrainment flow within a space (ASHRAE Handbook (Fundamentals), 2001)

Ideally, there will be no mixing of the room air which is desirable for removing generated pollutants within a enclosed space. However, due to the fast paced atmosphere of the snow crab industry it is reasonable to assume that an ideal case does not exist therefore resulting in various degrees of mixing. Generally, air is typically supplied at low velocities via air outlets in an occupied workplace at the floor or ceiling level and exhausted at similar locations. As a rule, air supplied into rooms through the various types of outlets (e.g. grilles, ceiling diffusers, perforated panels) is distributed by turbulent air jets which are the primary factor affecting room air motion (ASHRAE Handbook (Fundamentals), 2001). If a jet is not obstructed by obstructions such as walls or the ceiling, then it is considered a free jet. Determining the velocity and other flow characteristics of linear free jets is not a priority here as they have only been mentioned as a means to supply air to a general room configuration such that the flow characteristics surrounding the exhaust hoods can be examined. Supply outlets have been classified in the following manner by Straub et al (1956) and Straub and Chen (1957);

- Group A - Outlets mounted in or near the ceiling that discharge air horizontally.
- Group B - Outlets mounted in or near the floor that discharge air vertically in a non-spreading jet.
- Group C - Outlets mounted in or near the floor that discharge air vertically in a spreading jet.
- Group D - Outlets mounted in or near the floor that discharge air horizontally.
- Group E - Outlets mounted in or near the ceiling that project primary air vertically.

Variations of the outlets described by groups A, B, C, and D have been used in the realistic numerical simulations to produce local hood airflow patterns. Specific sizes of air inlets will not be important for the upcoming 2-D simulations as only the trends of the airflow patterns are of interest here. The location and strength of air supply outlets would become important were a full analysis of a ventilation system undertaken, which has not been done here. Therefore, the entire side, bottom, or top of a domain will be specified as a pressure inlet, which means simply that Fluent will assume that it can use these locations to obtain the makeup air needed to produce the airflow patterns around the exhaust hood. In essence, Fluent will think the walls are not there at all.

4.9 Fan Selection and Duct Design

All exhaust systems make use of hoods, ducting segments, and an exhaust fan of some sort. In general, the main design steps that should be followed for system design are;

- Select and design each exhaust hood to suit the particular operation
- Determine minimum duct velocity based on required transport velocity (hood face and capture velocities)
- Determine duct size by dividing design flow rate by the minimum duct velocity

Design Methods

According to the American Conference of Governmental Industrial Hygienists, the design methods are listed as follows in Industrial Ventilation (1988);

- Calculate the pressure losses for the exhaust system using either the velocity pressure or equivalent pressure method
- Check for correct balance at entries and adjust volumetric flow rate, duct size, or hood design to obtain the correct flow
- Select fan based upon final volumetric flow rate and calculated system resistance

The velocity pressure method is normally used as the basis for system design. The method is based on the fact that all frictional and dynamic losses in ducts and hoods are functions of the velocity pressure and can be calculated by a factor multiplied by the velocity pressure. The following steps will establish the overall pressure loss of a duct segment that starts at a hood (Industrial Ventilation, 1988);

1. Determine the actual velocity by dividing the flow rate by the area of the commercial duct size chosen. Then determine the corresponding velocity pressure VP.

2. Determine the hood suction

3. Multiply the design duct length by the loss factor

4. Determine the number and type of fittings in the duct segment. For each fitting type determine the loss factor and multiply by the number of fittings.

5. Add the results of steps 3 and 4 above and multiply by the duct VP. This is the actual loss in inches of water or Pa for the duct segment.

6. Add the result of step 5 to the hood suction, along with any additional losses. This establishes the cumulative energy required, expressed as static pressure, to move the design flow rate through the duct segment.

As the fan draws air in and discharges it at a higher velocity and static pressure it provides the energy needed to overcome the pressure losses as air flows through the system.

The total pressure and available energy at any cross-section in a duct is defined as the sum of the static and velocity pressures. In any ducting system the total pressure will always decrease in the direction of the airflow. Static pressure (SP) is the suction pulling inward on the ducts of a ventilation system before the fan and pushing outwards on the ducts after the fan and is used as the basis for system design. SP can be positive or negative with respect to the local atmospheric pressure. It produces an initial velocity in the system that is needed in order to be able to overcome friction and turbulence and can be thought of as potential energy. Velocity pressure (VP) is created by air accelerating from zero velocity to some velocity (V) greater than zero and can be thought of as kinetic energy. VP is always exerted in the same direction as the flow and is also always positive. The size of the fan needed to make any system work correctly is obtained from the pressures losses throughout the system and the amount of airflow required. Typical pressure losses are summarized in Table 4.2 produced by McDermott (1977).

Table 4.2: Summary of typical ventilation system pressure losses

Type of Loss	***Magnitude, Inches of Water***	***Reason***
Acceleration Loss	0.25–1.5	Energy need to accelerate air to duct velocity
Hood Entry Loss	0.1–2.0	Turbulence as air enters hood and ducts
Duct Friction Loss	1.0–5.0 per 100 ft of duct	Friction as air moves through duct
Turbulence Losses Elbow Branch Entry Enlargements and Contractions	 0.1–0.3 per 90deg elbow 0.1–0.3 per 45deg entry 0.1–0.3 per enlargement or contraction	Turbulence as air changes direction of velocity
Air Cleaners	0.5-1.0	Friction and Turbulence

Fan and duct design involve the calculation of the pressure losses through the different components of the system. Fan total pressure (FTP) is defined as the increase in total pressure through or across the fan (ACGIH, 1988). However, the fan size has to be specified by a flow rate and fan static pressure (FSP). FSP is the amount of static pressure that the fan must achieve in order to move the required amount of air through the system. It basically equals the static pressure on the inlet and outlet sides of the fan plus the velocity pressure entering the fan. This relationship has been expanded and shown below.

$$FSP = FTP - VP_{Outlet} \tag{4.42}$$

$$FSP = [TP_{Outlet} + TP_{Inlet}] - VP_{Outlet} \tag{4.43}$$

$$FSP = [SP_{Outlet} + VP_{Outlet}] - [SP_{Inlet} + VP_{Inlet}] - VP_{Outlet} \tag{4.44}$$

$$FSP = SP_{Outlet} - SP_{Inlet} - VP_{Inlet} \tag{4.45}$$

It should be noted here that VP_{Inlet} is always positive, SP_{Inlet} is usually negative, and SP_{Outlet} is usually positive. The velocity pressure method mentioned above can be easily applied with the help of a typical calculation sheet shown in Table 4.3.

This calculation sheet provides the cumulative static pressures generated by the inlet ducting, outlet ducting, fan section, and the hood. The values for the VP_{Inlet}, SP_{Inlet}, and SP_{Outlet} are obtained from this sheet to obtain the fan static pressure (FSP). This pressure is then used to select the appropriate fan from manufacturer fan data and curves.

However, the design of ducting and all other components of a ventilation system have not been actually executed here due to the fact that the interest lies in the flow fields surrounding the hood exhaust and supply inlets and not the flow inside the ducting. Various pressures and velocities have been imposed at the face of the hoods having a magnitude capable of producing the required hood face velocity and capture velocity at a distance from the hood face. The pressures and supply inlet velocities have been varied until the required hood face and capture velocities were obtained. The only variables that change in the simulations are the distances from the contamination sources, the capture velocity values, and the corresponding hood face velocities and

Table 4.3: Typical calculation sheet outlining the velocity pressure method

	Required Information	Hood	Inlet Ducting	Fan	Outlet Ducting
1	Duct Segnentation ID				
2	Volumetric Flowrate				
3	Minimum Transport Velocity				
4	Duct Diameter				
5	Duct Area				
6	Actual Duct Velocity				
7	Duct Velocity Pressure				
8	Slot Area				
9	Slot Velocity				
10	Slot Velocity Pressure				
11	Slot Loss Factor				
12	Acceleration Factor				
13	Plenum loss per VP				
14	Plenum SP				
15	Duct Entry Loss Factor				
16	Acceleration Factor				
17	Duct Entry Loss per VP				
18	Duct Entry Loss				
19	Other Loss				
20	Hood Static Pressure				
21	Straight Duct Length				
22	Friction Factor (Hf)				
23	Friction Loss per VP				
24	No. of 90 Degree Elbows				
25	Elbow Losses per VP				
26	No. Entries				
27	Entry Loss per VP				
28	Special Fittings Loss Factors				
29	Duct Loss per VP				
30	Duct Loss				
31	Duct SP Loss				
32	Cumulative Static Pressure				
33	Governing Static Pressure				
34	Corrected Volumetric Flowrate				
35	Resultant Velocity Pressure				

flow rates. The design procedure has been outlined above to show how the system would be designed if needed.

4.10 Exhaust Re-entry

Reentry is basically defined as the inadvertent return of previously exhausted air from an enclosure back into a supply air intake thus re-contaminating the inside air, as is shown in Figure 4.33.

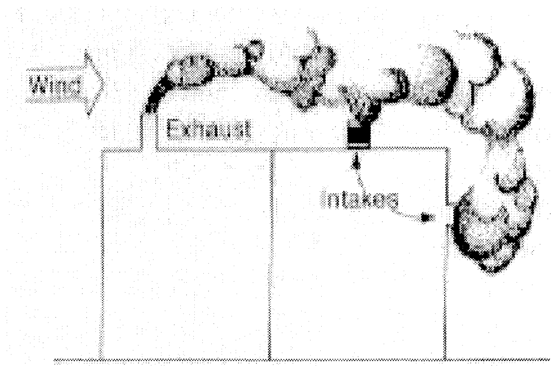

Figure 4.33: Basic schematic of exhaust reentry via roof and wall air supply intakes (ASHRAE Handbook (Applications) 1999)

Some common design flaws include insufficient exhaust stack height, proximity of the stack to HVAC intakes, and the lack of a rain cap on the exhaust stack (Burgess et al, 1989). Design of intakes and exhausts to avoid these problems is further complicated due to under/over compensating for changing wind directions and magnitudes. Airflow around relatively simple, cube-shaped buildings can be quite complex when placed in the path of varying wind directions and speeds. Neglecting these characteristics can not only cause reentry problems but may cause downwind air pollution in the nearby community. In addition, buildings that are located in uneven terrain, as is often the case in Newfoundland and Labrador, can experience airflow patterns that are very complex and difficult to determine. As a result, empirical experiments using scale models or numerical modeling may be required to produce accurate flow patterns. This has been left for future work and not included in the upcoming simulations.

4.11 Other Exposure Control Techniques

Up to this point in the thesis all efforts to control exposures have been focused on the implementation of some type of ventilation system. In actuality, ventilating the contaminated space is only one method used to reduce worker exposure to harmful substances. As was shown, the exposure to an airborne substance of any kind is directly proportional to the amount of contaminant present in the workplace at any given time. Any factors that could alter exposure by either limiting the exposure time of the worker in the contaminated area or reducing the amount of contaminant in the worker breathing zone will aid in reducing overall exposure. Ongoing research is being carried out to determine if variations in the actual processing methods would in fact reduce contaminant release or exposures. To date, an experiment described in chapter 5 has attempted to determine if crab processing using raw crab rather than cooked crab would reduce the amount of airborne allergens.

Chapter 5

Results and Numerical Simulations

Numerical simulations of typical cleaning/sorting, sawing, and cooling processes in crab plants with associated local ventilation systems has been completed to determine the airflow patterns produced in the vicinity of the hoods. The patterns will provide valuable information on airflow characteristics to aid in the ultimate goal of contaminant capture and removal.

5.1 Contaminant Motion and Diffusion

Theories of hood performance with non-buoyant pollution sources are commonly based on the turbulent diffusion equation which allows the determination of contaminant concentration decay in the uniform airflow upstream from the contaminant source (Zhivov et al, 1997);

$$C_x = C_o e \left[\frac{-Vx}{D}\right] \tag{5.1}$$

where C_x is the concentration at some distance x from the contaminant source of concentration C_o. Air velocity into the hood V depends on the exhaust flow rate, whereas the coefficient of turbulent diffusion D is based on the air change rate in the area of the hood as well as the method by which the air is being supplied/exhausted. This equation predicts the contaminant concentration decay along the centerline normal to the hood face. Knowledge of how far the concentrations extend away from their source is of interest when determining if an applied exhaust flow rate at the hood face will be effective in capturing the contaminants.

The air velocity across a hood face has been assumed to have a value of 0.5 m/s but is increased by a factor of 2 resulting in a value of 1.0 m/s due to normal air disturbances caused by the presence of workers (Zhivov et al, 1997). With V = 1.0 m/s the value for D becomes 0.3 m^2/s as opposed to 0.15 m^2/s at V = 0.5 m/s. The air velocity across the hood face mentioned here is analogous to the cross draft velocity V_d. It is important to understand that if the cross draft velocities become extreme it may become necessary to install side curtains around the process or possibly examine a booth configuration. In an upcoming section, the workers themselves have been examined as a sort of human air curtain. To illustrate the effects on concentration levels when increasing the distance from the source, consider the following in Figure

5.1.

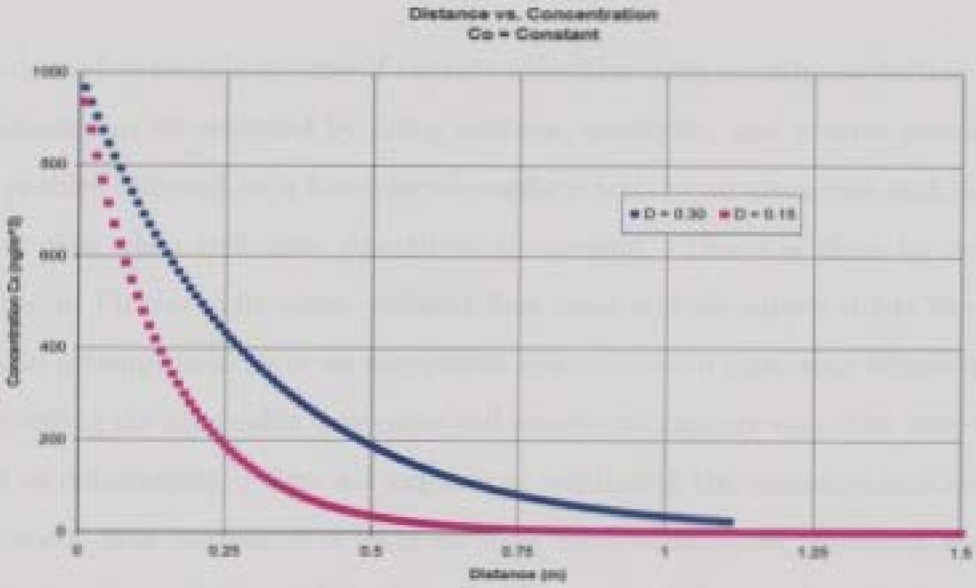

Figure 5.1: Concentration decay as distance from source concentration is increased

It is important to keep in mind that this plot only shows concentration decay directly along centerline but says nothing about how it behaves laterally. Their lateral movement will be significantly controlled by the airflow patterns in the immediate area, which are extremely difficult to determine without either obtaining empirical data through scale model testing or the use of numerical simulations. At a distance of only twenty five centimeters from the source, the concentration of the pollutant is reduced to only 20% of its original value. This significant decrease in concentration indicates that the pollutants have dispersed into the environment and may now be difficult to capture and exhaust, thus placing greater emphasis on designing hoods to ensure capture and exhaust at the source.

5.2 Numerical Modeling

It was desired to be able to show if capture velocities using existing centerline velocity correlations can be obtained by using uniform, parabolic, and inverse parabolic velocity profiles imposed on a hood face boundary both in an ideal case and in a more realistic case when turbulent structures are present. This was done by numerical modeling in Fluent(v6.0) where exhaust flow rates and air supply inlets were specified in an attempt to achieve an acceptable contamination capturing situation. From this modeling the attainable flow rates and associated capture velocities were realized as well as determining if they are capable of ventilating the contaminated area. The environment that surrounds a local exhaust hood constitutes turbulent structures that impact the velocity profile of the hood and the diffusion characteristics of the contaminants. It is important to realize that the initial proposed centerline velocity models do not take into account the different structure configurations present in an industrial crab processing plant and therefore ignore the effects of turbulence, thus spurning the need to investigate a variety of different velocity profiles. It is highly unlikely that these initial centerline velocities predicted by Dalla Valle, Fletcher, Conroy, and Silverman will be attainable in a realistic situation due to their above mentioned limitations. Turbulent structures and their effects can be summarized as follows;

- turbulent structures created in the wake of objects near the hood
- structures caused by hood geometry
- impinging airflows on velocity fields generated by the hood
- free-stream turbulent structures

The turbulent structures created by the above listed effects must be considered when designing a ventilation system even in light of the fact that empirically derived centerline velocity relationships continue to be the basis of standard design approaches. With this in mind the centerline model predictions have been used as a guide in an attempt to obtain the required capture velocities as well as provide sound guidance toward a feasible solution.

5.2.1 Velocity Profile Determination in an Ideal Domain

Examination of the proposed centerline models is essential in order to begin to understand the airflow patterns predicted by the various models using a CFD package such as Fluent. Due to the increased complexity of simulating 3-D geometries and obtaining converged solutions the simulations have been executed in 2-D. This is a reasonable approach as it is essentially modeling a 2-D plane through the center of each of the hoods. The end effects caused on the flow patterns by a 3-D hood have not been taken into account, nor have the interaction of the hoods with each other.

Firstly, the relationships will be examined by imposing the three velocity profiles on a hood face in an idealized domain such that there are no effects from turbulent structures or any other flow disturbance sources. Three hood face velocities will be implemented and the corresponding capture velocities at certain distances x returned by the numerical simulations will be compared to the values predicted by the empirical relationships. This has been done by using the overhead cleaning/sorting hood case with the corresponding unflanged rectangular centerline velocity models proposed by Dalla Valle and Fletcher. Secondly, in the following sections, a more realistic environment in which the hoods will have to operate will be used to again determine the capture velocities and velocity profiles.

These relationships, like many other similar ones refer only to the centerline air velocity along a line extending out from the center of the hood but do not define the velocity distribution across the hood face in any way. In addition, the sharply bending air streams flowing into the hood from behind the hood face interfere with smooth velocity contours in front of the hood where contaminants are generated (McDermott, 1977). The proposed relationships indeed provide a starting point to aid the simulations but due to the fact that they are strictly centerline velocity correlations and the exact circumstances by which they were formulated are unknown, velocity profiles need to be introduced as they provide a more realistic scenario. For all ideal simulations a constant hood face width of 2.44 meters has been used. It should also be noted here that only overhead hoods have been used to determine appropriate velocity profiles. In addition, one or all of the profiles determined will be used in the real simulations for overhead, canopy, and slotted hood configurations. The profile may not be the ideal for all three cases but to demonstrate the flow patterns and possible capture zones it is easily sufficient.

Uniform Profile

To begin, a hood of width 2.44 m has been shown in 2-D with its width fully displayed in the view. The 2-D plane has been constructed to simulate a slice along the width of the cleaning/sorting hood directly through the centerline of the hood face. Figure 5.2 depicts this tri-grid meshed, 2-D view of the hood. It can be seen that the mesh has been refined at the hood face inlet boundary to promote a more accurate solution.

The cleaning table and simulated workers have not been constructed in the ideal domain so as to avoid any turbulent interference with the velocity distribution. The domain consists of the hood, with its face specified as a velocity inlet and the boundaries of the domain specified as pressure inlets, which has been done to allow the hood to draw air in from all directions. The gage pressure has been set to zero at the pressure inlet boundaries and the velocity profiles at the hood face boundary have taken on uniform V_f values of 2, 4, and 6 m/s. Figure 5.3 shows a theoretical uniform velocity imposed on the hood boundary.

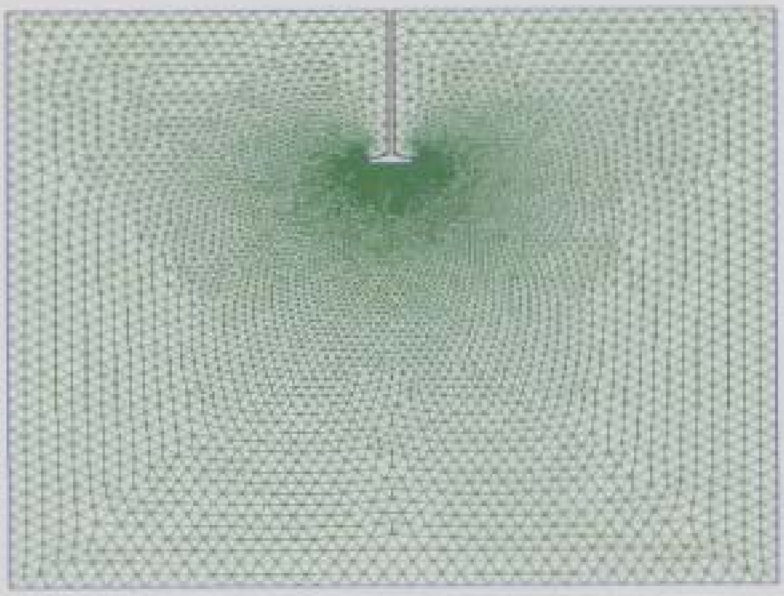

Figure 5.2: Tri-gridded domain

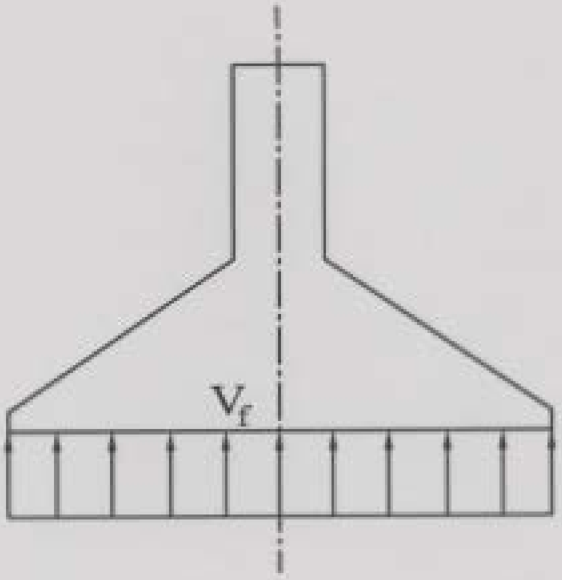

Figure 5.3: Uniform velocity profile

Four different domain sizes have been used mainly to check for grid dependence when using them in Fluent. It should be noted there that in order to obtain a flow rate in 2-D the hood face velocity was multiplied only by the width of the hood face, or an effective width L_e rather than the hood face area A_f. This procedure implicitly assumes a unit length of 1 meter for the hood face. This unit length will also be implemented in any correlations involving aspect ratios. Each of the three specified velocities has been applied uniformly to the hood face in each of the four domains to simultaneously determine how accurate the relationships are at predicting centerline velocity values in the hood face vicinity as well as the effect of the domain, if any, on the velocity profiles. The results have been summarized in Figures 5.4, 5.5, and 5.6.

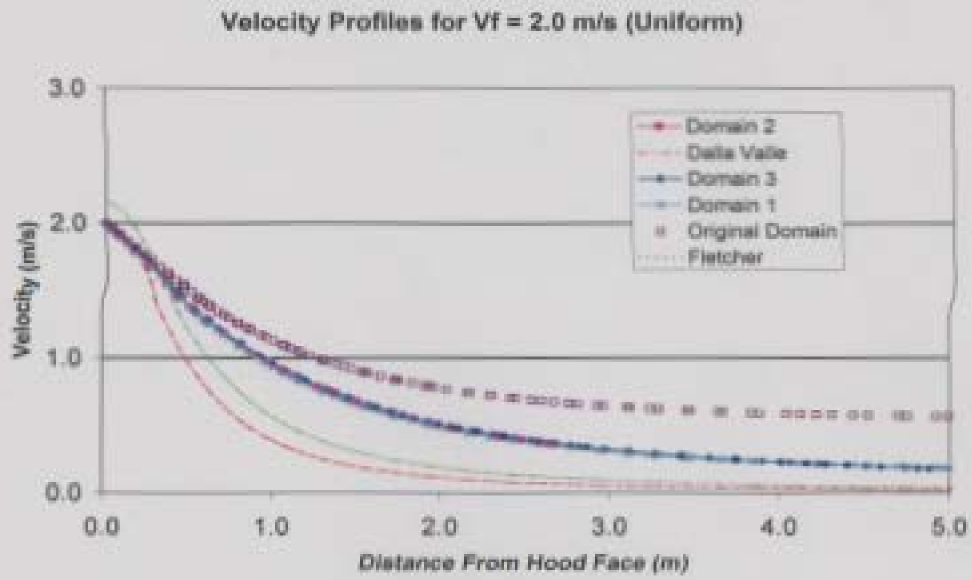

Figure 5.4: Centerline velocity profiles at Vf = 2.0 m/s

The lines depicted in these plots denote centerline profiles extending down normal from the hood face to the bottom of the domain. The profile denoted 'Original Domain' was included to illustrate the importance of allowing supply air to be introduced from all directions instead of just the bottom portion of the domain, as was the case with the 'Original Domain'. In addition, the velocity profile lines denoted by 'Original Domain' and 'Domain 1' have the exact same physical dimensions, however 'Domain 1' allows air to be introduced from all directions whereas 'Original Domain' only al-

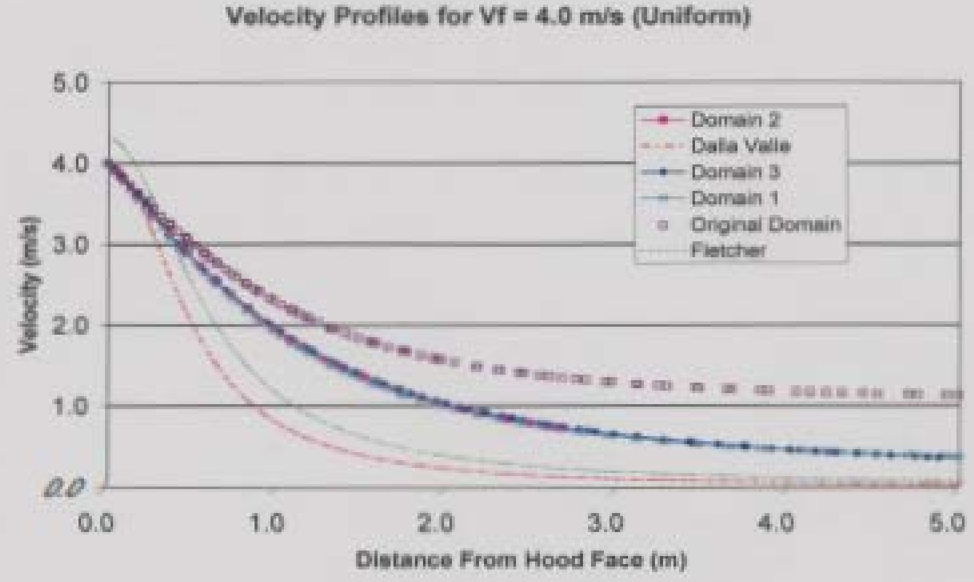

Figure 5.5: Centerline velocity profiles at Vf = 4.0 m/s

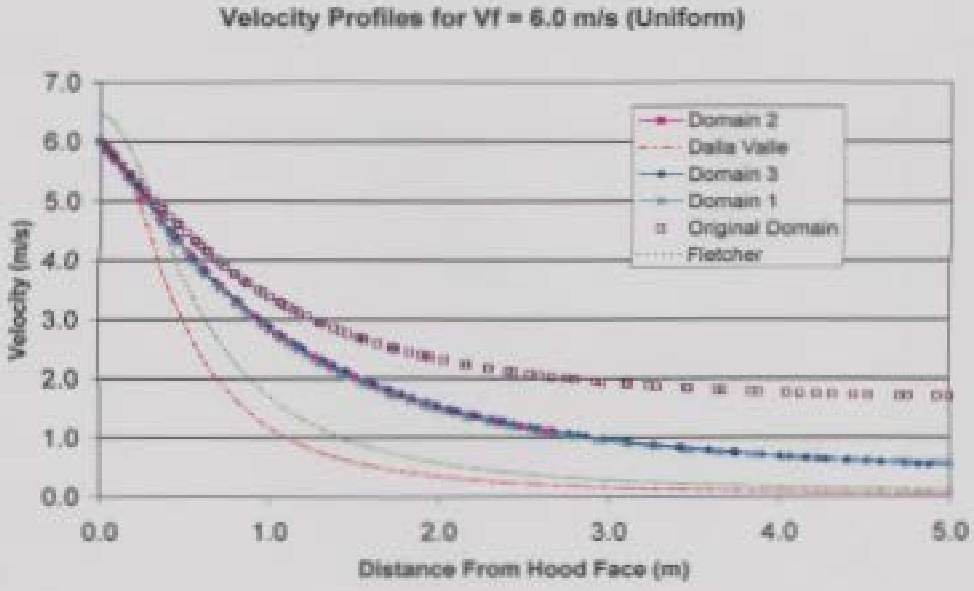

Figure 5.6: Centerline velocity profiles at Vf = 6.0 m/s

lows air to be introduced from the bottom boundary. The effect that this variation has on the profiles is drastic and can be easily seen in the plots. It can be seen that the domain has been made sufficiently large to rule out any grid dependence issues as the solution converges in domains 1, 2, and 3, evident by the fact that the lines fall on top of one another (domain 1 is sufficiently large, domain 2 is twice as large as domain 1 and domain 3 is twice as large as domain 2). However, the relationships by Dalla Valle and Fletcher, also plotted on the graphs, show a considerable difference in capture velocity values at varying distances from the hood when the profile trends obtained using the three face velocities are compared to these predicted values. The results here seem to indicate that a uniform velocity distribution at the hood face produces a trend very similar to the Dalla Valle's and Fletcher's relationships but may not be realistic and other profiles need to be examined.

Upcoming profiles have used only domain 2 as the test domain. In addition, only a velocity of 2 m/s has been used to produce corresponding velocity profiles.

Parabolic Profile

A parabolic velocity profile has been described by the following equation and shown in Figure 5.7.

$$V_y = V_{Max} - V_{Max}\left[\frac{x-20}{R}\right]^2 \tag{5.2}$$

The variable R is equal to half the width of the hood face, x is taken from the centerline of the hood face (at x = 20) to the maximum value of R, and Vmax is equal to $1.5V_f$, where V_f is the value of the previously specified uniform velocity. As mentioned previously, instead of applying each of the three specified hood face velocities in each of the four domains as was done in the uniform profile case, a maximum velocity obtained from the uniform velocity profile of 2 m/s has been used in the profile for simulations in domain 2. A maximum velocity of 3 m/s is found to be equivalent to the uniform velocity of 2 m/s from the application of flow continuity. Selecting

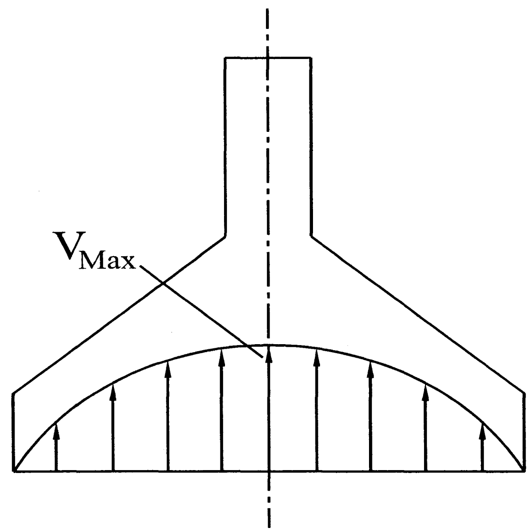

Figure 5.7: Parabolic velocity profile

one domain has been done as the trends are essentially identical for all three hood face velocities used in the uniform case. The parabolic case will also produce three essentially identical trends thus only one has been shown here added to the uniform profile in Figure 5.8.

Here it can be seen that the parabolic profile provides very similar trends but moves no closer to the trends predicted by Dalla Valle and Fletcher and is actually less predictive than the uniform profile. The main difference in the parabolic profile is that the maximum velocity is higher and drops off to almost the identical values that were produced using the uniform profile. When imposing a parabolic (and subsequent inverse parabolic) profiles on the hood face boundary an inherent variation has to be recognized. The hood has to produce a parabolic profile inside the hood rather than on the outside. This means that the flow at the hood face is assumed to have a fully developed parabolic velocity profile, which is impossible due to the entrance effects (become obvious later) caused by hood geometry. In theory, a parabolic profile should

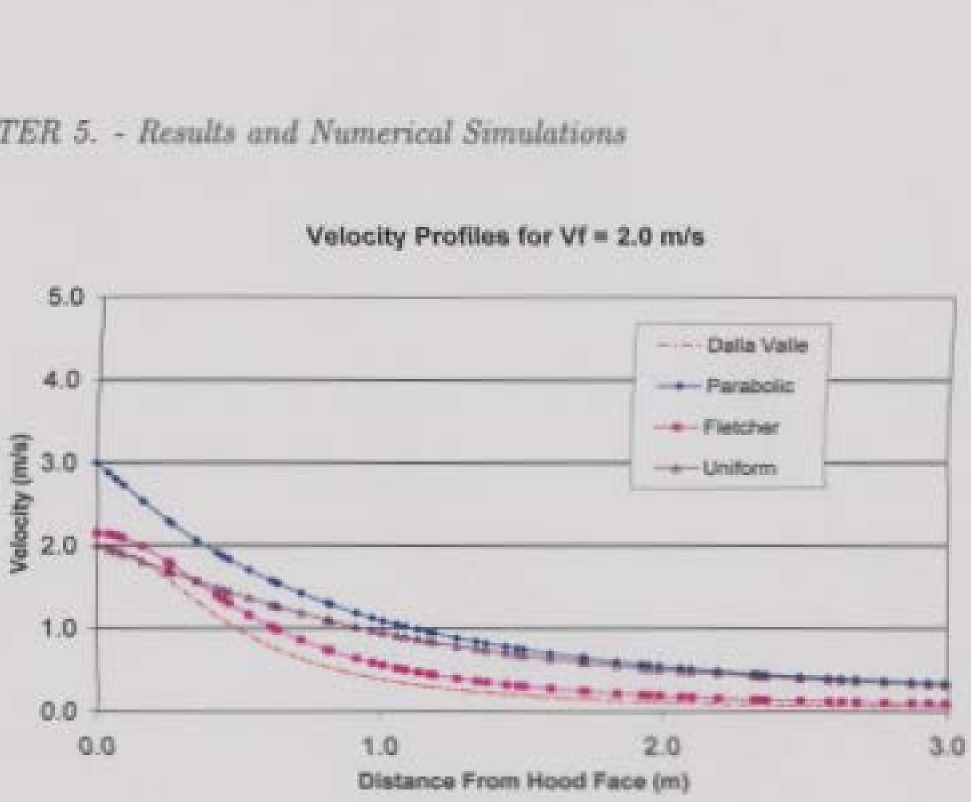

Figure 5.8: Centerline velocity trends at Vf = 2.0 m/s

be at its maximum at the centerline and zero at both ends of the hood face boundary. In actuality, this is not exactly the case as the profile is being imposed onto a situation that causes the flow to speed up at the edges of the hood when zero flow is expected and required to obtain a fully developed parabolic flow.

Inverse Parabolic Profile

For the purposes of this study the exhaust fan that would be connected to the simulated hood is assumed to be located at a distance far from the hood face. As a result an inverse parabolic velocity profile has been defined and shown below in Figure 5.9at the hood face boundary to determine its affect on velocity distributions.

$$V_y = 0.6366V_f \left[\frac{-1}{\sqrt{1 - \left[\frac{x-20}{1.22}\right]^2}} \right] \qquad (5.3)$$

The variables are identical to the ones used for the parabolic profile case. The

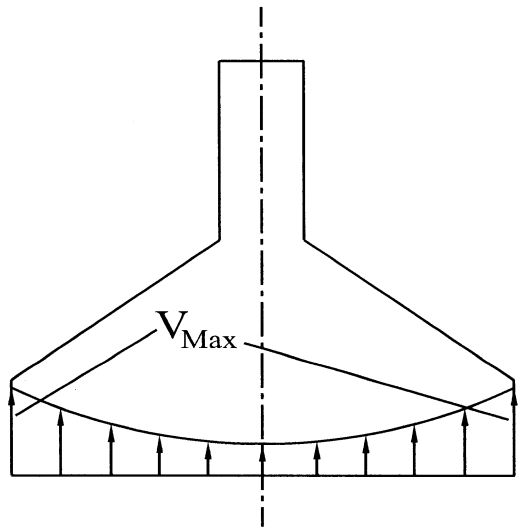

Figure 5.9: Inverse parabolic velocity profile

value 0.6366 is obtained from flow continuity in a similar manner as was done in the parabolic case. The inverse parabolic case will also produce three essentially identical trends, thus only one has been shown here in Figure 5.10, in addition to the uniform and parabolic profiles.

Here we can see that the inverse parabolic profile line is still not in total agreement with the empirical data however it again produces a very similar trend. Manipulation of the inverse parabolic profile as well as imposing an exponential (shown in Figure 5.10) profile for interest has been attempted to produce and alternative fit, keeping flow continuity in mind.

Custom Velocity Profiles

Recall that in the three profiles presented above an initial uniform velocity of 2 m/s was assumed whereby the total flow was determined and conserved to produce the other two profiles. Consider the following formula used for the inverse parabolic case.

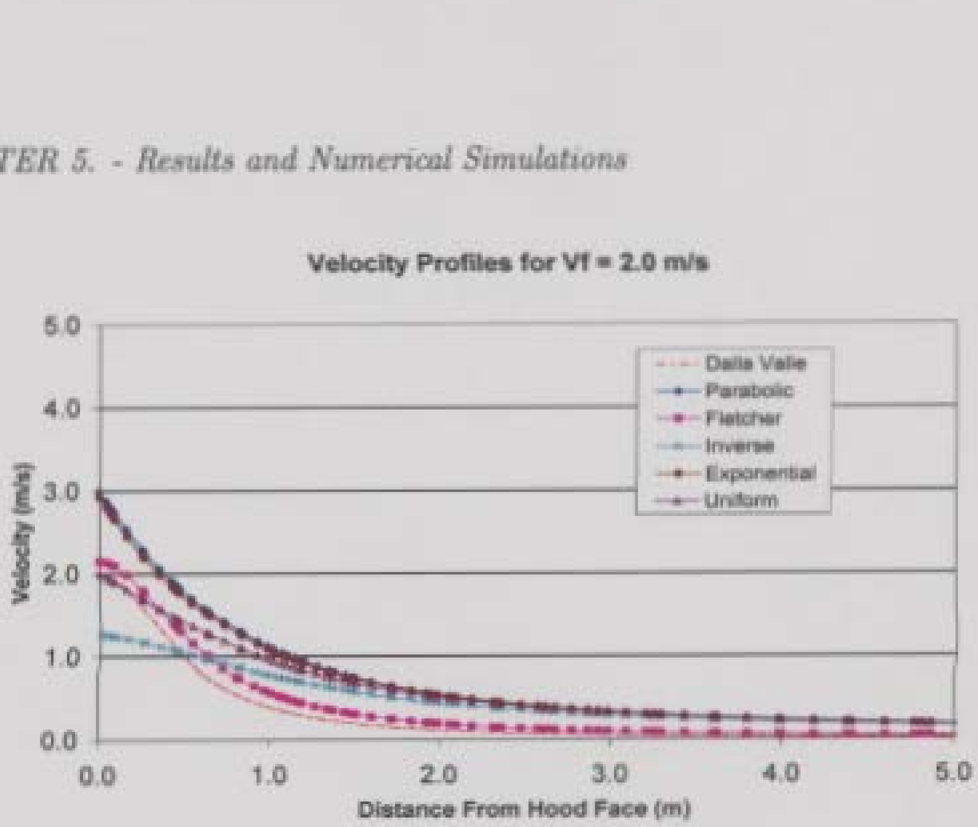

Figure 5.10: Centerline velocity trends at Vf = 2.0 m/s

$$V_y = CV_f \left[\frac{-K}{\sqrt{R - \left[\frac{z-20}{1.22}\right]^N}} \right] \tag{5.4}$$

Variation of the constants C, K, R, N, and M causes the apex of the parabola to vary in height as well as altering its shape. After numerous combinations the only realistic profile found is plotted in Figure 5.12 and given by the equation

$$V_y = -\left[1.27 \left[\frac{2.556}{\sqrt{3 - \left[\frac{[z-20]^4}{1.22^4}\right]}} \right] \right] \tag{5.5}$$

however no profiles were found here that fit the data considerably better than the classic ones already examined. This particular modified inverse profile has produced essentially the same as the uniform profile with a little lower face velocity.

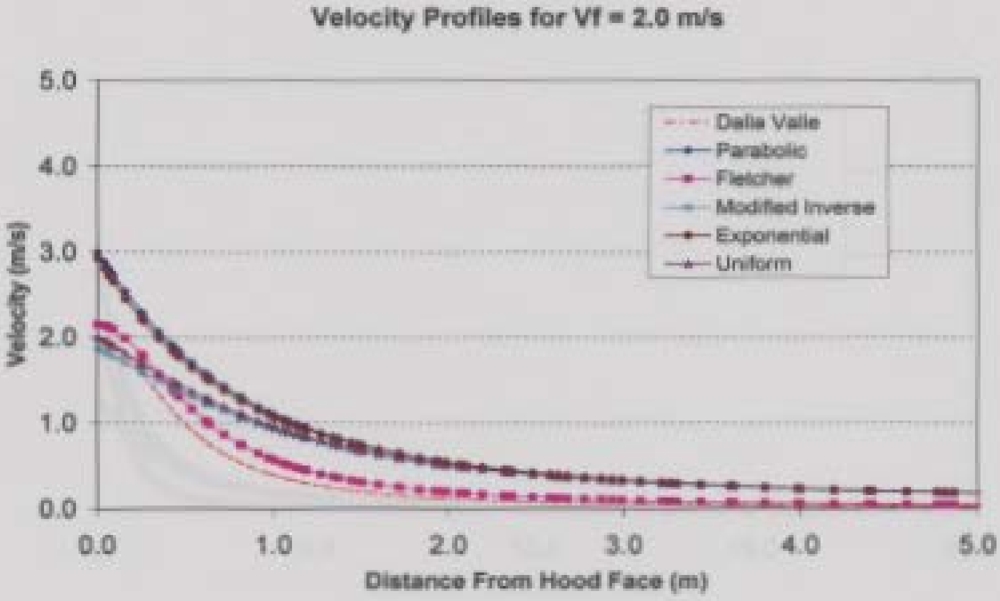

Figure 5.11: Centerline velocity trends at Vf = 2.0 m/s for a modified inverse parabolic profile

Profile Selection

The choice of which profile to use will ultimately reside with the design engineer based on individual design specifications. If a higher face velocity at the centerline is required with a relatively focused capture zone then a parabolic profile may be used. In contrast, if a low face velocity is desired with a greater capture zone then perhaps an inverse parabolic profile may be most suitable. Each of the profiles presented vary considerably in the 0.5 m - 1 m range from the hood face opening and get drastically closer to one another as the distance increases, as is shown in Figure 5.12.

In actuality, efforts to attain the exact profiles produced by Dalla Valle, Fletcher, and similar researchers like them may be impossible due to the fact that they are centerline velocity profiles only. Generally, in any engineering design, a factor of safety should always be incorporated into the analysis. The profiles produced by the uniform, parabolic, inverse parabolic, and exponential are obviously higher than

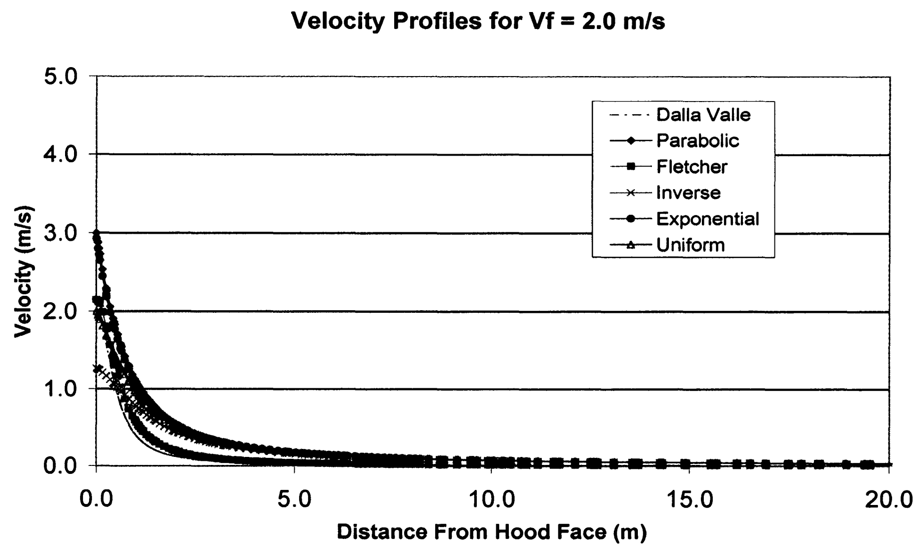

Figure 5.12: Centerline velocity trends at Vf = 2.0 m/s for large x-values

predicted, which could be thought of as a reasonable factor of safety inherent in the application of the particular profiles, thus avoiding the actual specification of a separate factor of safety. Either profile can possibly be used in realistic simulations depending on factors such as duct size, fan location, and degree of flow development. A parabolic or inverse parabolic profile may be the most realistic situation but since similar trends have been reproduced it can be justified that using any of the profiles in the upcoming realistic simulations is a valid course of action.

5.2.2 Flow Patterns in a Realistic Processing Environment

The cleaning/sorting and sawing processes have been examined using an unflanged overhead hood while only a slotted hood has been examined at the sawing table. The cooling tank has been modeled only with a canopy hood. The canopy simulation has included a flange of width equal to the square root of the hood face area(which is the width as all simulations are in two dimensions). Simulations have been completed such that the airflow pattern trends around the hoods could be visualized. From the previous section it seemed that any of the uniform, parabolic, or inverse parabolic profiles could be used depending on the situation. Each profile produced similar trends that could be scaled to fit the empirical data if necessary.

The effects of turbulent structures in the form of processing equipment will now come into play in the form of a cylinder that will be placed in the flow field representing a worker. This will allow fluent to determine its effects on the surrounding flow fields. In addition, two dynamic types of sources (brushes and saws) will be modeled such that the effect that the hood induced flows has dynamic sources can be determined (all previous simulations have assumed a non-buoyant type of contaminant source). This is a very important consideration as the brushes and table saws constitute dynamic sources capable of distributing particulate into the workers breathing zone.

Simulation Domains

The three processes that will be simulated with hoods are;

- Cleaning/Sorting
- Sawing
- Cooling

The constructed domains for the overhead, canopy and slotted simulations have been shown for illustrative purposes here in Figures 5.13, 5.14, 5.15, and 5.16.

Subsequent simulations will be restricted to the following parameters;

1. one uniform hood face profile that induces solution convergence
2. one x-value of 0.75 m above the process (overhead unflanged and flanged)

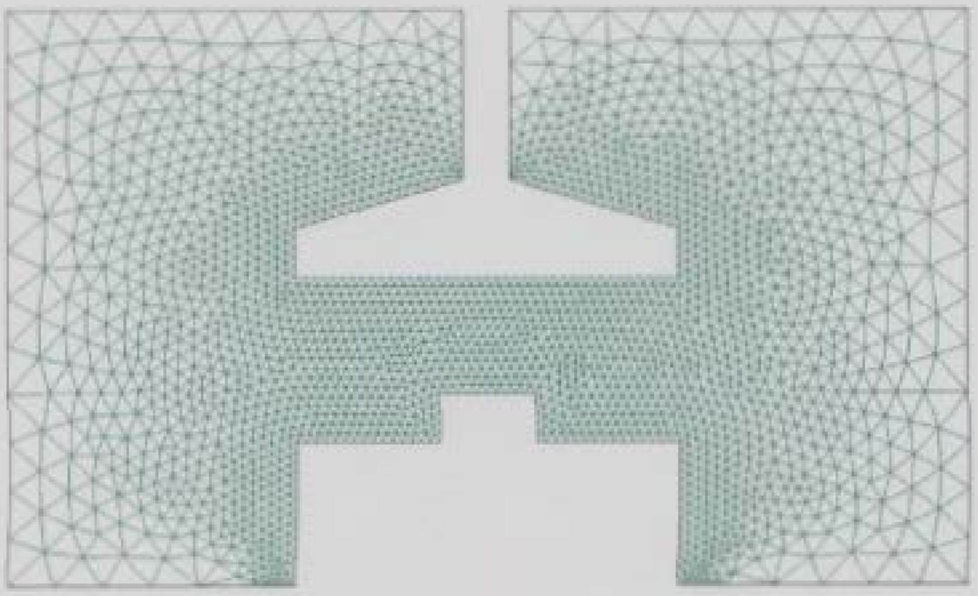

Figure 5.13: Cleaning/Sorting domain

3. one x-value of 0.30 m away from the process (slotted)

4. one x-value of 0.75 m above the process (canopy)

5. a general air supply method

Since the simulations are now taking place in a realistic environment the chosen face velocities may not be achievable due to the interaction of the parameters. If it is unlikely that a face velocity of 2 m/s can be achieved, the simulations will be run until a value for the face velocity is achieved such that the solution converges and produces the corresponding flow behavior.

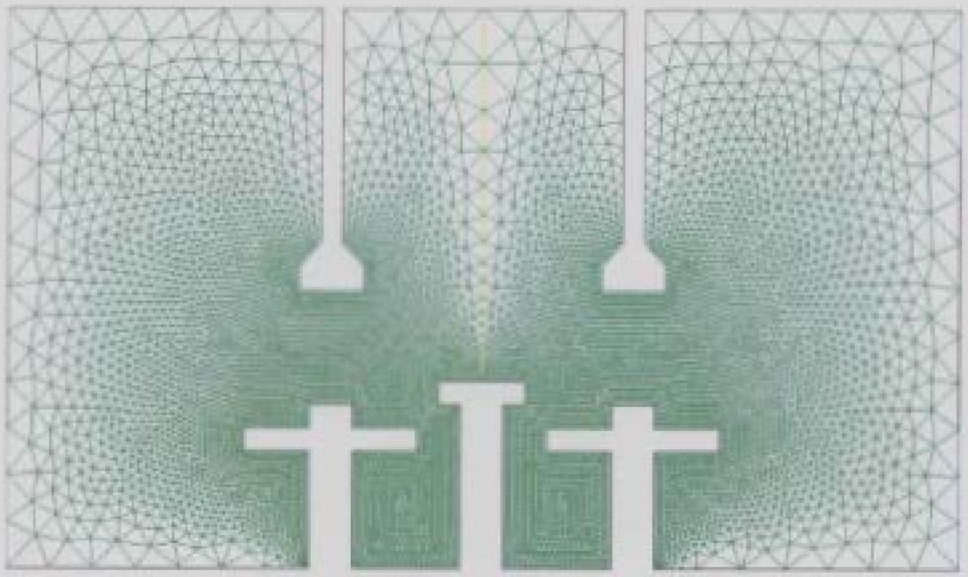

Figure 5.14: Sawing domain (overhead)

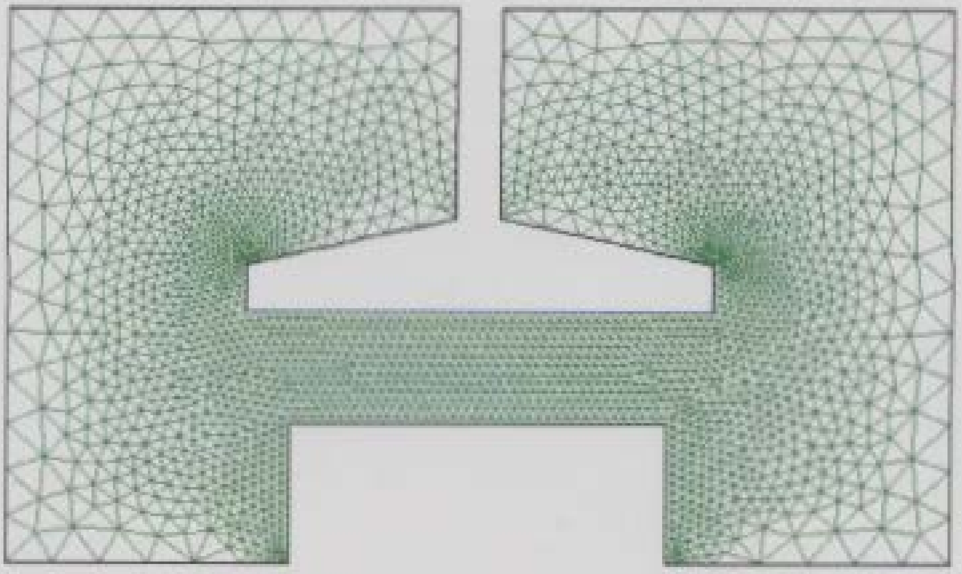

Figure 5.15: Cooking/Cooling domain

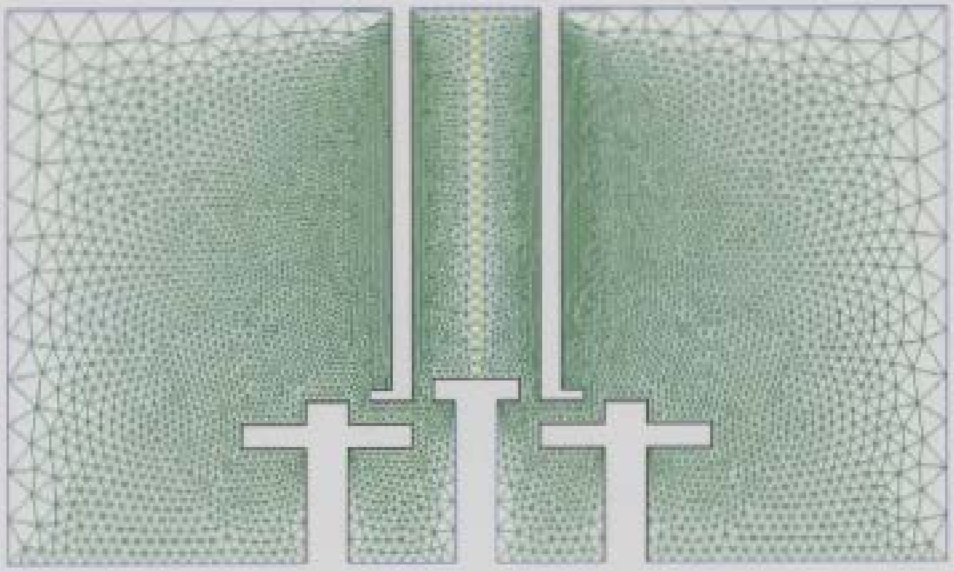

Figure 5.16: Sawing domain (slotted)

5.2.3 Overhead Simulation 1

The following simulation specifies a uniform face velocity of about 0.5 m/s, x-value of 0.75 m from the hood face to the contamination source, and the air being supplied from all boundaries in the domain. The velocity and pressure vectors and velocity contours are shown in Figures 5.17, 5.18, and 5.19.

It can be seen here that the velocity vectors follow a very distinct pattern and are clearly affected by the table structure. A velocity of only 0.5 m/s could be obtained at the hood face to produce solution convergence. The vectors have also been colored by the magnitude of the pressure at each vector location. A small negative pressure is evident underneath the hood face confirming an area of suction. The effects of the table structure also cause visible recirculation patterns and areas of stagnant flow. Also, the airflow tends to speed up at the edges of the hood face entrance, as is expected and shown by the vector magnitudes. Centerline profiles have been obtained and compared to Dalla Valle and Fletcher in Figure 5.20 for a face velocity

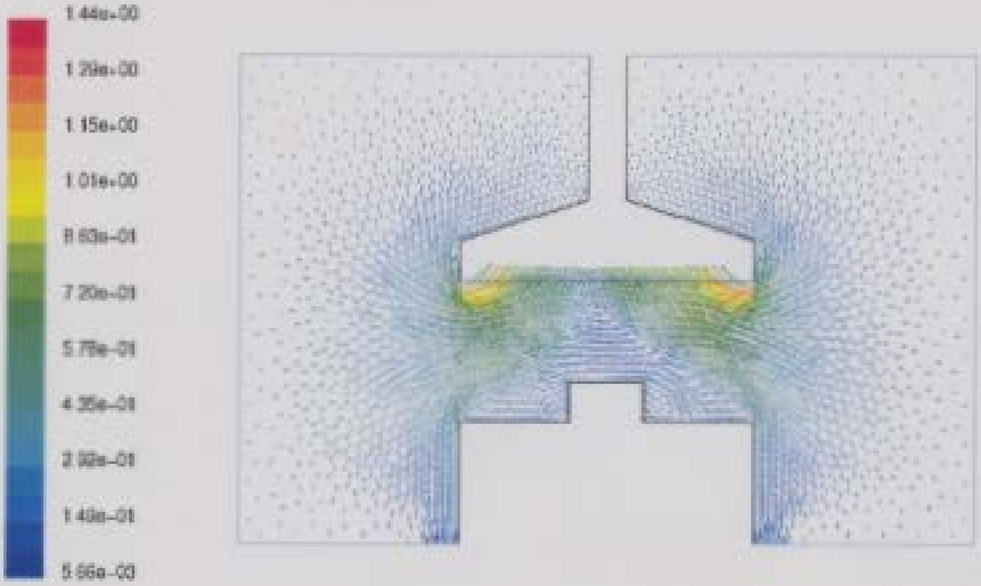

Figure 5.17: Velocity vectors colored by velocity magnitude

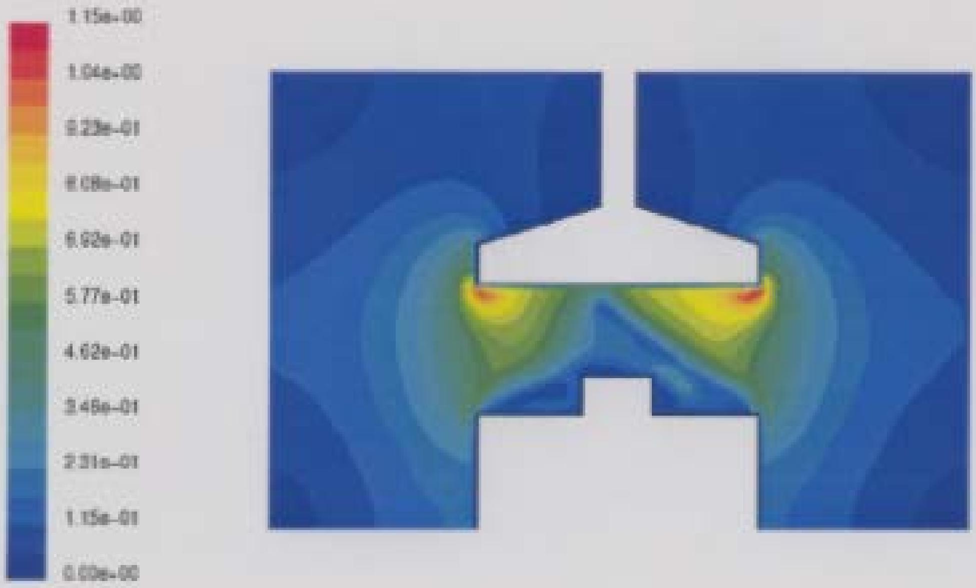

Figure 5.18: Contours of velocity magnitude

of 0.5 m/s.

The profile produced here follows the same trend and indicates a better fit to Dalla

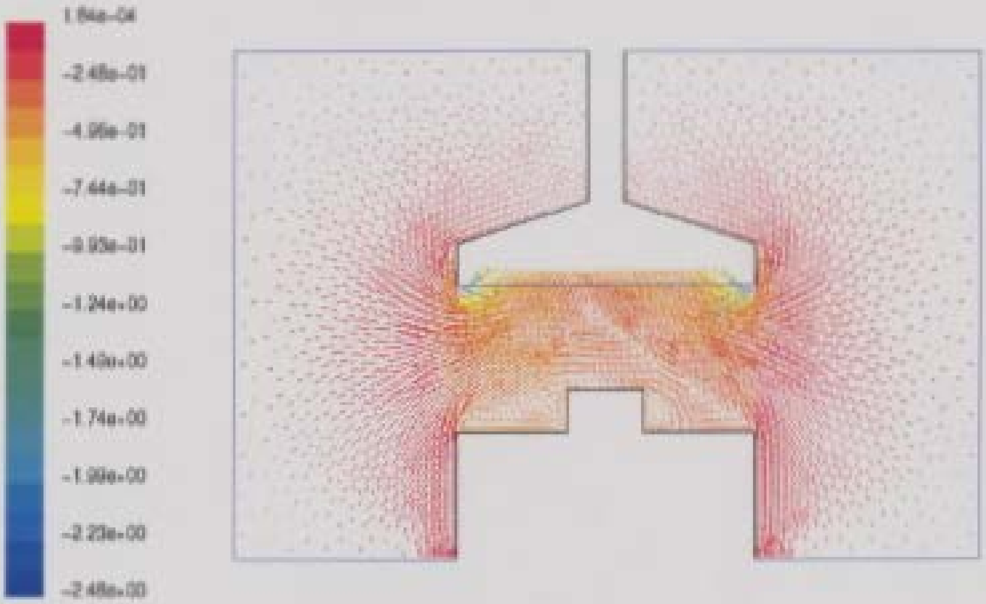

Figure 5.19: Velocity vectors colored by static pressure

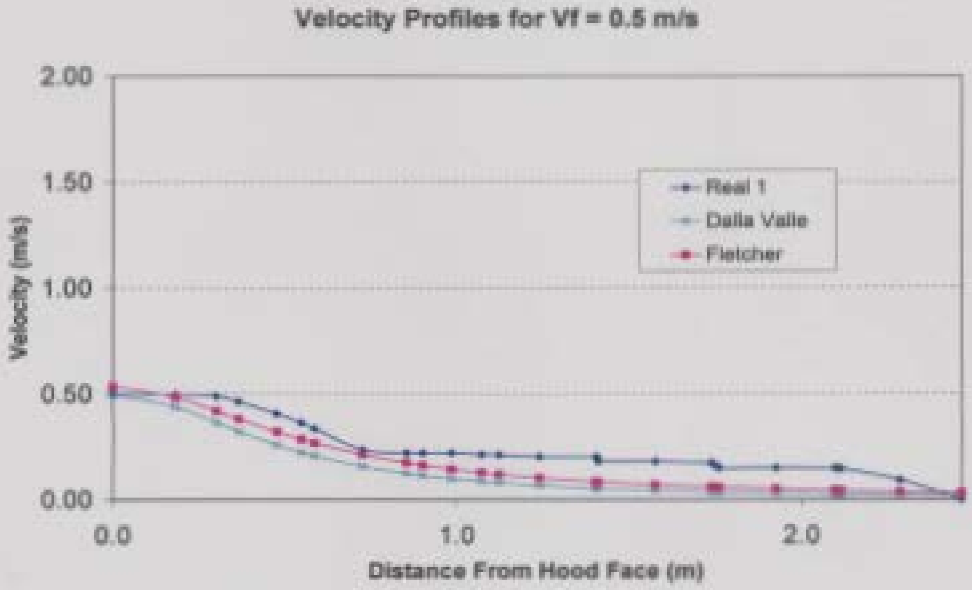

Figure 5.20: Comparison of centerline velocity profiles

Valle and Fletcher's profiles. The fact that the realistic simulation produced a better trend also indicates that the structures in the vicinity play an important role in the resulting airflow patterns. However, due to the interaction of the airflow with turbulent structures in the room, the flow patterns are virtually impossible to predict.

5.2.4 Overhead Simulation 2

The same process in now carried out with the sawing domains using a uniform face velocity of 0.45 m/s, x-value of 0.75 m from the hood face to the contamination source, and the air being supplied from all boundaries in the domain. The velocity and pressure vectors and velocity contours are shown in Figures 5.21, 5.22, and 5.23.

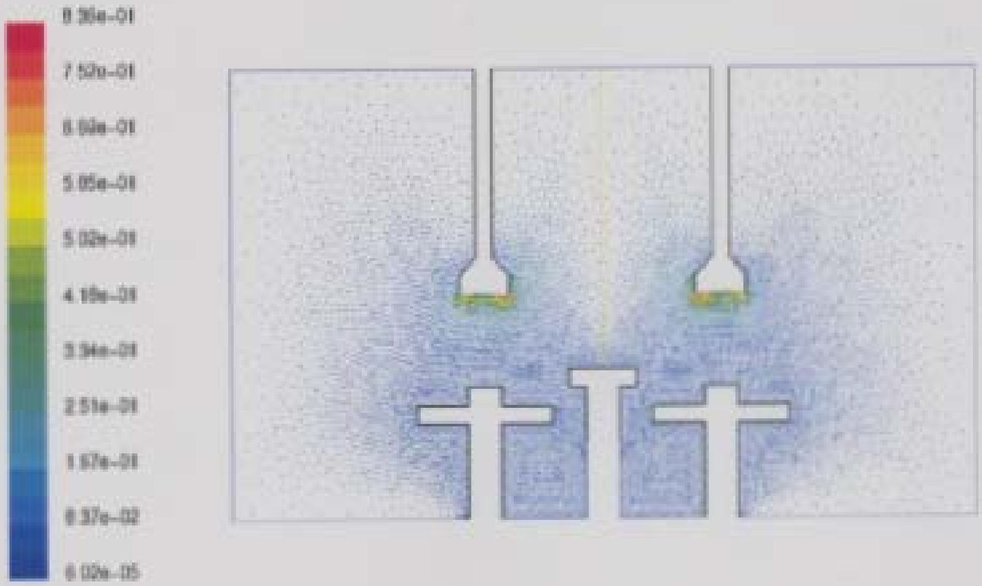

Figure 5.21: Velocity vectors colored by velocity magnitude

Here the velocity vectors again follow a very distinct pattern and are clearly affected by the table structure, however they are very different than those generated in the cleaning simulations. The vectors displayed have also been colored by the magnitude of the pressure at each vector location. A small negative pressure is evident underneath the hood face confirming an area of suction.

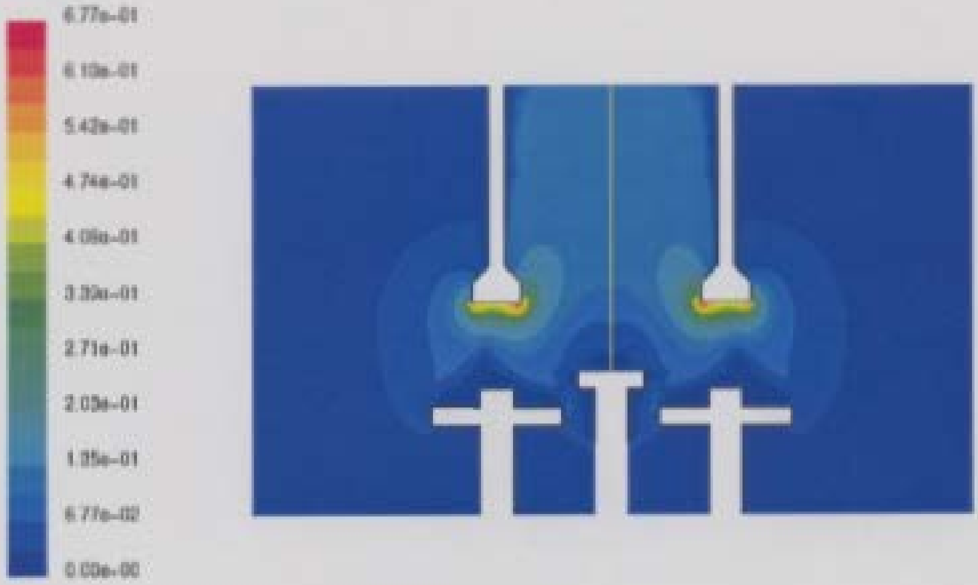

Figure 5.22: Contours of velocity magnitude

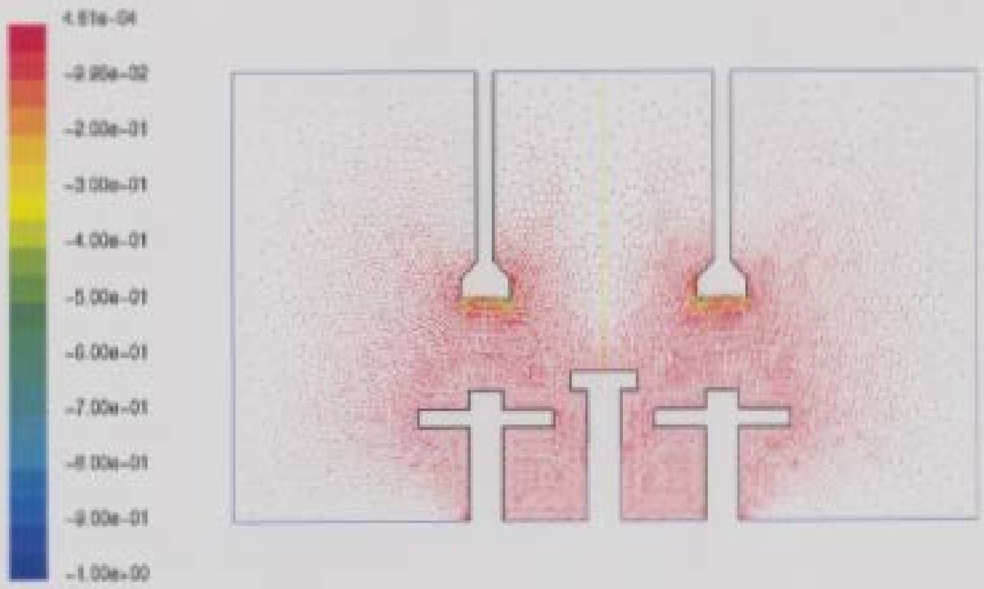

Figure 5.23: Velocity vectors colored by static pressure

5.2.5 Slotted Simulation

The process in now carried out with a slotted hood of width 0.18 m (aspect ratio of 0.18), a uniform face velocity of 2 m/s, x-value of 0.30 m from the hood face to the center of the contamination source, and air being supplied from all boundaries in the domain. Only the sawing process has been fitted with a simulated slotted hood as the cleaning/sorting and cooking/cooling processes would require a large slot in order to compensate for the extensive length (in excess of 20 ft). The velocity and pressure vectors and velocity contours corresponding to this simulation are shown in Figures 5.24, 5.25, and 5.26.

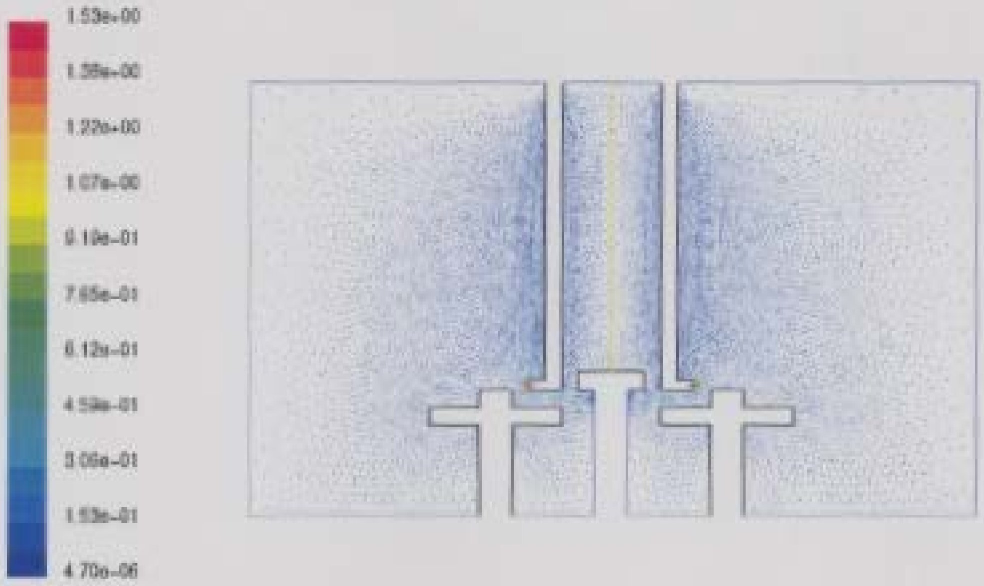

Figure 5.24: Velocity vectors colored by velocity magnitude

The solution converged much more quickly with this configuration than with any other presented. The fact that the hood is now in a horizontal configuration allows it to draw in air much easier than in the vertical overhead configuration. The overhead simulations as they have been constructed allowed only small face velocities of approximately 0.5 m/s in order to obtain solution convergence, whereas it seems that any number of velocities can be used for the hood face velocity in the slotted configuration. In addition, pulling in air horizontally is easier than vertically as the air does not have to make any turns, thus contributing to improved airflow characteristics.

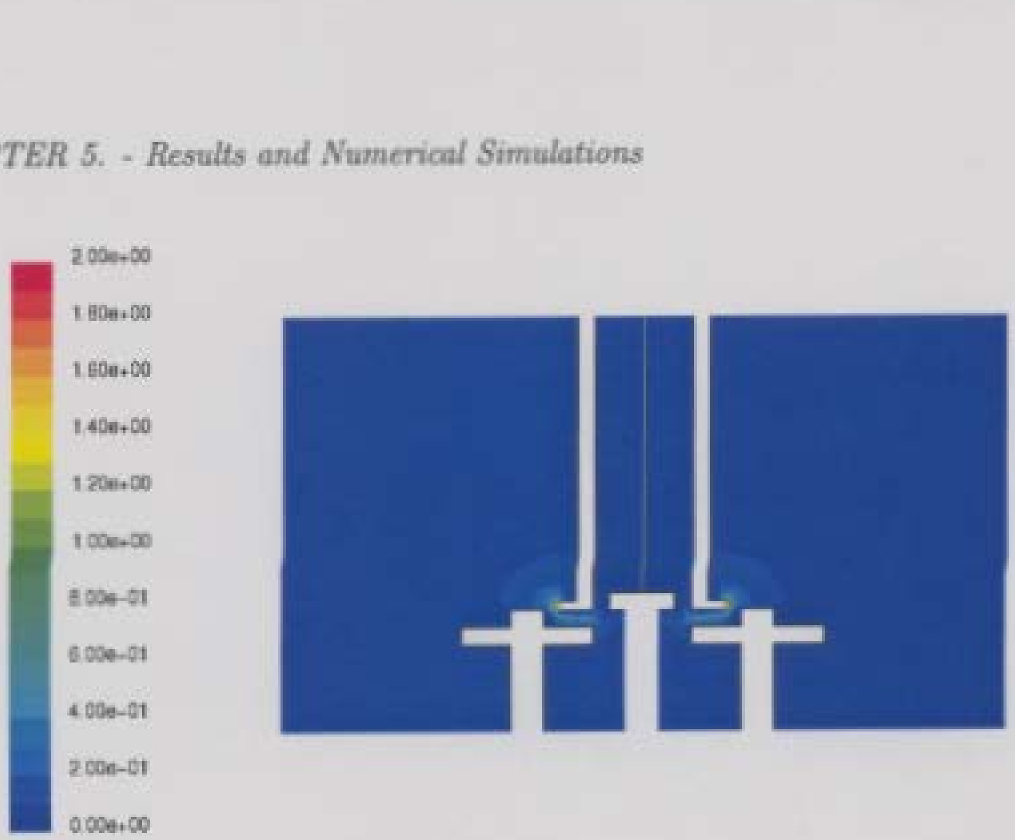

Figure 5.25: Contours of velocity magnitude

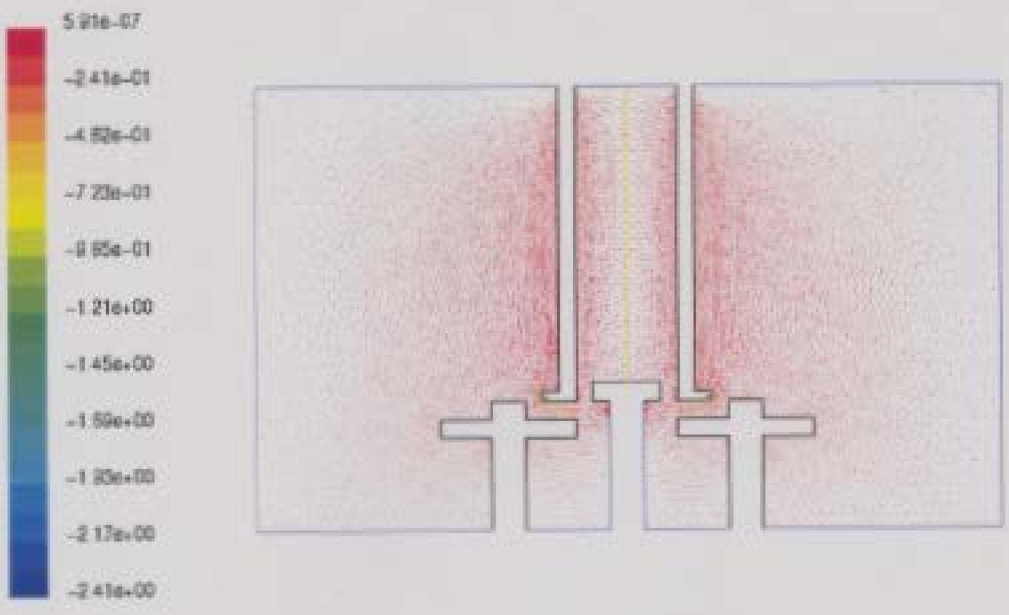

Figure 5.26: Velocity vectors colored by static pressure

5.2.6 Canopy Simulation

The process is now carried out with a canopy hood of approximate total width of 4 m (2.44 m width hood with 0.781 m width overhang on either side), a uniform face velocity of 2 m/s, x-value of 0.75 m from the hood face to the contamination source, and air being supplied from all boundaries in the domain. Only the cooling process has been fitted with a simulated canopy hood as the cleaning/sorting and sawing processes require the workers to lean in over the process to perform the necessary tasks. This is sometimes avoided in cases where the cooker and cooling tanks are automated and only require workers to load and unload the crab at the respective ends. The velocity and pressure vectors and velocity contours corresponding to this simulation are shown in Figures 5.27, 5.28, and 5.29.

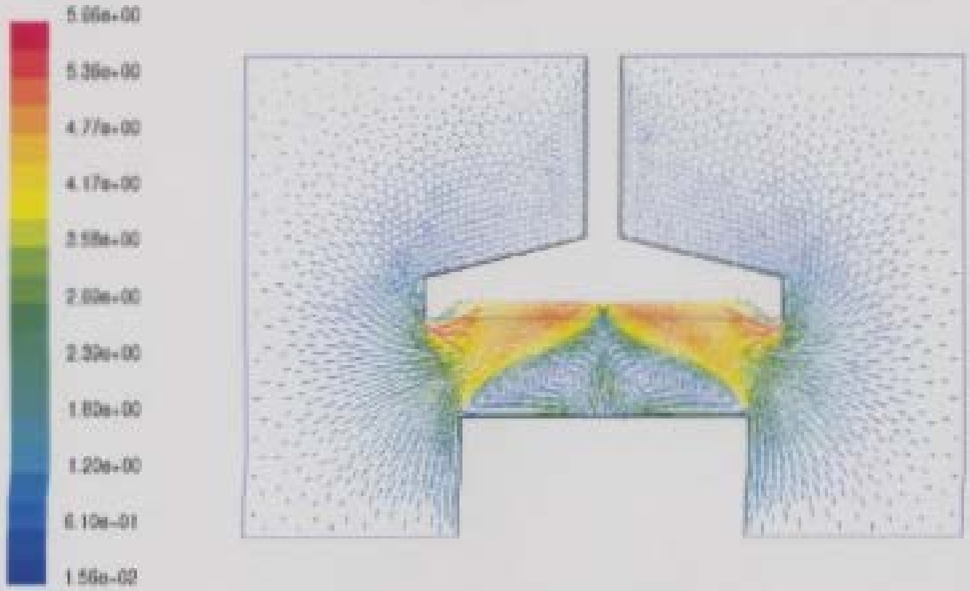

Figure 5.27: Velocity vectors colored by velocity magnitude

Again the solution converged quickly with this configuration in a similar manner to the slotted sawing simulation. The fact that the hood has a slight overhang has changed the flow patterns that were observed in the overhead simulations.

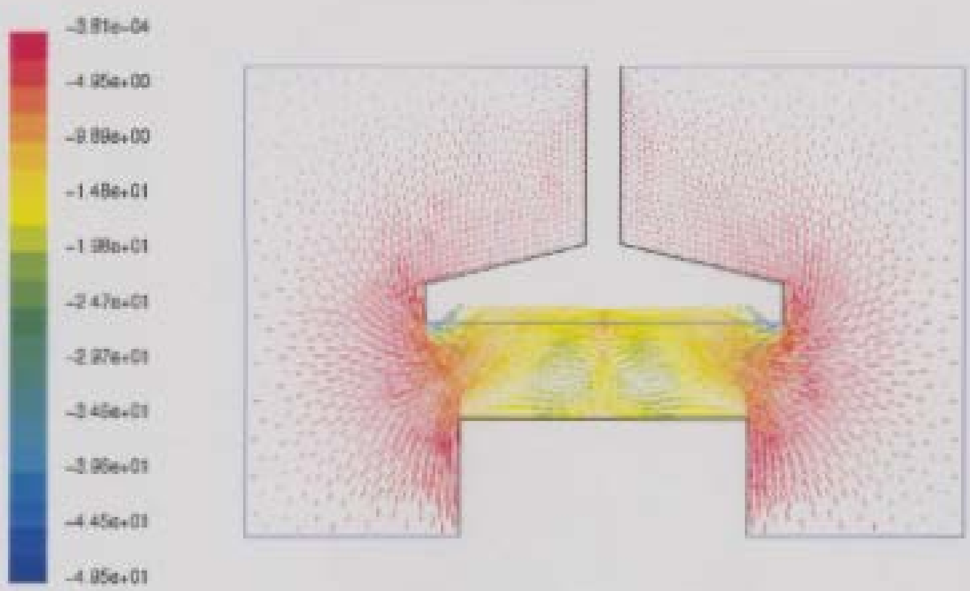

Figure 5.28: Contours of velocity magnitude

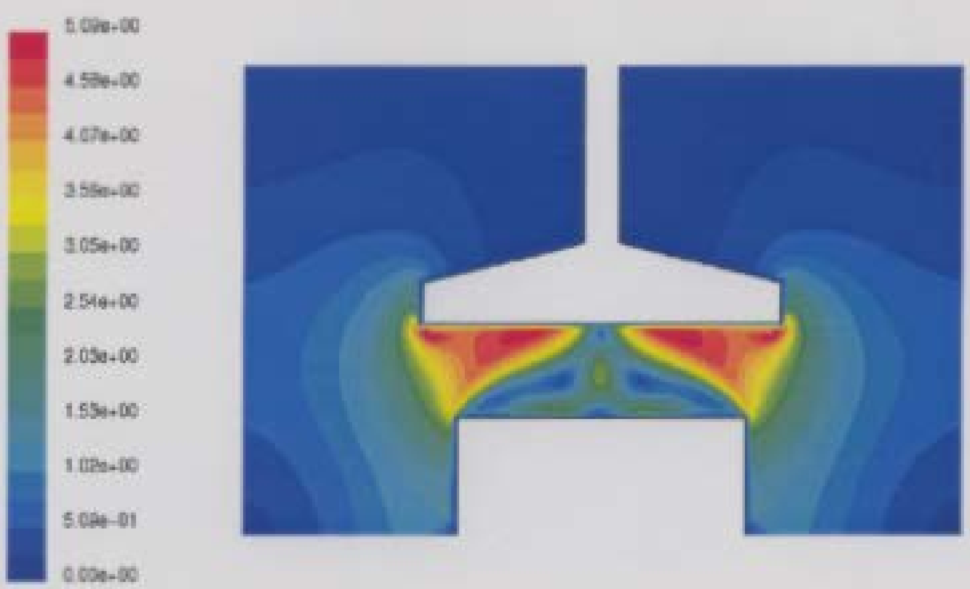

Figure 5.29: Velocity vectors colored by static pressure

5.2.7 Flanged Simulation

The canopy simulation has been run again here only now a flange equal to $\sqrt{Area}$ has been used. Addition of a flange is normally done to decrease the airflow required to produce the same velocity as an unflanged hood. However, the uniform velocity of 2 m/s will still be used initially with the ramifications being portrayed in the simulations. In addition to decreasing the airflow required the velocity distribution is significantly improved in the hood vicinity. The velocity and pressure vectors and velocity contours corresponding to this simulation are shown in Figures 5.30, 5.31, and 5.32.

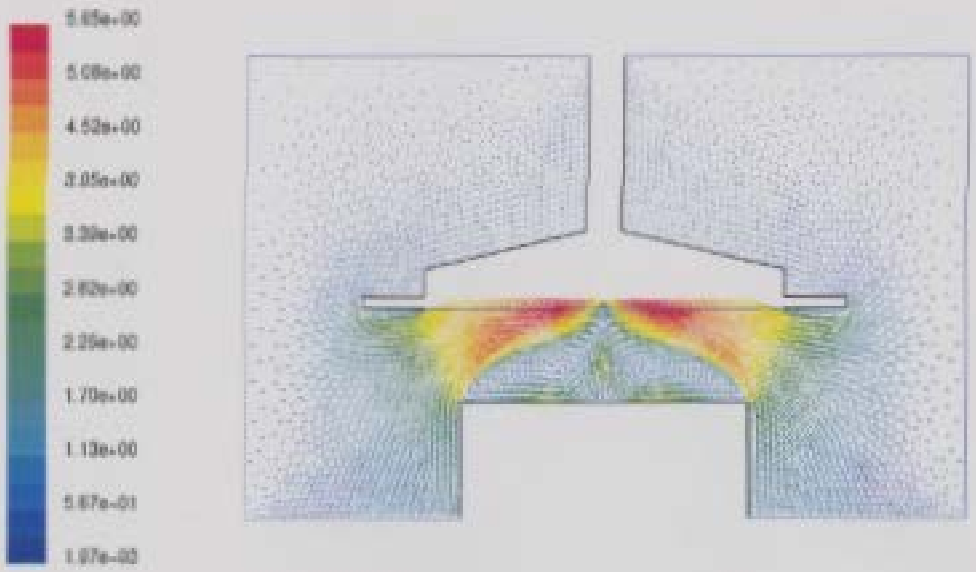

Figure 5.30: Velocity vectors colored by velocity magnitude

The flange allows air to be drawn in from in front of the hood, rather than behind, at a greater efficiency thus promoting increased contaminant capture. The flange also allows the air to enter with an increased distribution near the edges of the hood even though the same uniform velocity has been specified in both cases. In both cases, the air has to turn to enter the hood. However, without the flange the air is very turbulent and chaotic near the edges of the hood thus decreasing the effective hood face area for exhausting contaminants.

To examine the effects of including a flange, various profiles parallel to the hood face

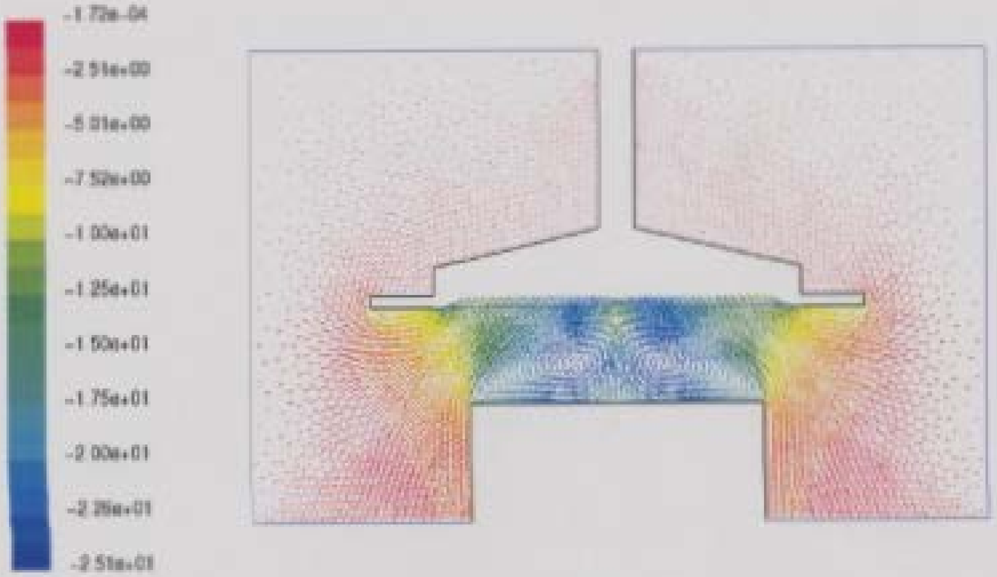

Figure 5.31: Contours of velocity magnitude

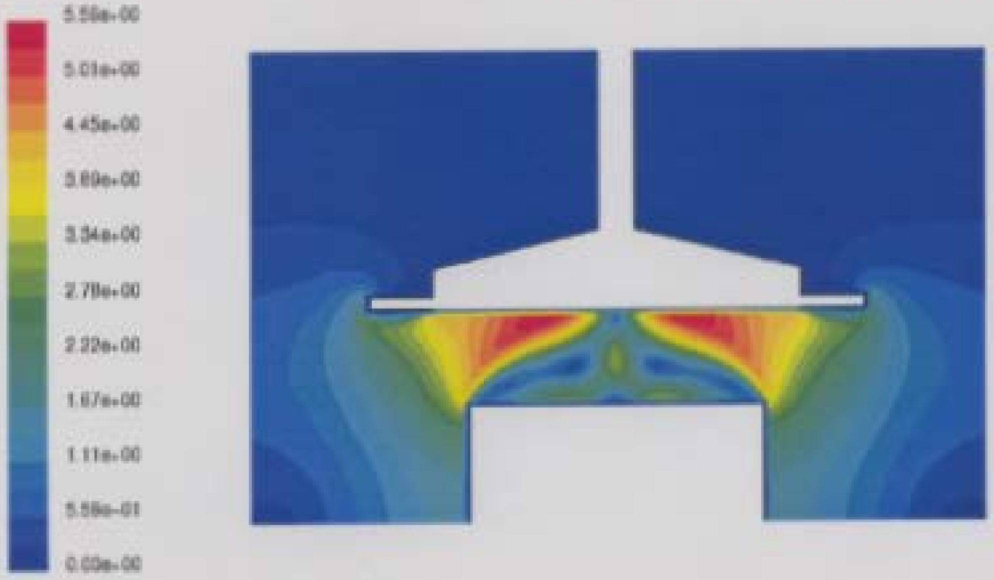

Figure 5.32: Velocity vectors colored by static pressure

at predetermined distances from the hood face have been extracted from the above simulations. Figure 5.33 shows profiles at selected distances for the unflanged case.

Similarly for the flanged case, Figure 5.34 shows profiles using the same distances as in the unflanged case.

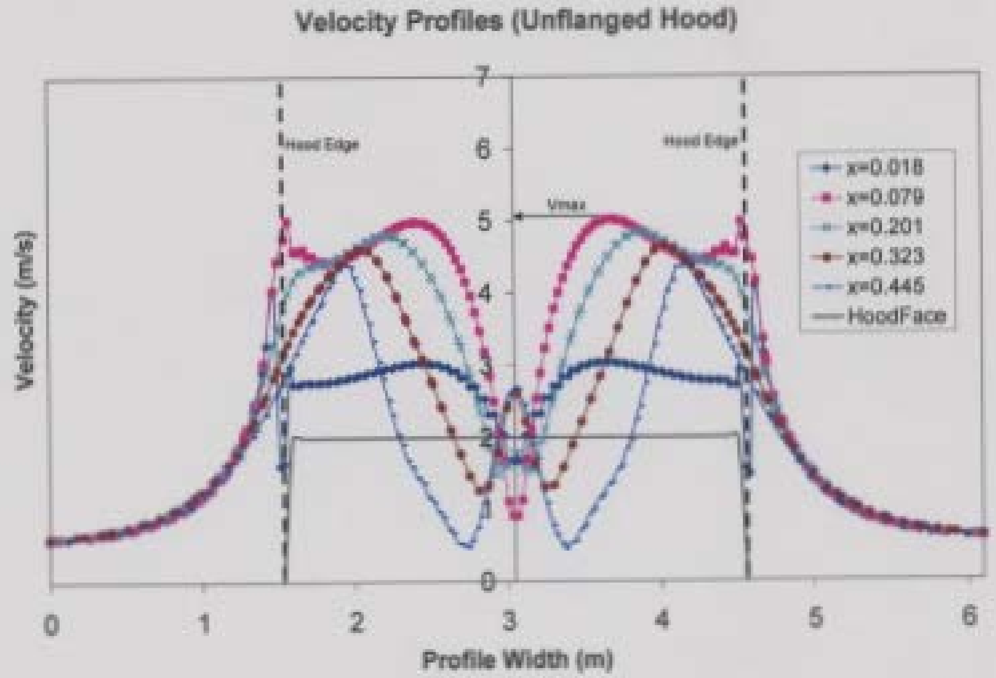

Figure 5.33: Horizontal velocity profiles from the unflanged canopy hood simulation

The difference in the profiles produced with the addition of a flange are noticeable. The flange increases the maximum attainable flow rate along the centerline as well as in the area outside the edge of the hood face, thus improving capture capability in the horizontal direction. A direct comparison of three of the profiles is shown in Figure 5.35 where it can be seen that profiles produced in the flanged simulation are consistently higher than that produced in the unflanged simulation.

The insertion of a flange did not ignore the fact that the air still had to physically turn, but it has done so with an improvement in airflow distribution. The velocity spiked as it rounded the hood edge in the unflanged case and caused the air to undoubtedly become choppy in that area. The flange caused this spike to occur as the air rounded the flange and by the time it got to the hood face it only had to turn 90 degrees

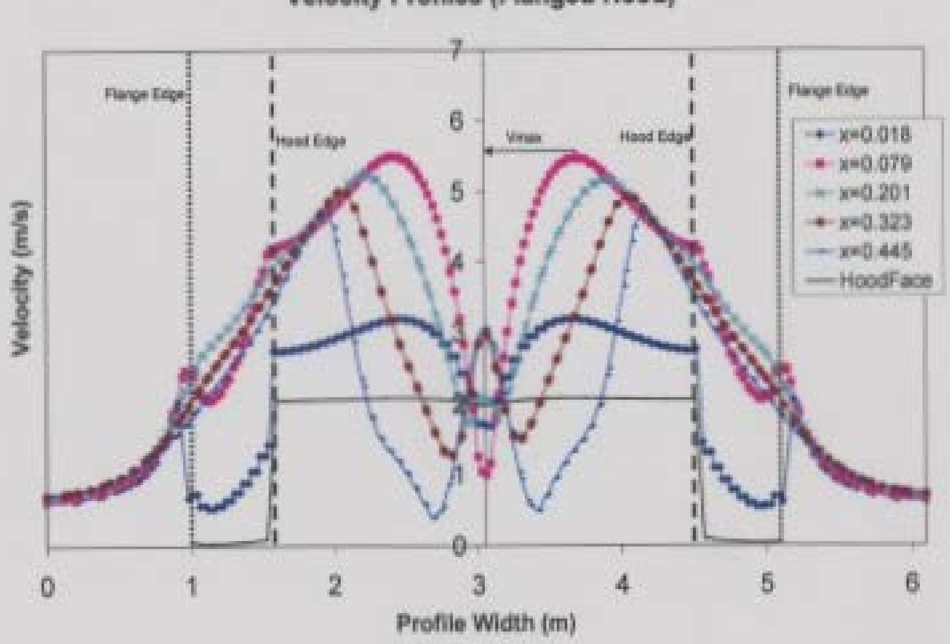

Figure 5.34: Horizontal velocity profiles from the flanged canopy hood simulation

instead of 180 degrees, as was the case in the unflanged case. This causes the air to distribute more evenly and reduces turbulence. Although the gains may seem to be relatively small they are nonetheless gains that were obtained by the simple addition of a flange, rather than increasing fan power or hood size.

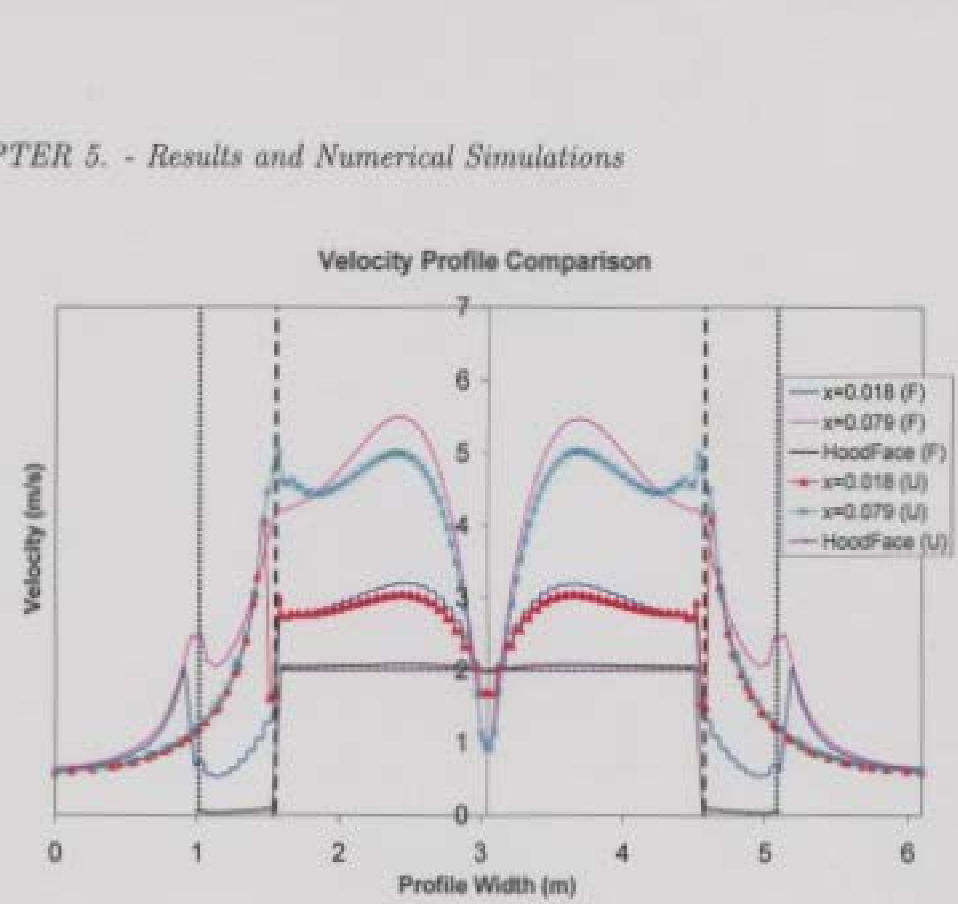

Figure 5.35: Horizontal velocity profile comparison between flanged and unflanged simulations

5.2.8 Worker Interaction Simulation

The cleaning/sorting domain has been modified to include a cylinder on either side of the table measuring 1 ft wide by 5 ft high to simulate the presence of a worker. The associated velocity and pressure vectors and velocity contours corresponding to this modified simulation are shown in Figures 5.36, 5.37, and 5.38.

As a result of the inclusion of the two cylinders simulating adjacent workers the airflow patterns have drastically changed shape. The workers have effectively provided a double sided 'human air curtain' to protect the exhaust hood and allow it to perform more efficiently. If it were assumed that workers were shoulder to shoulder along the full length of the table then this assumption could be realistic. However, the workers are spaced at varying intervals in normal processing with little or no consistency. The gaps that therefore exist between workers hinder the effectiveness of the 'human air

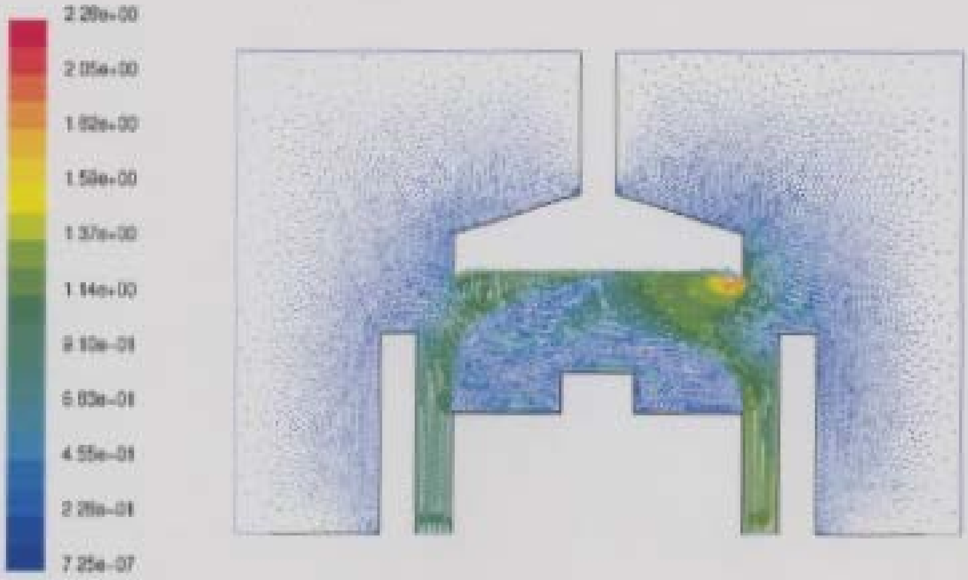

Figure 5.36: Velocity vectors colored by velocity magnitude

Figure 5.37: Velocity vectors colored by velocity magnitude

curtain', which would be evident if the simulations were in three dimensions rather than two. This 'curtain' also serves to eliminate some of the cross drafts that may

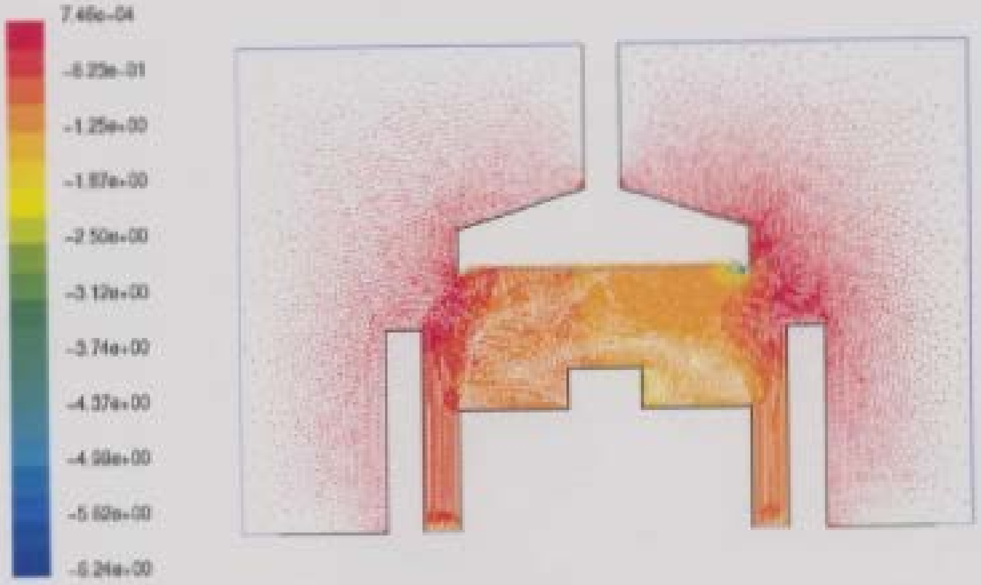

Figure 5.38: Velocity vectors colored by static pressure

be present in the processing area thus leading to more effective exhausting of contaminants. Figure 5.39 below shows the centerline contour profile resulting from the worker simulation.

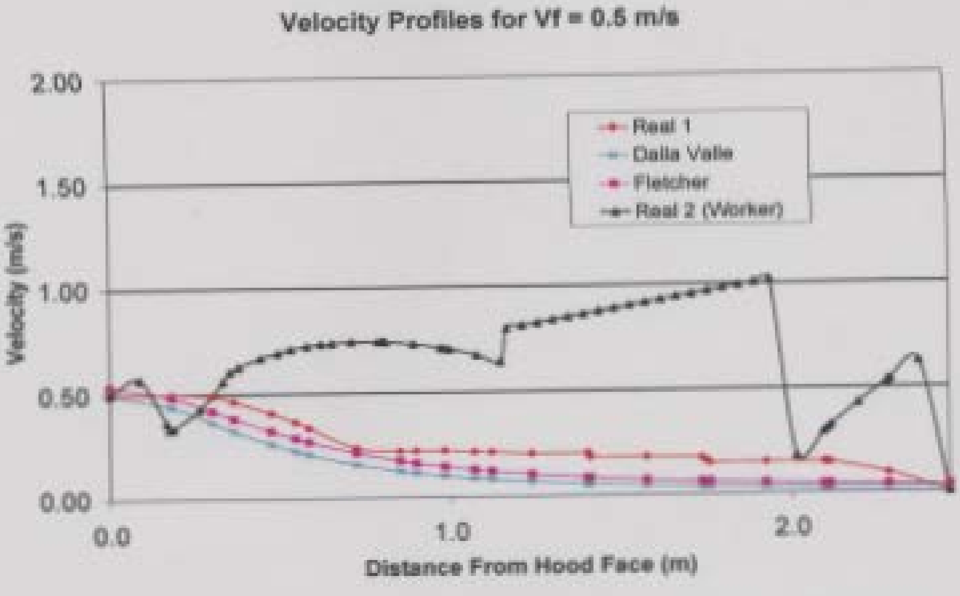

Figure 5.39: Comparison of centerline velocity profiles with simulated workers

It should be noted here that the solution did not converge to the degree of accuracy of all previous simulations. The profile has still been shown here as is illustrates the drastic effect that turbulent structures have on airflow patterns. Flow separation is undoubtedly a key factor in the somewhat inaccurate solution produced.

5.2.9 Dynamic Source Simulation 1

The overhead hood cleaning/sorting domain has been modified to now include a simulated brush on either side of the table measuring 8 inches in diameter. The brush boundaries have been modeled on the basis of a tip velocity of 2.66 and the hood face modeled with a small velocity of 0.1 m/s (It should be noted here that the minimal value of 0.1 has been chosen for the hood face velocity such that the system is only slightly influenced by the hood). The brushes are known to spin at 250 rpm, making the conversion into 2.66 m/s trivial. However, tip velocities are tangential to the spinning surface and could not be modeled in that manner at this time. Instead, velocities normal to the brush boundaries have assumed the tip velocity values. This is reasonable for simulation purposes due to the fact that the hood face velocities have also taken on assumed values to facilitate the simulations. The associated velocity and pressure vectors and velocity contours corresponding to this modified simulation are shown in Figures 5.40, 5.41, and 5.42.

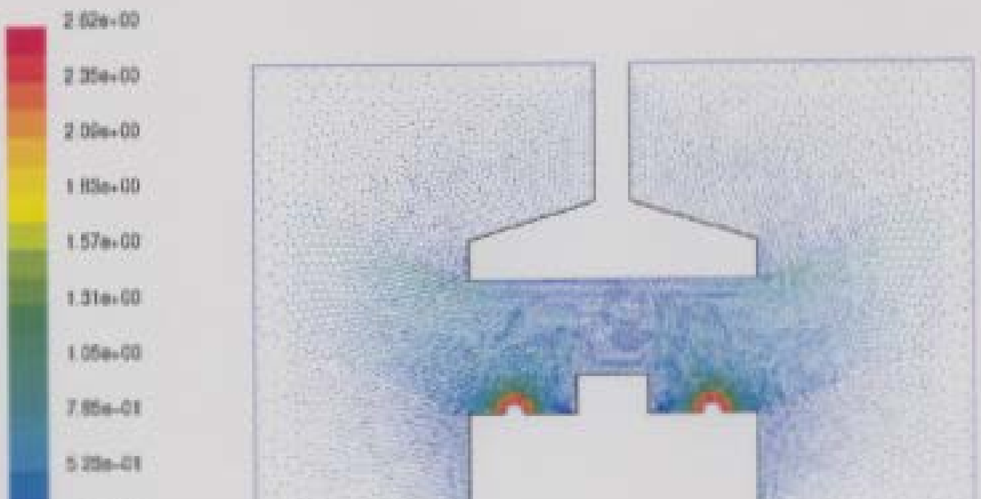

Figure 5.40: Velocity vectors colored by velocity magnitude

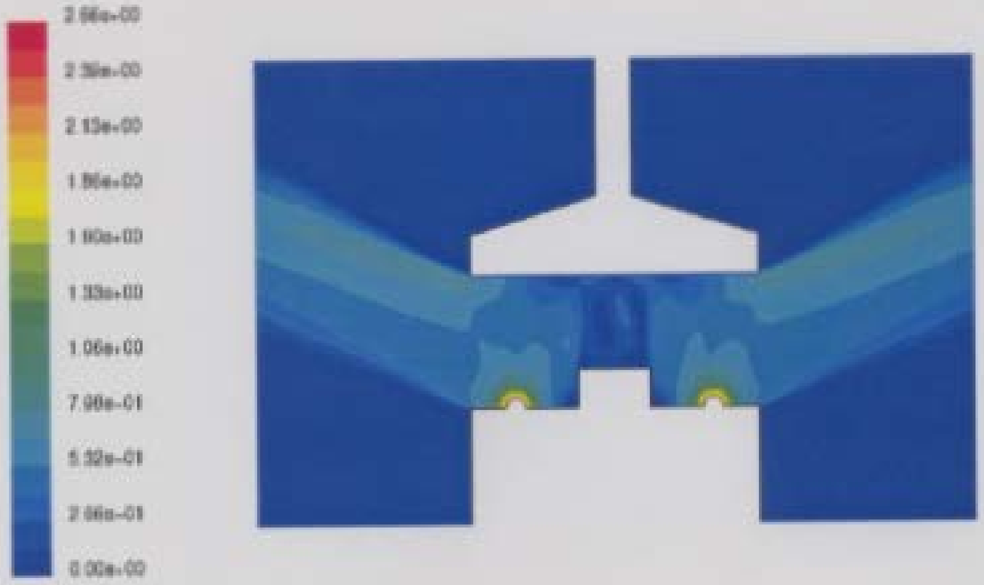

Figure 5.41: Velocity vectors colored by velocity magnitude

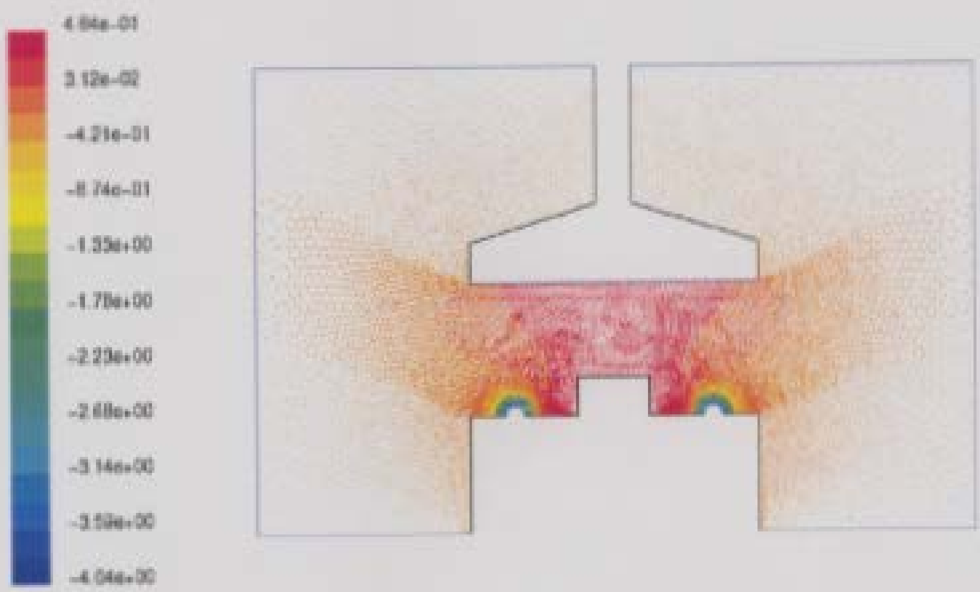

Figure 5.42: Velocity vectors colored by static pressure

Here it can be seen that the rotary brushes can indeed force contaminants in the direction of the worker. It is important to realize that the plots show the range of all particles leaving the brush were the particles leaving at a constant value of 2.66 m/s normal to the surface. From previous discussions on particle size and their associated trajectories, the larger particles will tend to be released from the brush at the point of contact with smaller particulates being released at a location further along the brush surface.

Obviously, a hood face velocity of only 0.1 m/s proved ineffective in producing a contaminant capturing situation. The hood was unable to alter the path of the allergens as they were released from the brushes at the specified speed of 2.66 m/s. Increasing the hood face velocity to 0.35 m/s has altered the flow dynamics, as can be seen in Figures 5.43, 5.44, and 5.45.

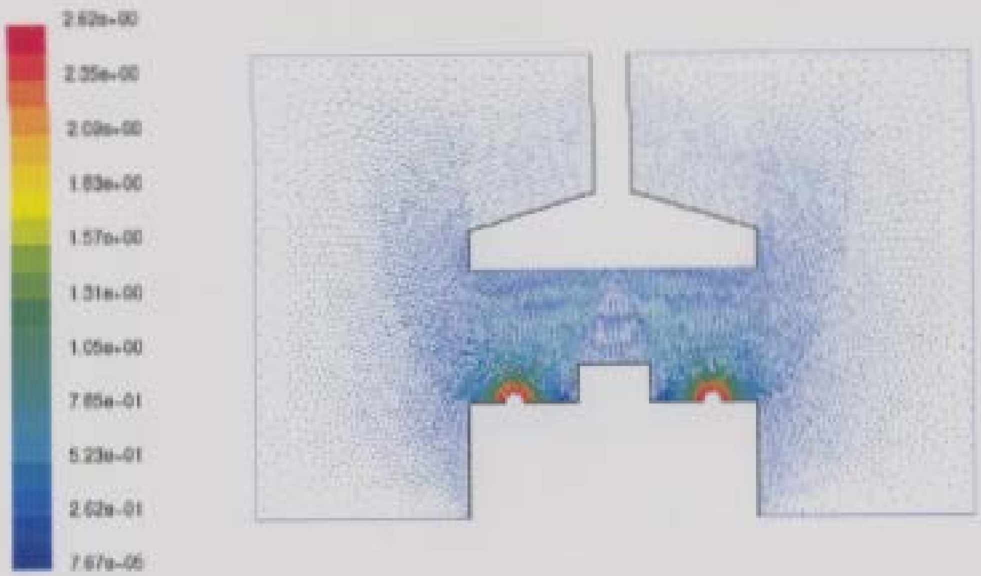

Figure 5.43: Velocity vectors colored by velocity magnitude

The solution shows a marketable difference in the flow patterns. By increasing the hood face velocity some of the contaminants may now be exhausted by the exhaust airflow. Even though the solution does not converge exactly (2.62 m/s at the brush boundary vs 2.66 m/s), this simulation shows that the hood has an effect on the

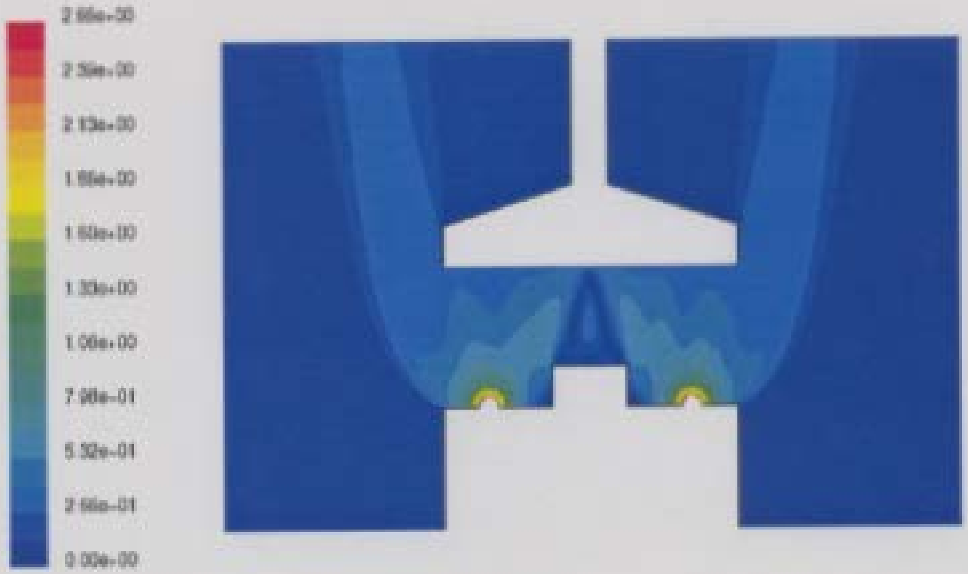

Figure 5.44: Velocity vectors colored by velocity magnitude

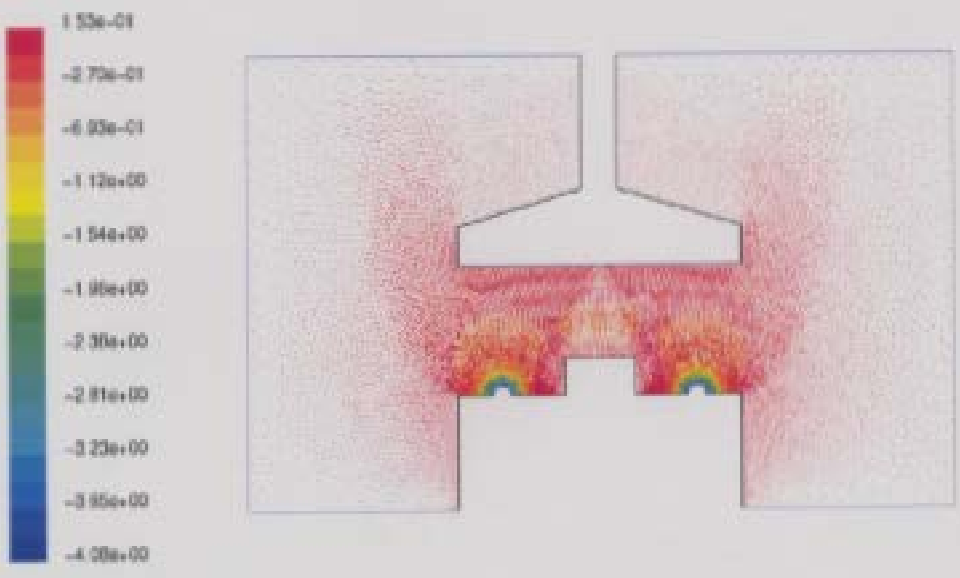

Figure 5.45: Velocity vectors colored by static pressure

brush induced flow patterns. Further increase of the hood face velocity will cause the hood to draw in more of the air stream produced at the brush locations. Since an optimal hood face velocity will depend on a variety of factors, values for the hood face velocity are chosen to illustrate the behavior of the flow patterns. Exact values for velocities are unknown at this time.

5.2.10 Dynamic Source Simulation 2

Removing the hooding altogether and including simulated workers, as would be the case in a realistic situation, produced the simulations shown in Figures 5.46, 5.47, and 5.48.

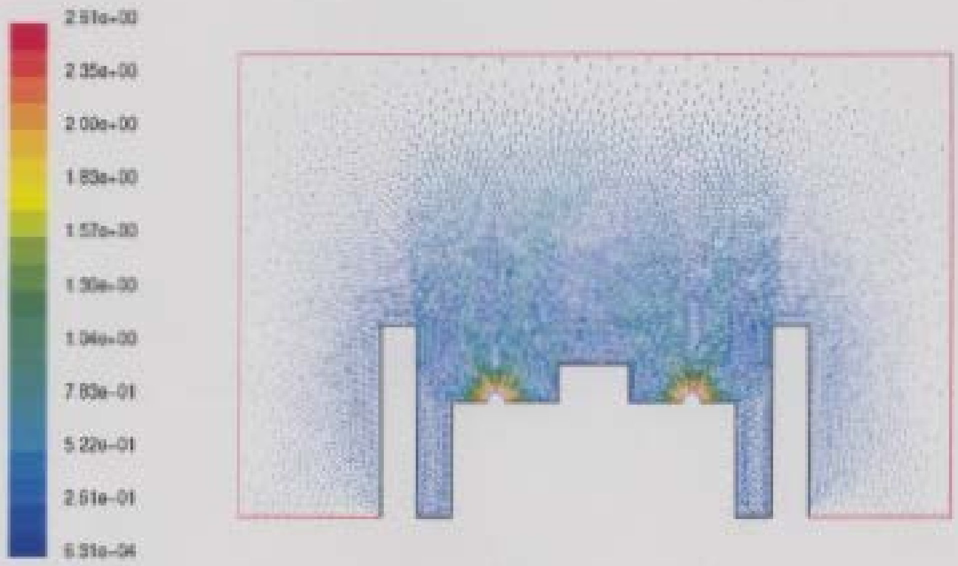

Figure 5.46: Velocity vectors colored by velocity magnitude

This situation would be the best representation of the range that particulate could be released from the brushes and enter the working environment without hooding in place. The lack of a hood proves to be critical as the contaminants could be either forced into the personal breathing zone of the worker or dispersed into the general processing areas, neither of which is a desirable scenario.

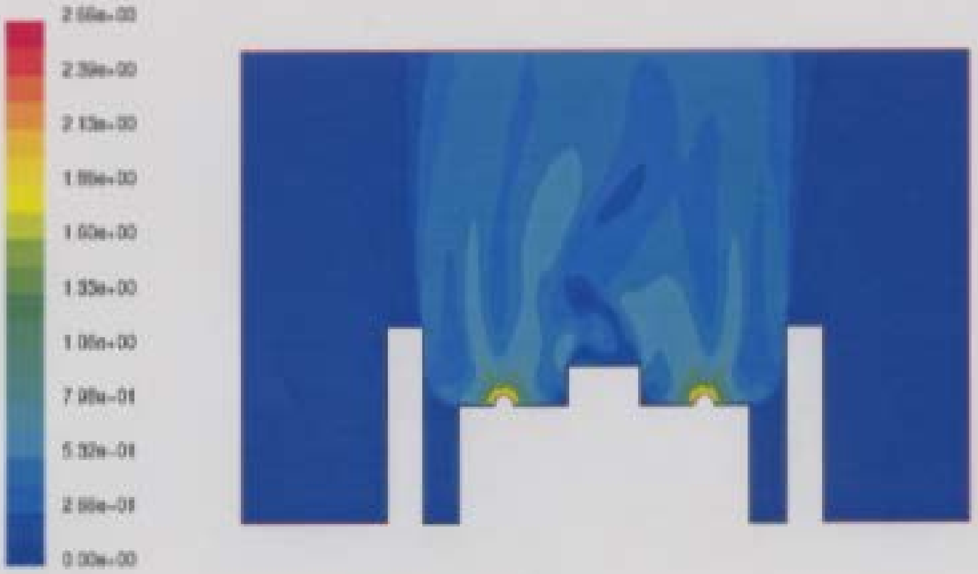

Figure 5.47: Velocity vectors colored by velocity magnitude

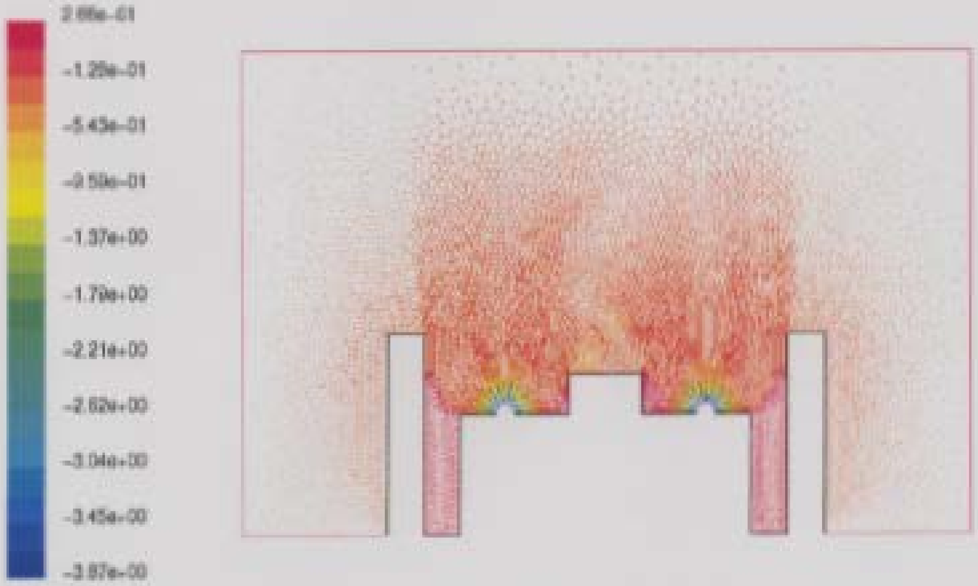

Figure 5.48: Velocity vectors colored by static pressure

5.2.11 Dynamic Source Simulation 3

Using a minimal hood face velocity of 0.1 m/s and including the hood, together with the simulated workers, has produced the simulations shown in Figures 5.49, 5.50, and

5.51.

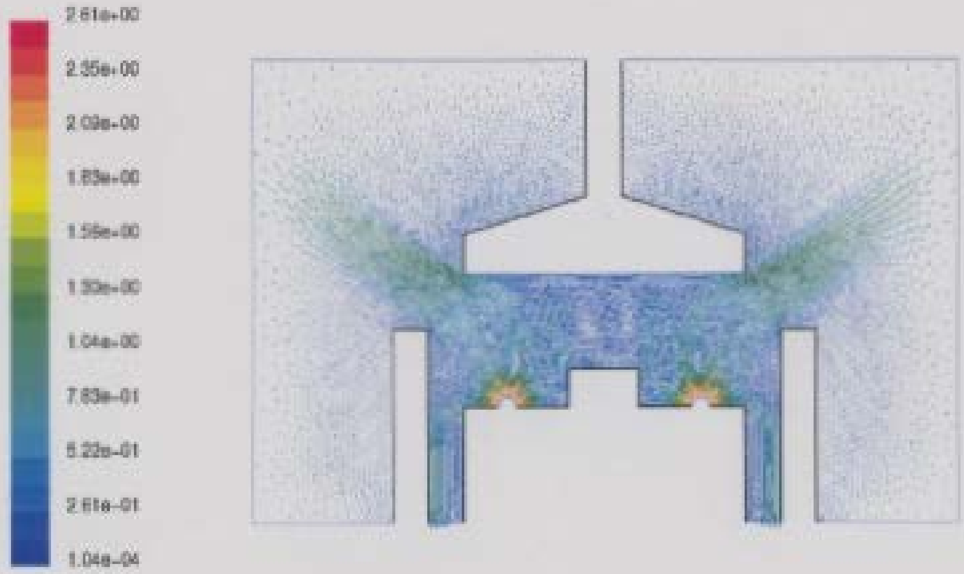

Figure 5.49: Velocity vectors colored by velocity magnitude

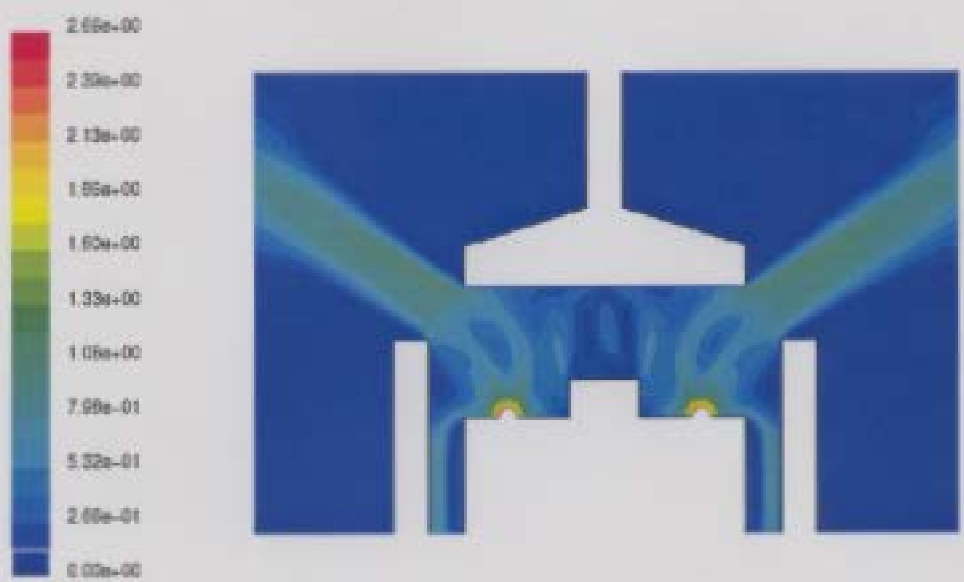

Figure 5.50: Velocity vectors colored by velocity magnitude

Keeping all variables the same except for the hood face velocity, which has been changed to 0.35 m/s produces Figures 5.52, 5.53, and 5.54.

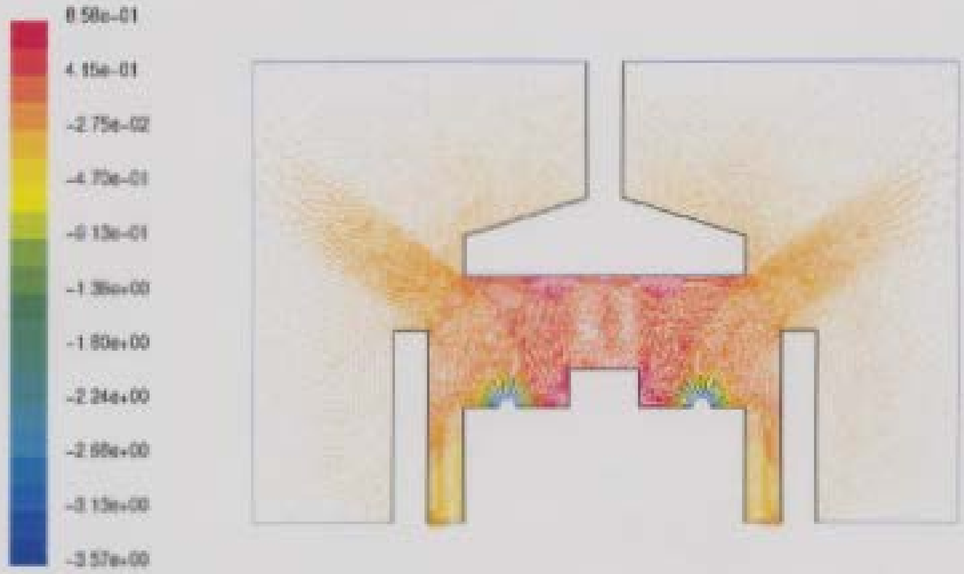

Figure 5.51: Velocity vectors colored by static pressure

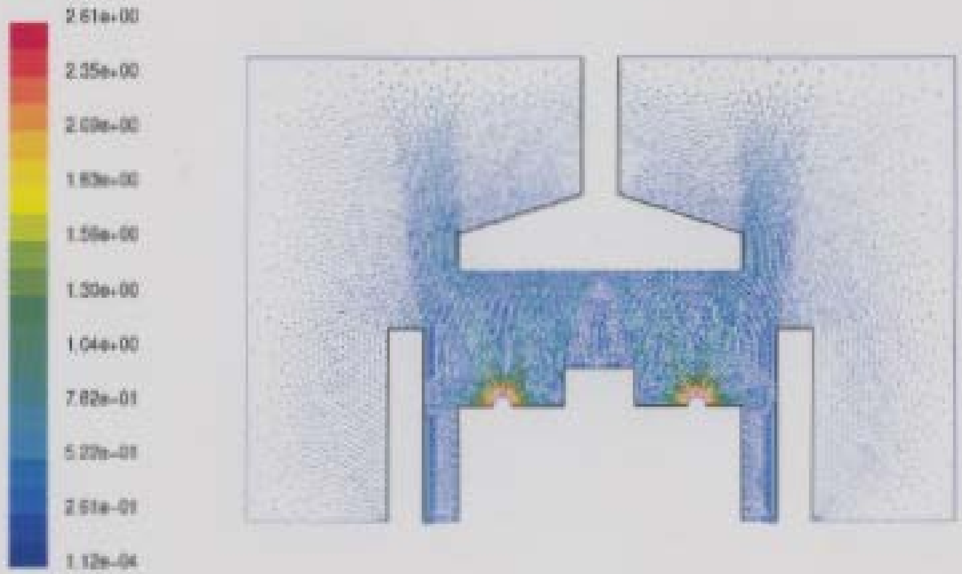

Figure 5.52: Velocity vectors colored by velocity magnitude

Here it can be seen that once the hood face produces some appreciable exhaust velocity, the airflow patterns produced by the brushes are altered. The airflow patterns

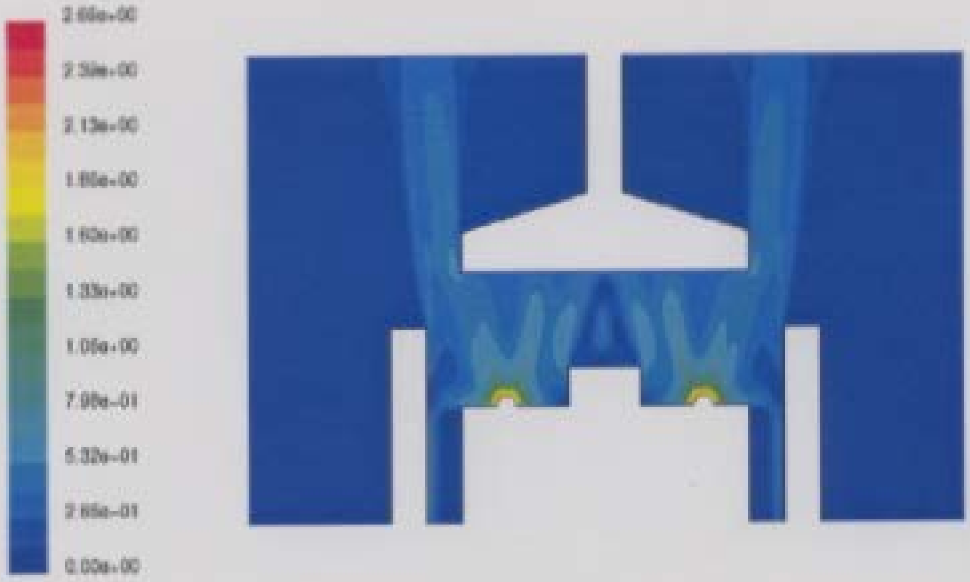

Figure 5.53: Velocity vectors colored by velocity magnitude

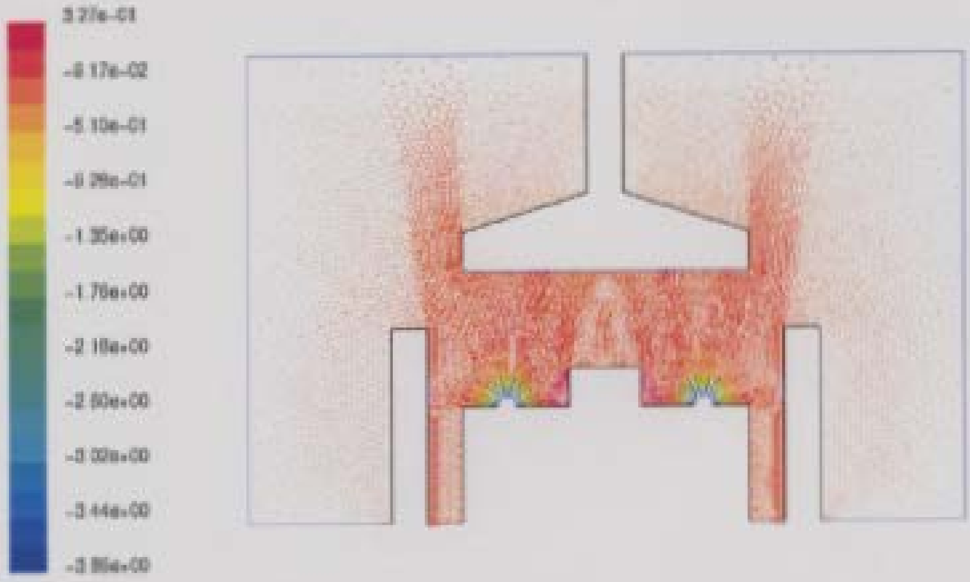

Figure 5.54: Velocity vectors colored by static pressure

that would most likely be carrying contaminants are redirected upwards toward the hood face instead of hitting the worker directly. Increasing the hood face velocity while varying hood face size and height above the contaminant will produce a variety of different results.

5.2.12 Dynamic Source Simulation 4

For interest, removing the hooding and workers altogether produced the simulation shown in Figure 5.55. Only the contour plot has been shown here.

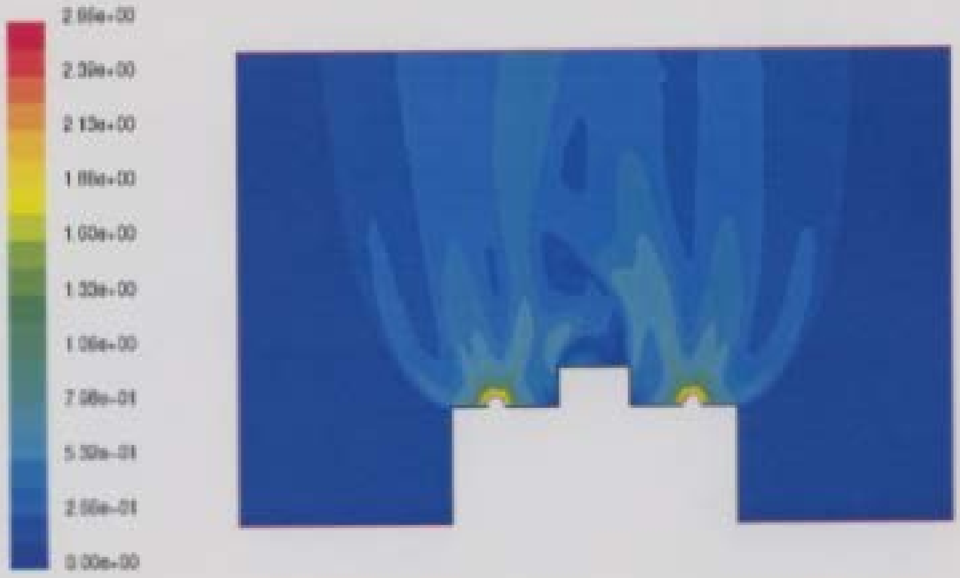

Figure 5.55: Velocity vectors colored by velocity magnitude

The results are similar to the ones produced when only the exhaust hood was present.

5.2.13 Dynamic Source Simulation 5

The slotted hood sawing domain has been modified to now include a simulated saw measuring 10 inches (0.254 m) in diameter. The saw boundaries have been modeled based on a tip velocity of 45.9 m/s and hood face modeled with a minimal velocity of 0.1 m/s. Since table saws normally spin at 3450 rpm, this value has been assumed and converted into the value of approximately 45.9 m/s. The tip velocity magnitudes have again been applied normal to the saw boundary to produce a probable range of particulate release. The associated velocity vectors, velocity contours, and pressure contours corresponding to this modified simulation are shown in Figures 5.56, 5.57, and 5.58.

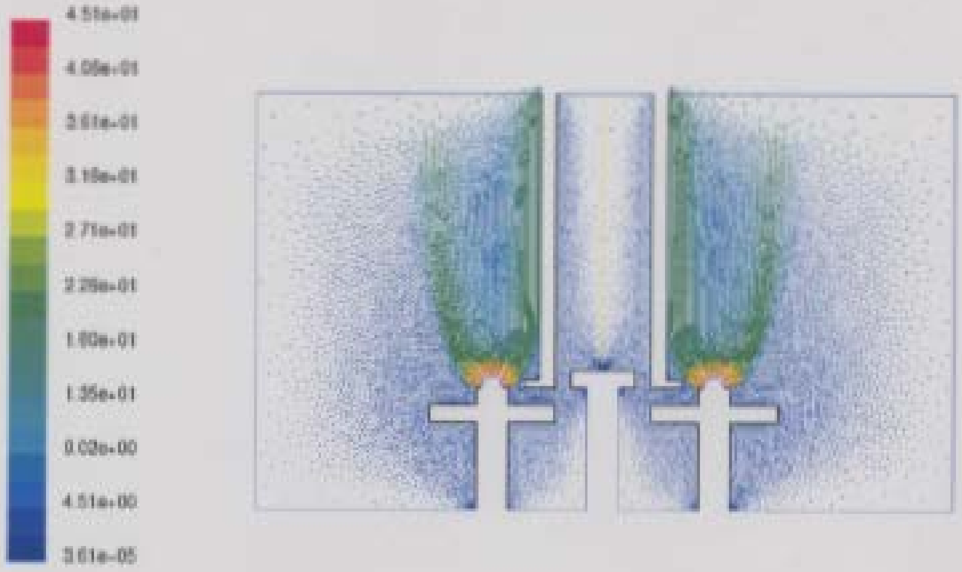

Figure 5.56: Velocity vectors colored by velocity magnitude

Here it can be seen that the table saws also force contaminants in the direction of the worker at much higher speeds. It is important to realize that the plots again show the range of all particles leaving the saw blade were the particles leaving at a constant value of 45.9 m/s along its whole surface. Obviously, a hood face velocity of only

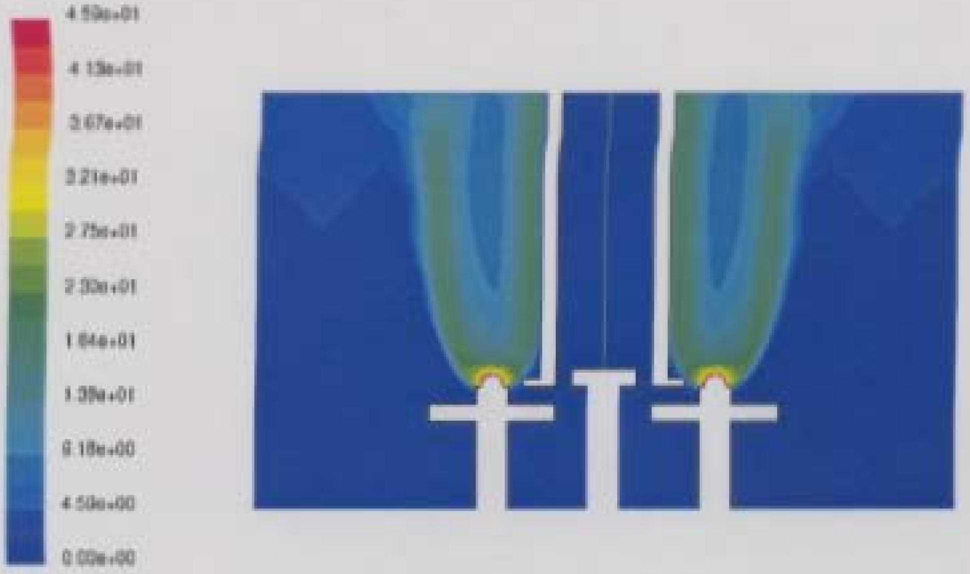

Figure 5.57: Velocity vectors colored by velocity magnitude

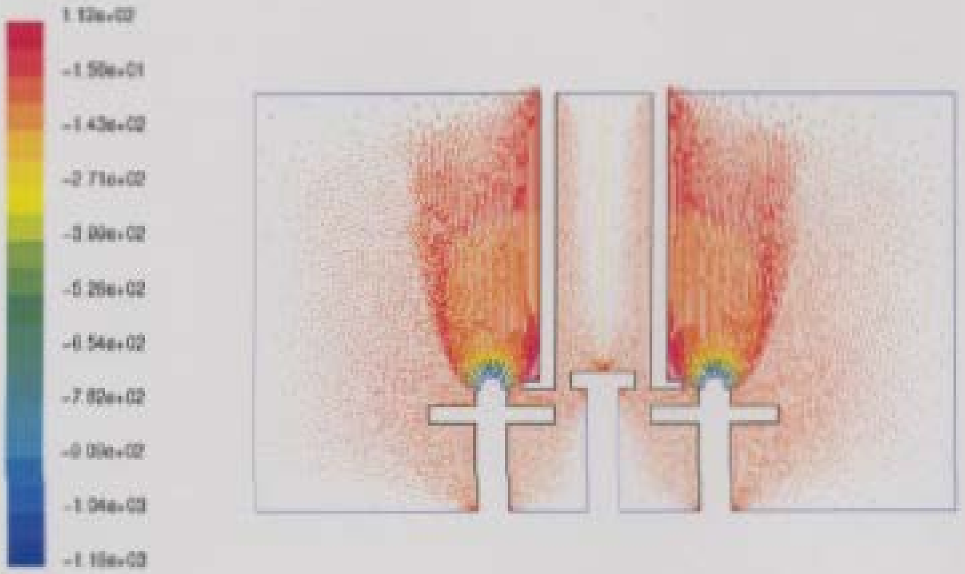

Figure 5.58: Velocity vectors colored by static pressure

0.1 m/s proved extremely ineffective in producing a contaminant capturing situation. The hood was unable to alter the path of the allergens as they were released from the saw blade as speeds much greater than were examined for the brushes. Increasing the hood face velocity to 5 m/s has again altered the flow dynamics, as can be seen in Figures 5.59, 5.60, and 5.61.

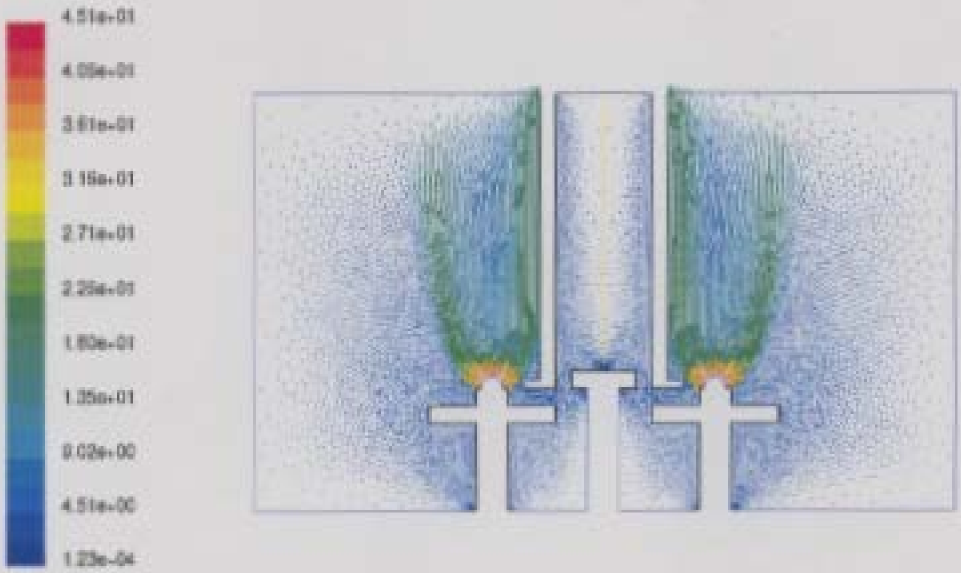

Figure 5.59: Velocity vectors colored by velocity magnitude

Increasing the hood face velocity to 5 m/s had little effect on the flow patterns due to the speed at which the saw is releasing particles. For simulation purposes, the hood face velocity has now been increased to 180 m/s with the results given in Figures 5.62, 5.63, and 5.64.

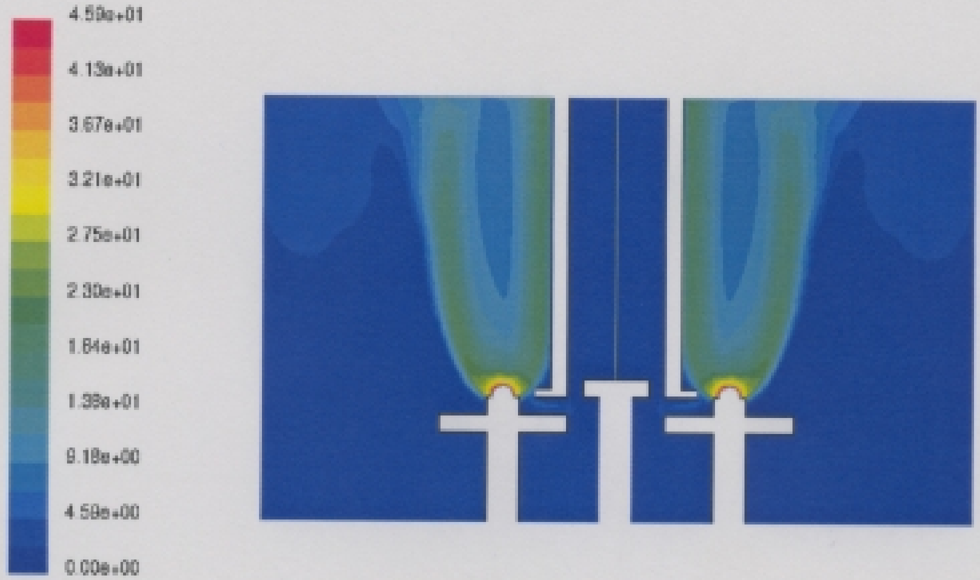

Figure 5.60: Velocity vectors colored by velocity magnitude

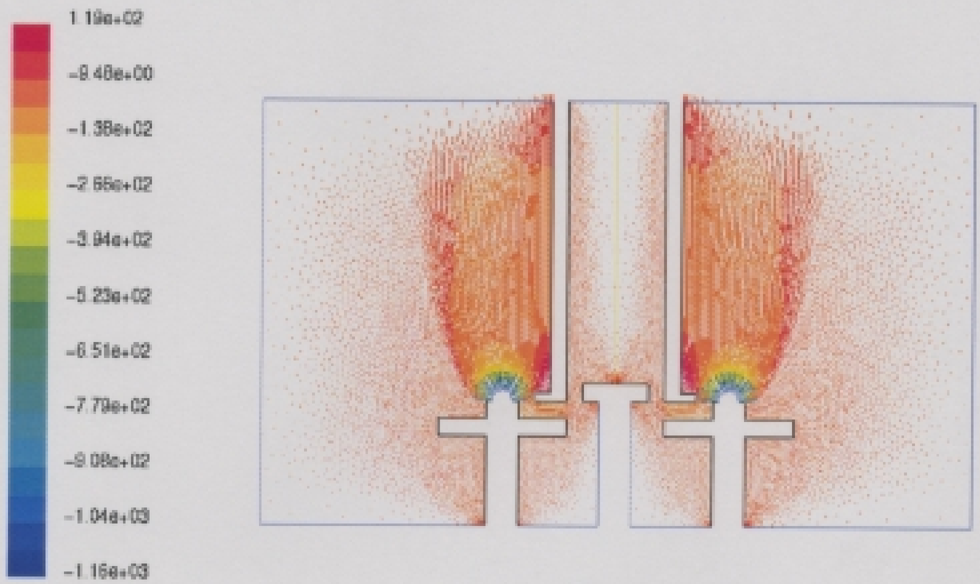

Figure 5.61: Velocity vectors colored by static pressure

With this increased hood face velocity it may be indeed possible to exhaust particles embedded in the airflow that is produced by the spinning blades or brushes. Although

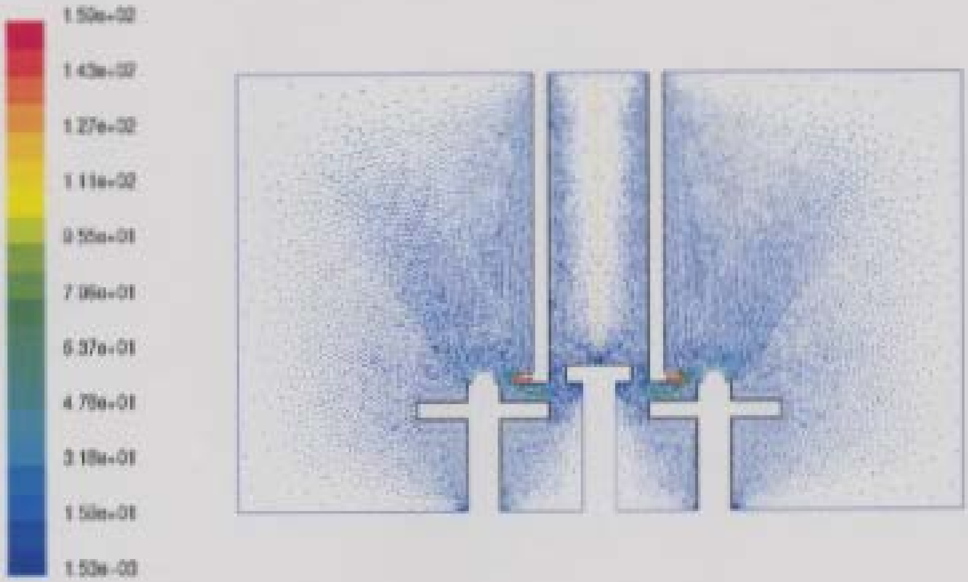

Figure 5.62: Velocity vectors colored by velocity magnitude

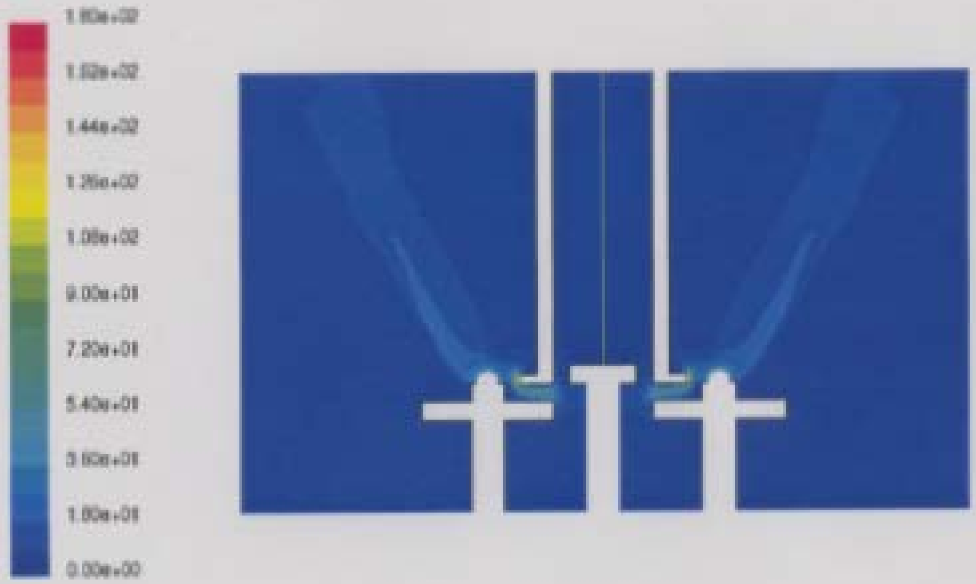

Figure 5.63: Velocity vectors colored by velocity magnitude

these simulations have incorporated some assumptions into the results, they can still be used as a basis for a more detailed and robust study on contaminant propagation

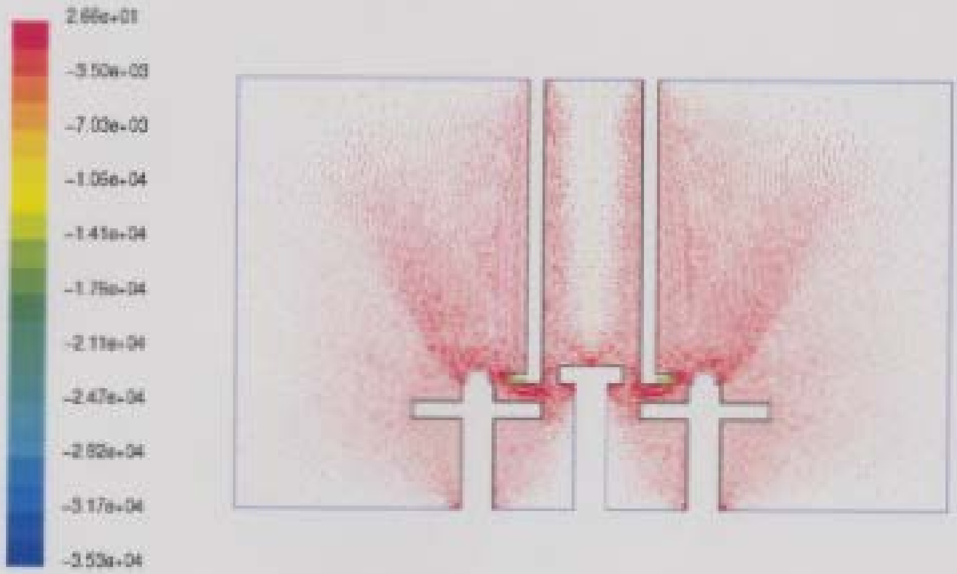

Figure 5.64: Velocity vectors colored by static pressure

and distribution.

5.2.14 Dynamic Source Simulation 6

In a manner similar to the cleaning/sorting simulations, the hood has been removed altogether and simulated workers have been included to produce the simulations shown in Figures 5.65, 5.66, and 5.67.

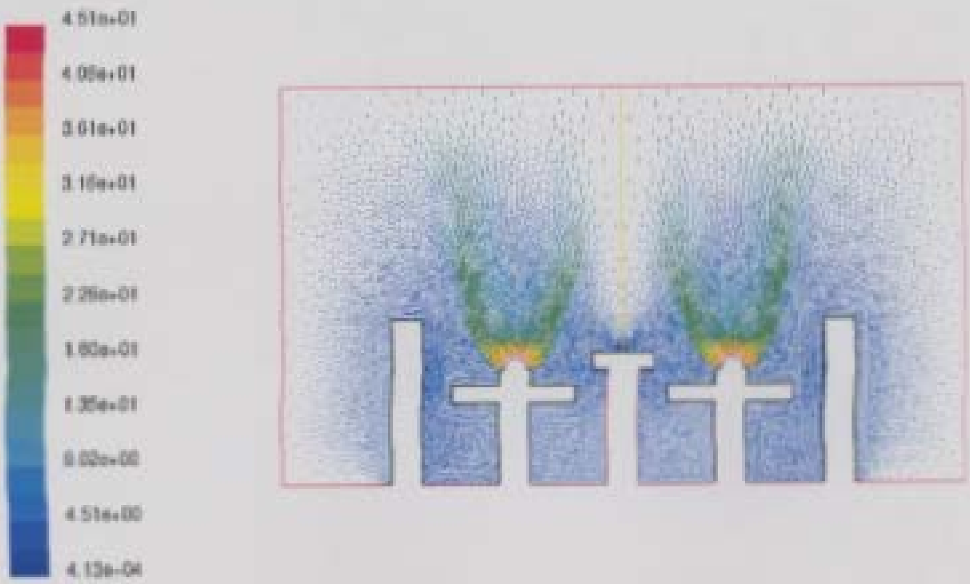

Figure 5.65: Velocity vectors colored by velocity magnitude

This situation would be the best representation of the range that particulate could be released from the saws and enter the working environment without hooding in place. The lack of a hood proves to be critical as the contaminants could be either forced into the personal breathing zone of the worker or dispersed into the general processing areas in a similar manner to that of the cleaning table brushes. The solution did not converge exactly but the airflow patterns show how the air is moving.

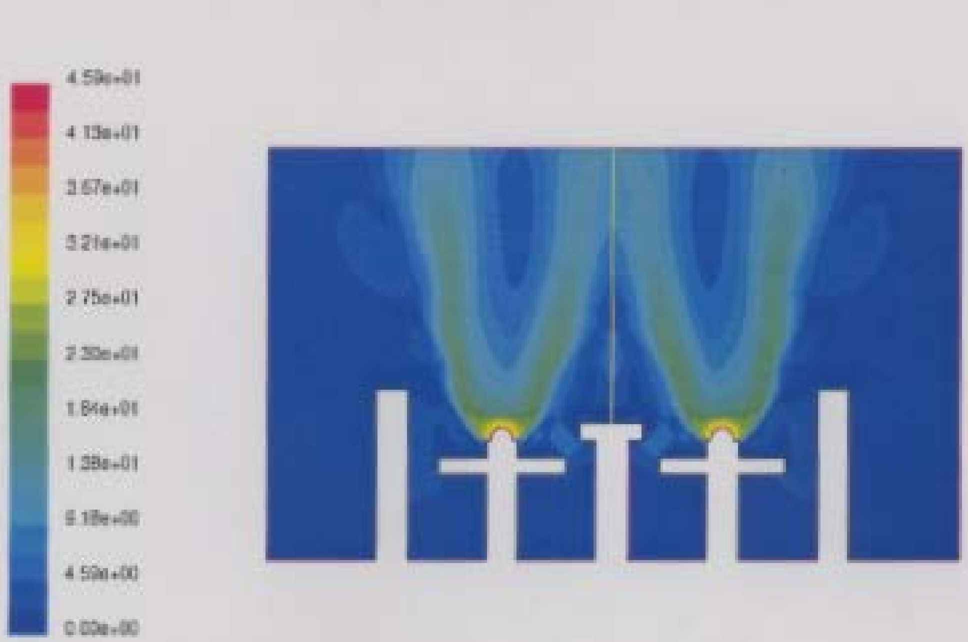

Figure 5.66: Velocity vectors colored by velocity magnitude

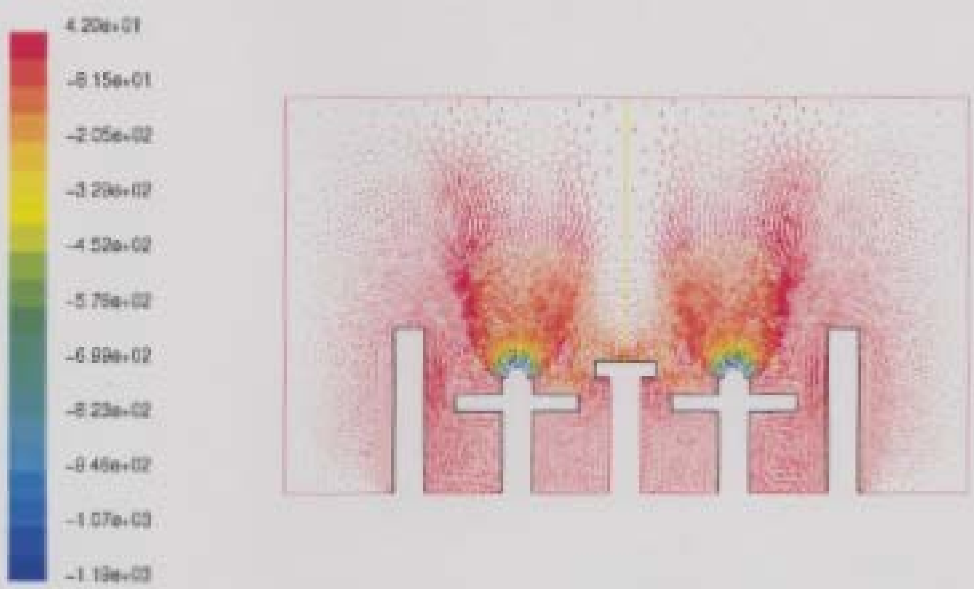

Figure 5.67: Velocity vectors colored by static pressure

5.2.15 Dynamic Source Simulation 7

Again using a minimal hood face velocity of 0.1 m/s and including the hood, together with the simulated workers, has produced the simulations shown in Figures 5.68, 5.69, and 5.70.

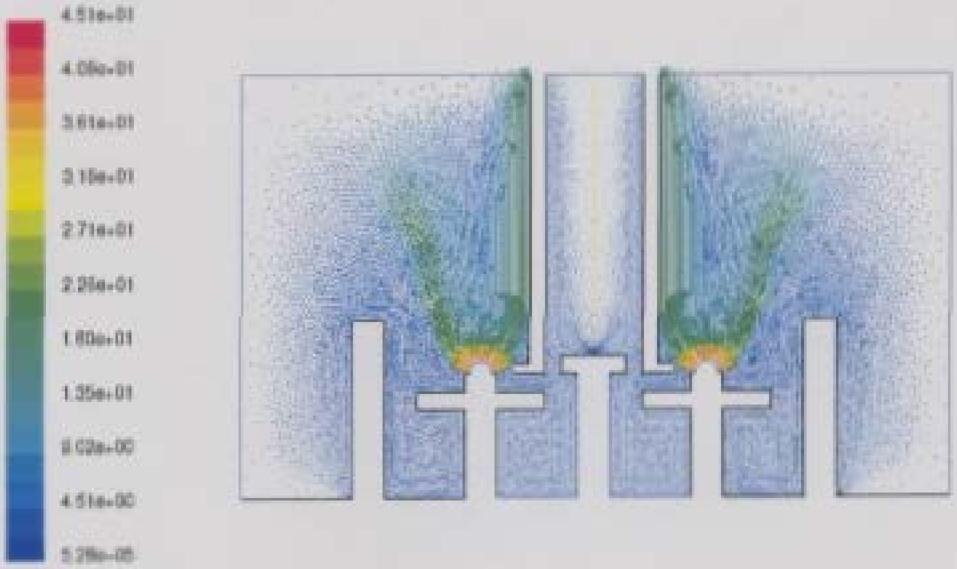

Figure 5.68: Velocity vectors colored by velocity magnitude

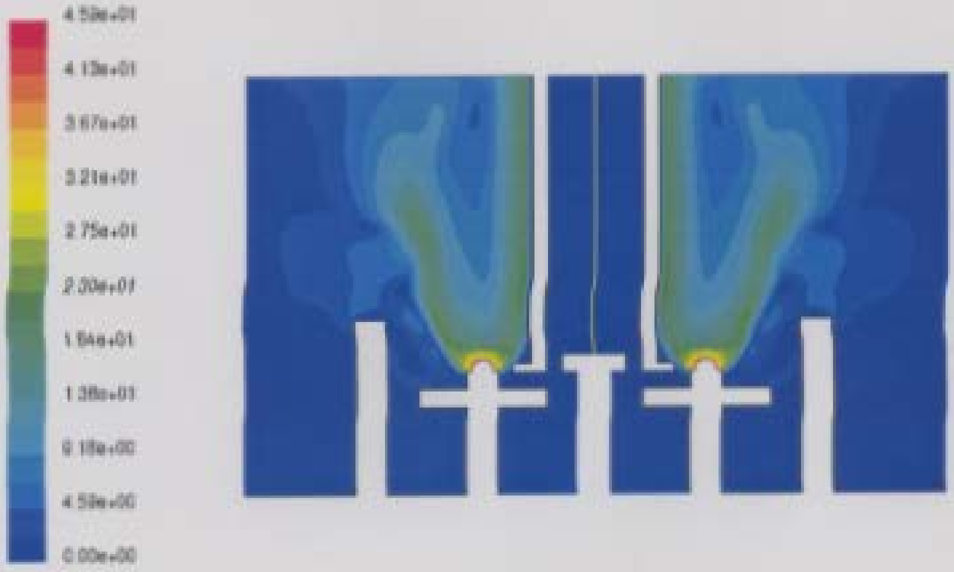

Figure 5.69: Velocity vectors colored by velocity magnitude

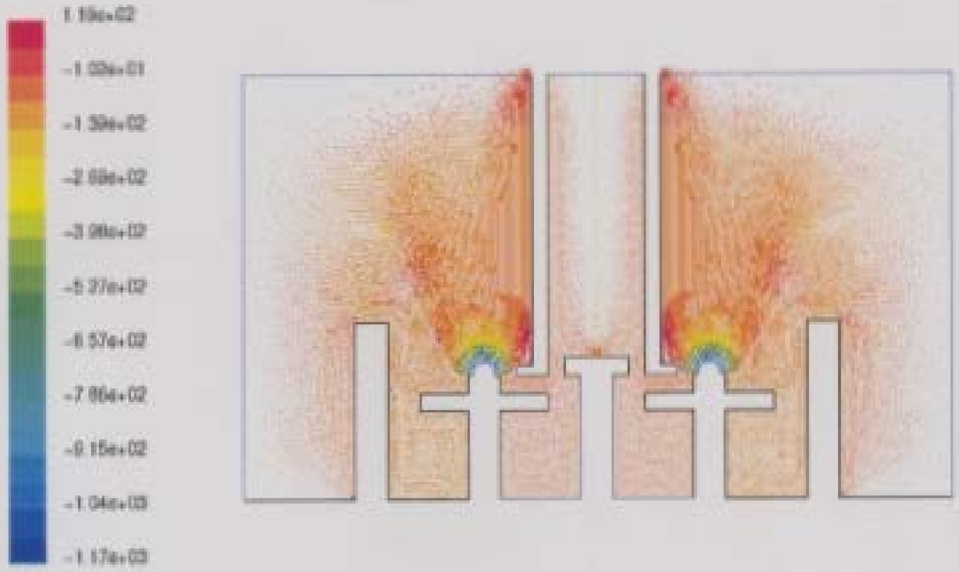

Figure 5.70: Velocity vectors colored by static pressure

5.2.16 Dynamic Source Simulation 8

Similarly, removing the hooding and workers altogether produced the simulation shown in Figure 5.71. Only the contour plot has been shown here. The results are similar to the ones produced when only the exhaust hood was present.

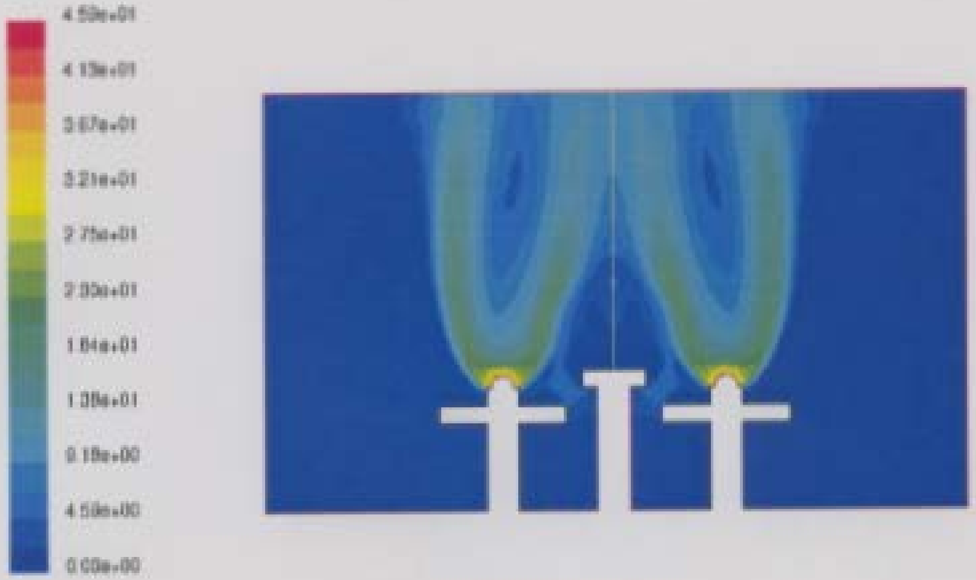

Figure 5.71: Velocity vectors colored by velocity magnitude

5.2.17 Dynamic Source Simulation 8

Keeping all variables the same except for the hood face velocity, which has been changed to 180 m/s, Dynamic Source Simulation 7 produces figures 5.72, 5.73, and 5.74. Here it can be seen that once the hood face produces some appreciable exhaust velocity, the airflow patterns produced by the saws are altered. Part of the airflow pattern that would most likely be carrying contaminants is redirected into toward the hood face instead of being dispersed throughout the plant. A portion of the airflow is still directed toward the worker, which may be remedied by better enclosure of the saw or the incorporation of some sort of protective guard. However, this modification has not been examined in this thesis.

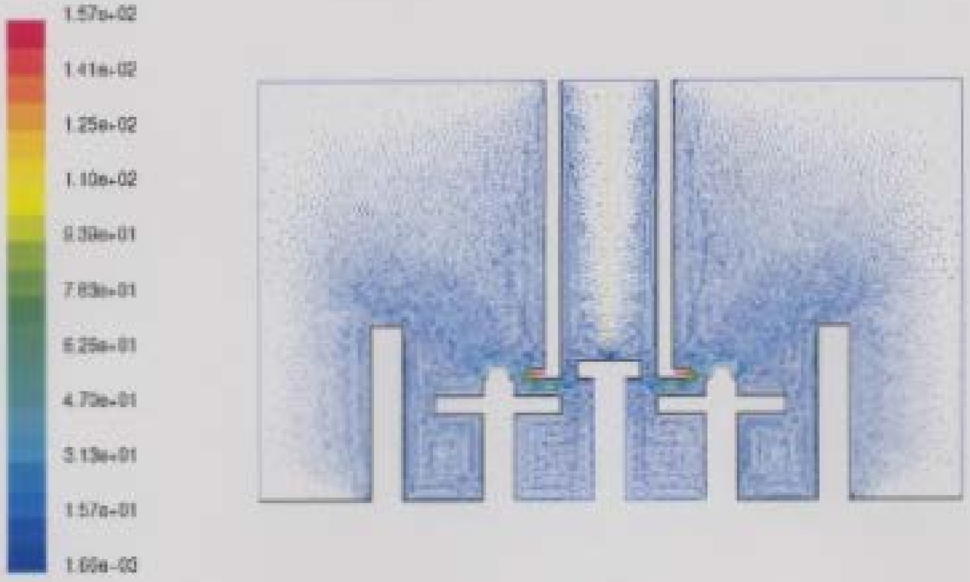

Figure 5.72: Velocity vectors colored by velocity magnitude

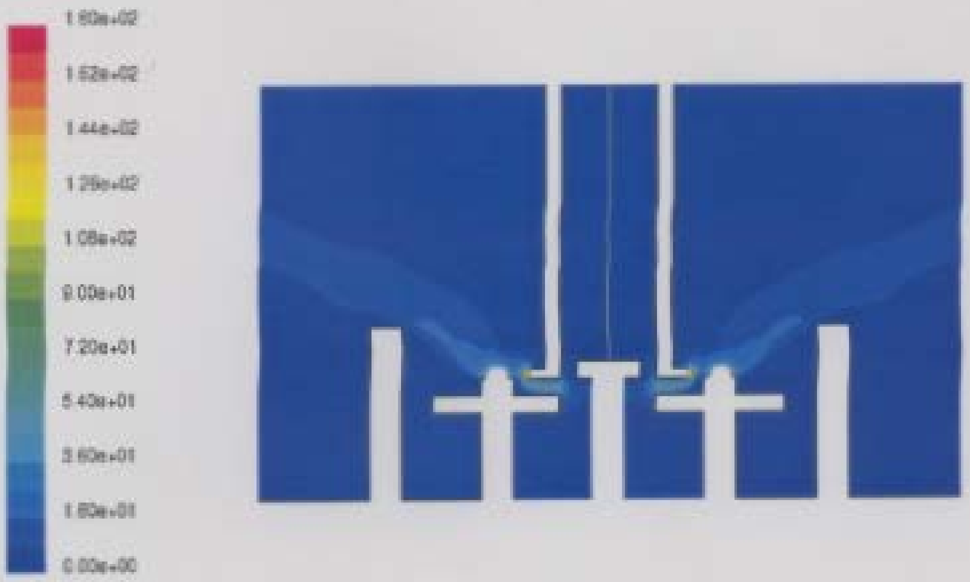

Figure 5.73: Velocity vectors colored by velocity magnitude

Important Notes for Dynamic Source Simulations

Since the brushes and saws are spinning away from the workers it may not be totally

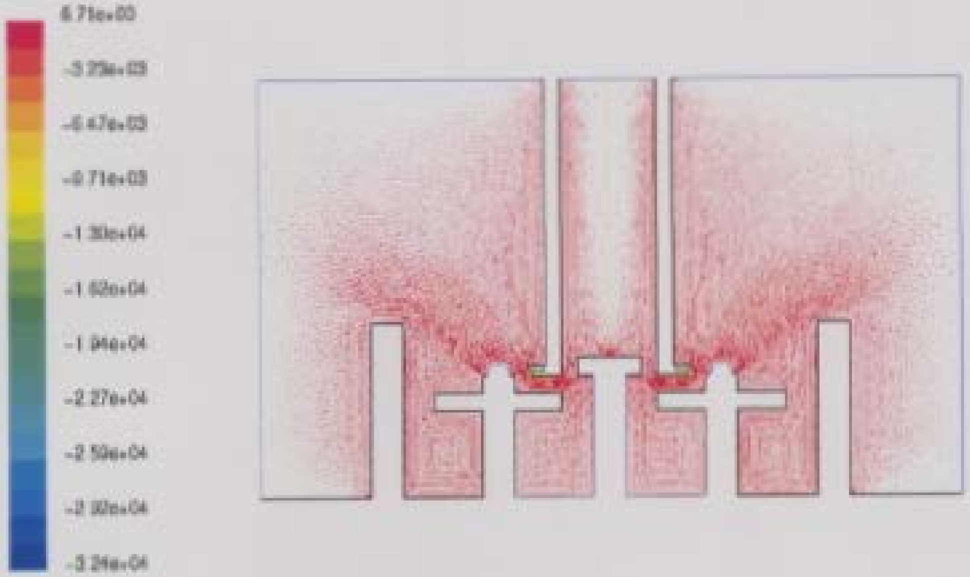

Figure 5.74: Velocity vectors colored by static pressure

correct to assume that the airflow ranges identified in these simulations are exact representations. However, the ranges do provide an area of probable particle release. Particles may leave the brushes or saws at a variety of different trajectories depending on the way in which the crab is contacted with the spinning brush/blade, which makes the actual path taken by these particles difficult to determine. Also, the magnitudes of the hood face velocities may seem unreasonable, but it has to be understood that they were chosen in order to facilitate the airflow simulations. Therefore, they should not be thought of as the actual velocities that would be needed to produce these airflow patterns in real life. Only after a complete ventilation analysis, which has not been undertaken here, will the exact velocities and airflows be determined.

Chapter 6

Conclusions and Recommendations

The main goals of this project were to both identify areas in the snow crab processing environment that displayed various degrees of aerosolized allergen contamination and to explore alternative hood and related ventilation designs that could be used to minimize aerosolization and improve contamination control for aerosolized allergen.

6.1 Conclusions

Allergen Levels

The first phase of the work consisted of collecting air samples in each of the four participating crab processing plants. PBZ and area samples produced a variety of allergen concentrations ranging from values less than 10 ng/m^3 to values in the 1000's of ng/m^3. As can be seen in Neis et al (2003), two plants demonstrated maximum measured airborne concentrations in the 100's of nanograms while the other two had maximum concentrations in the 1,000s. In instances when bio-aerosol concentrations of asthmagenic agents are observed to vary in orders of magnitude, such as is observed here, a significant risk exists for sensitization to occur. This is supported by the prevalence component of the study which has identified a relatively high percentage

(18.1%) of almost certain or highly probable cases of OA to snow crab in the study population. In the case of occupational allergy to snow crab, defined as rhinitis (runny nose), conjunctivitis (red or runny eyes) or rash, an average of 18% overall were diagnosed as highly probable for occupational allergy (Neis et al 2003).

High concentrations of allergens have been observed more often in certain areas of the processing plants and also associated with discrete tasks. Recent Quebec research has identified plants with allergen levels in all areas below 100 ng/m^3 and two of the four plants in this study have levels that are close to this limit suggesting that this maximum level could be achieved in these plants with a combination of changes in ventilation and changes in processing layouts and procedures.

Raw/Cooked and Processing

Comparisons between plants revealed that in general, manipulation (sawing, crushing, brushing, scraping, etc.) of the crab after it was cooked resulted in much higher allergen concentrations than when processing in the raw state. The raw crab experiment that was designed to incorporate variations in ventilation, while not conclusive, seemed to support this hypothesis. Findings reported in Neis et al (2003) show that the proteins to which workers are reacting are somewhat different in raw and cooked crab, meaning that in the short term at least, air samples need to be analyzed using sera from workers sensitized to both raw and cooked crab. This should guarantee that apparent low allergen levels associated with processing raw crab are real. The raw crab experiment also needs to be redone using a slightly different protocol (more crab, different sampling methods) because raw crab allergen levels were generally below detectable limits and cooked crab allergen levels were not much above detectable limits.

Cleaning, sawing, cooling, and cooking processes were identified as areas that need to be addressed by possibly redesigning processing procedures and/or examination of existing or required exhaust ventilation systems. Plant histories and processing overviews provided a sense of any modifications made to the plant, if any, as well as the typical processing methods used on a daily basis. This information is essential in attempting to correlate worker symptoms and medical histories to occurrences of asthma or snow crab occupational asthma. Knowledge of the ventilation history and crab processing methods is also needed in order to both design a suitable ventilation system and to identify processing techniques that may be modified to reduce allergen release, thus reducing worker exposure.

Airflow

In the airflow modeling part of this thesis the focus was placed on local exhaust hoods rather than a general type of exhaust system. Due to the fact that most of the problematic areas are centered around a processing table or tank of some kind, local non-enclosing hoods were the most appropriate choice for effective contaminant capture and removal at the source. Overhead, slotted, and canopy types of hoods were examined as probable means of exhausting these processes in the workplace. An enclosing type of hood may be more suited for cooking processes but these were not modified in this thesis. Potential flow theory was also implemented to produce theoretical streamlines that would most likely resemble those that would occur around geometric structures similar to those found in the designs of typical exhaust hoods. These streamlines provided a mathematical check to the velocity profiles produced by the numerical simulations.

Approximating airflows from point and line sources of suction led to the examination of various centerline velocity profiles presented by authors such as Dalla Valle and Fletcher. These profiles provided a value for a capture velocity at a specified distance from the hood face given that the hood face velocity and area were known. Profiles were plotted for a variety of possible capture velocities at a variety of distances from the hood face. This allows the required hood face airflow to be readily obtained and applied to a specific situation. Since the centerline profiles could not predict any behavior away from the centerline, the trends they provided were used as guides for the development of subsequent profiles. In addition, these centerline relationships did not take into account turbulent structures that are present in a realistic environment such as a crab plant.

CFD

The usage of Fluent for the simulations has proved to be very effective in illustrating the possible airflow patterns present in typical crab plants. The finite volume method inherent within Fluent allowed for efficient convergence of the governing equations of mass and momentum. The cleaning, sawing, and cooling processes were numerically modeled using a variety of overhead, slotted, and canopy types of hoods. Initially, ideal simulations were carried out whereby uniform, parabolic, exponential, and inverse parabolic velocity profiles were imposed on a hood face boundary for a general type of overhead hood. The profile results were compared to the centerline profiles proposed by Dalla Valle and Fletcher and were found to produce similar trends. For the realistic simulations a uniform profile was used for all three processes and all three hood types. However, profiles imposed on the hood face boundary will yield different results. For the purpose of this study a uniform profile proved sufficient. Velocity and pressure vectors were obtained in the entire domain as well as the velocity contours. The results obtained from the various simulations proved that structures in the vicinity of the exhaust hood have a drastic effect on the resulting airflow patterns and velocity distribution. The height of the hood above or away from the process proved to be important as the velocity drops off considerably as the distance from the hood face to the contaminant source increases.

Slotted hoods provided a much smaller affected flow field than the overhead hoods, mainly due to the horizontal nature of the airflow and the reduced hood face area. With the configurations used, they seemed to produce a more concentrated capture zone located directly at the contamination source, as opposed to the overhead configurations that produced a much larger affected area thus limiting direct capture at the source. Slotted hoods need to be designed with great care for the sawing process as the table saws tend to force the particulate into the air which may make it difficult to capture without a correctly designed hood. The airflow patterns for this case show that a slotted hood generates a desirable flow field for source capture and exhaust at a fraction of the airflow needed by an overhead type hood. However, the flow profile produced from the overhead simulation closely mimicked the centerline trends produced by Dalla Valle and Fletcher.

The canopy hood simulations produced a different flow field than the overhead case even though the height above the process and hood face velocities remained unchanged. The different configuration of the simulated table and the inclusion of an overhang in the canopy simulation undoubtedly caused the variation in the airflows. The addition of a flange improved the capturing capability of the hood by a considerable amount while maintaining the same hood face velocity as in the unflanged simulation. Profiles obtained by taking slices in the y-direction from the flanged simulation at varying distances from the hood face depicted increases in velocity when compared to identical slices taken from the unflanged simulation, suggesting improved air distribution characteristics.

Modeling of a brush and a saw introduced the dynamic element to the simulations. A velocity was imposed normal to the surface producing a possible range that any particulate leaving the brushes or saws might follow. It should be noted that large particles will have different dynamics than small particles but was not controlled for. However, the airflow ranges shown are useful in identifying the motion of these crab particles. Modeling with workers placed near the table has also shown interesting results. The insertion of two simulated workers caused the airflow to remain relatively contained in the area enclosed by the two workers, the processing table, and the hood itself. The capturing efficiency seems to be enhanced due to the virtual air curtain produced by the workers.

In a similar fashion to Horstman (1988), the velocity distributions and flow patterns produced here can be used as a basis for establishing contamination propagation and distribution. The contaminants considered for propagation will most likely come from crab proteins but may come from sources that have not been confirmed as contaminant sources such as cleaning chemicals, sulfites, and endotoxins. Due to the rate of contaminant decay predicted by the turbulent diffusion equation, knowledge of the capturing range of a local exhaust hood when any number of turbulent structures are present is critical.

This work has provided invaluable insight into the airflow patterns that are quite possibly present in typical crab plants and in the vicinity of local exhaust hoods. The effectiveness of contaminant capture with local hooding has been shown to be a distinct possibility in this type of environment. Differences in the airflow patterns produced by overhead, slotted, and canopy hoods based on specified velocity profiles are important and are evident in these simulations. The way in which particulate may be released from brushes and table saws as well as the effects of introducing simulated workers have also been shown to be important considerations.

6.2 Recommendations

Neis et al (2003) are recommending that until permissible exposure limits shown not to sensitize workers are objectively established, permissible maximum exposure limits not exceed 100 ng/m^3 from PBZ samplers, lower for area samples. Plants have been identified in Quebec and in Newfoundland that show maximum concentrations that are already largely below 100 ng/m^3 suggesting that this is an achievable goal in at least some types of plants. While it is true that some workers who are already sensitized may react to lower concentrations (i.e. less than 100 ng/m^3) it seems prudent to recommend target concentrations which appear to be achievable and are likely to reduce the risk of sensitization. If the maximum is set at 100, there will be many areas in the plants with substantially lower levels where sensitized workers could be relocated, although this will have to be done with close monitoring and understanding that levels may still be too high for highly sensitized individuals. This maximum permissible exposure limit should be reviewed and adjusted in response to any future research.

The need for future work is evident due to the complex nature of the airflows in crab processing plants. A complete design should be undertaken that takes into account fan sizing and power, ducting, and supply/exhaust air methodologies. A number of additional simulations should also be completed whereby a variety of geometric configurations, hood face velocities, distances from the source, and turbulent structures present are varied and tested. Research into different air supply methods from various locations (entrainment, displacement, etc.) in the plant domain should be investigated to determine if an optimal air supply method is linked to each specific hood design. The current usage of the cleaning brushes and scoring saws should be specifically re-examined with containment of crab allergens in mind. Either a better processing system or hood design that prevents the brushes and saws from actually delivering allergenic particles into the environment should be investigated. Particles should be modeled using the particle tracing feature in Fluent to determine their exact propagation and distribution properties with the hopes of identifying an effective exhaust hood design that can be robustly implemented. Since no two crab plants are the same it is very difficult to develop a simulation domain that represents all plants. With this in mind, when designing a ventilation system, each design should be plant specific such that all the nuances have been taken into account.

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Appendix A

Plant 1 Sample Results

Air sampling results for plant 1 have been tabulated and presented in the following tables. Unfortunately there was no air sampling done of any kind in year 2, thus making any comparisons between the two years impossible.

Plant 1, Allergen Personal Samplers June 9th, 2002. Sampler: Brad Pelley										
Calibrated by: Brad Pelley **On:** June 7th, 2002										
Sample #	**Pump #**	**Sample Type**	**Time On**	**Time Off**	**Elapsed Time (min)**	**Flow Rate (lpm)**	**Area**	**Ng/m³ Results**	**Operations Monitored**	**Remarks/Conditions**
1		Allergen PBZ	7:00am	12:00pm	300	3.00	Jets	150	Monitors crab as it leaves the 30 deg. Bath and proceeds to the water jets.	Cooking in progress
2		Allergen PBZ	7:50am	12:00pm	250	3.00	Butcher	45	Butchers the crab after it comes from the high pressure water jets.	Cooking in progress
3		Allergen PBZ	7:15am	12:00pm	285	3.00	Grader	<15(ng/sample)	Grades crab as it comes from the butcher table.	Cooking in progress
4		Allergen PBZ	7:00am	12:00pm	300	3.00	Sorting/Packing	22	Packs sections in crates for the cooker.	Cooking in progress
5		Allergen PBZ	7:00am	12:00pm	300	3.00	Cooker	86	Loads continuous cooker with loaded crab crates.	Cooking in progress
6		Allergen PBZ	7:30am	12:00pm	300	3.00	Cooler/Weights	31	Removes Crab from cooker and it gets weighed at the same location.	The worker who removes the crab crates from the cooker and puts them in the cooler doesn't actually weigh the crab.
7		Allergen PBZ	8:00am	12:50pm	290	3.00	Packing	73	Boxing crab, off-loading, putting crab in Cold Storage.	Cooking in progress
Date: June 13th (Samples 15,16,17, & 21), 14th (Samples 18,19, & 20) 2002 - **Sampler:** Brad Pelley										
Calibrated by: Brad Pelley **On:** June 8th, 2002										
Sample #	**Pump #**	**Sample Type**	**Time On**	**Time Off**	**Elapsed Time (min)**	**Flow Rate (lpm)**	**Area**	**Ng/m³ Results**	**Operations Monitored**	**Remarks/Conditions**
15	1	Allergen PBZ	11:15am	4:08pm	265	3.00	Butcher	57	Butchers the crab after it comes from the high pressure water jets.	Cooking in progress
16	2	Allergen PBZ	9:30am	1:33pm	243	3.00	Grader	51	Grades crab as it comes from the butcher table.	Cooking in progress
17	4	Allergen PBZ	9:32am	2:00pm	268	3.00	Cooler/Weights	50	Removes Crab from cooker and it gets weighed at the same location.	The worker who removes the crab crates from the cooker and puts them in the cooler doesn't actually weigh the crab.
21	8	Allergen PBZ	9:31am	1:39pm	248	3.00	Cooker	66*	Loads continuous cooker with loaded crab crates.	Cooking in progress
18	5	Allergen PBZ	9:47am	2:28pm	251	3.00	Cooker	129	Loads continuous cooker with loaded crab crates.	Cooking in progress
19	6	Allergen PBZ	9:48am	2:00pm	242	3.00	Cooler/Weights	150	Removes Crab from cooker and it gets weighed at the same location.	The worker who removes the crab crates from the cooker and puts them in the cooler doesn't actually weigh the crab.
20	7	Allergen PBZ	10:00am	2:00pm	240	3.00	Pan Washer(static)	75	Worker clans crab crates in a fish box with a plastic brush.	The worker at this location did not wear the PBZ so it was attached to a pipe directly over the worker.

Table 1: Plant 1, Allergen Personal Samplers

Table 1: Tabulated plant 1 air sampling results from year 1

17		Allergen Area	10:15am	12:15pm	120	150	Butcher	19	Butchers the crab after it comes from the high pressure water jets.	Cooking in progress
18		Allergen Area	10:15am	12:15pm	120	150	Sorting/Packing	49	Clusters are graded and packed into crates.	Cooking in progress
19		Allergen Area	10:15am	12:15pm	120	150	Barnacle table	14	Table where the barnacles are removed from the crab	Cooking in progress
20		Allergen Area	10:15am	12:15pm	120	150	Weights	59	Crab is weighed after it is removed from the cooker	Cooking in progress

Figure 1: Tabulated plant 1 air sampling results from year 1

Plant 1, Area Allergen Samples June 8th, 2002 Sampler: Mark Swanson Calibrated by :Mark Swanson										
								Ng/m³		
Sample #	Pump #	Sample Type	Time On	Time Off	Elapsed Time (min)	Flow Rate (lpm)	Area	Results	Operations Monitored	Remarks/Conditions
1		Allergen Area	7:45pm	9:45pm	120	135	Blancher	7	Crab is bathed in 30deg water	Cooking in progress
2		Allergen Area	7:45pm	9:45pm	120	160	Butcher	26	Butchers the crab after it comes from the high pressure water jets.	Cooking in progress
3		Allergen Area	7:45pm	9:45pm	120	175	Barnacle table	30	Table where the barnacles are removed from the crab.	Cooking in progress
4		Allergen Area	7:45pm	9:45pm	120	160	Sorting/Packing	18	Clusters are graded and packed into crates.	Cooking in progress
5		Allergen Area	7:45pm	9:45pm	120	150	Weights	7	Crab is weighed after it is removed from the cooker.	Cooking in progress
6		Allergen Area	7:45pm	9:45pm	120	100	Blancher	8	Crab is bathed in 30deg water	* = based on estimated collection volumes.
7		Allergen Area	7:45pm	9:45pm	120	150	Butcher	19*	Butchers the crab after it comes from the high pressure water jets.	* = based on estimated collection volumes
8		Allergen Area	7:45pm	9:45pm	120	120	Barnacle table	79*	Table where the barnacles are removed from the crab	* = based on estimated collection volumes
9		Allergen Area	7:45pm	9:45pm	120	120	Sorting/Packing	11*	Clusters are graded and packed into crates.	* = based on estimated collection volumes
10		Allergen Area	7:45pm	9:45pm	120	150	Weights	40*	Crab is weighed after it is removed from the cooker	* = based on estimated collection volumes
Plant 1, Area Allergen Samples June 9th, 2002 Sampler: Mark Swanson Calibrated by :Mark Swanson										
								Ng/m³		
Sample #	Pump #	Sample Type	Time On	Time Off	Elapsed Time (min)	Flow Rate (lpm)	Area	Results	Operations Monitored	Remarks/Conditions
11		Allergen Area	7:30am	9:45am	135	150	Blancher	6	Crab is bathed in 30deg water	Cooking in progress
12		Allergen Area	7:30am	9:45am	135	150	Butcher	21	Butchers the crab after it comes from the high pressure water jets.	Cooking in progress
13		Allergen Area	7:30am	9:45am	135	150	Sorting/Packing	11	Clusters are graded and packed into crates.	Cooking in progress
14		Allergen Area	7:30am	9:45am	135	150	Barnacle table	21	Table where the barnacles are removed from the crab	Cooking in progress
15		Allergen Area	7:30am	9:45am	165	150	Weights	46	Crab is weighed after it is removed from the cooker	Cooking in progress
16		Allergen Area	10:15am	12:15pm	120	135	Blancher	9	Crab is bathed in 30deg water	Cooking in progress

Table 2: Tabulated plant 1 air sampling results from year 1

Plant1, Area Allergen Samples June 12th, 2002 Sampler: Mark Swanson Calibrated by :Mark Swanson										
Sample #	Pump #	Sample Type	Time On	Time Off	Elapsed Time (min)	Flow Rate (lpm)	Area	Results Ng/m³	Operations Monitored	Remarks/Conditions
31		Allergen Area	2:30pm	4:45pm	135	150	Blancher	nd	Pump was off	Cooking not in progress
32		Allergen Area	2:30pm	4:45pm	135	150	Butcher	139	Butchers the crab after it comes from the high pressure water jets.	Cooking not in progress
33		Allergen Area	2:30pm	4:45pm	135	150	Sorting/Packing	15	Clusters are graded and packed into crates.	Cooking not in progress
34		Allergen Area	2:30pm	4:45pm	135	150	Cooker	26	Loads continuous cooker with loaded crab crates.	Cooking not in progress
35		Allergen Area	2:30pm	4:45pm	135	150	Weights	20	Crab is weighed after it is removed from the cooker	Cooking not in progress
36		Allergen Area	4:45pm	7:15pm	150	150	Blancher	4	Crab is bathed in 30deg water	Cooking in progress
37		Allergen Area	4:45pm	6:45pm	120	120	Butcher	31	Butchers the crab after it comes from the high pressure water jets.	Cooking in progress
38		Allergen Area	4:45pm	7:15pm	150	50	Sorting/Packing	30	Clusters are graded and packed into crates.	Cooking in progress
39		Allergen Area	4:45pm	7:15pm	150	150	Cooker	87	Loads continuous cooker with loaded crab crates.	Cooking in progress
40		Allergen Area	4:45pm	7:15pm	150	150	Weights	96	Crab is weighed after it is removed from the cooker	Cooking in progress
41		Allergen Area	10pm	12am	120	40	Cooker	248*	Loads continuous cooker with loaded crab crates.	* = Based on estimated collection volumes.
42		Allergen Area	10pm	12am	120	10	Cooker	339*	Loads continuous cooker with loaded crab crates.	* = Based on estimated collection volumes.
43		Allergen Area	10pm	12am	120	150	Weights	36	Crab is weighed after it is removed from the cooker	Cooking in progress
Plant 1, Area Allergen Samples June 13th (Samples 44-46), June 14th (Samples 47 & 48), 2002 Sampler: Mark Swanson Calibrated by :Mark Swanson										
								Ng/m³		
Sample #	Pump #	Sample Type	Time On	Time Off	Elapsed Time (min)	Flow Rate (lpm)	Area	Results	Operations Monitored	Remarks/Conditions
44		Allergen Area	5:00pm	6:00pm	60	150	6' from batch cooker	86	Batch cooking whole crab for the Japanese market	Cooking in progress
45		Allergen Area	5:00pm	6:00pm	60	150	25' from batch cooker	12	Batch cooking whole crab for the Japanese market	Cooking in progress
46		Allergen Area	5:00pm	6:00pm	60	150	20' from batch cooker	61	Batch cooking whole crab for the Japanese market	Cooking in progress
47		Allergen Area	10:00am	12:00pm	120	150	Top of cooker	105	Loads continuous cooker with loaded crab crates.	Cooking in progress
48		Allergen Area	10:00am	12:00pm	120	150	Top of cooker	27	Loads continuous cooker with loaded crab crates.	Cooking in progress

Figure 2: Tabulated plant 1 air sampling results from year 1

Appendix B

Plant 2 Sample Results

Air sampling results for plant 2 have been tabulated and presented in the following tables.

Calibrated by: Jason Callahan On: July 11, 2001 (includes pumps # 1 to # 8)										
Sample #	Pump #	Sample Type	Time On	Time Off	Elapsed Time (min)	Flow Rate (lpm)	Area	Nanograms/m3 Results	Operations Monitored	Remarks/Conditions
1	3	Allergen PBZ	1:34 PM	~3:50 PM	???	3.00	Quality Control	593*	Moves around the plant checking on quality.	The battery went dead. She did not know the time it died (noticed around 3:50 PM). The minutes elapsed read 0.
2	8	Allergen PBZ	1:50 PM	5:48 PM	241	3.00	Cooker Room	<50	The cooking process of the crab.	Although treated as a personal sampler, the pump was fixed to a wall (no continuous worker). Condensation may have gotten into filter.
3	1	Allergen PBZ	1:54 PM	5:28 PM	215	3.00	Butcher Table	260	Breaking the crab and throwing it onto the conveyor.	There was some crab waste on the filter casing. Unsure if any of it got inside. This work is extremely messy and workers wear full oilskins.
4	2	Allergen PBZ	2:00 PM	5:25 PM	206	3.00	Holding Room	<50	Stacking crab crates, icing the crab, feeding the crates to the butchers.	
5	7	Allergen PBZ	2:08 PM	6:03 PM	236	3.00	Freezer Area	454	Boxing crab, off-loading, putting crab in Cold Storage.	
6	5	Allergen PBZ	2:18 PM	6:08 PM	14 ???	3.00	Section Packer (Start of Line)	598*	Taking sections of crab and packing them together to be weighed.	Elapsed time = 14 min! Assuming that pump was accidentally turned off and then on again (no cover on on/off switch), resetting time. Unsure of time in between being reset.
7	4	Allergen PBZ	2:36 PM	6:06 PM	211	3.00	Section Packer (End of Line)	2011	Taking sections of crab and packing them together to be weighed.	
8	6	Allergen PBZ	2:51 PM	6:43 PM	234	3.00	Weigher	895	Weighs the crab that come from the section packing table.	
Date: July 12, 2001 - **Sampler**: Jason Callahan										
Calibrated by: Jason Callahan **On**: July 11, 2001 (includes pumps # 1 to # 8)										
Sample #	Pump #	Sample Type	Time On	Time Off	Elapsed Time (min)	Flow Rate (lpm)	*Area*	Nanograms/m3 Results	Operations Monitored	Remarks/Conditions
9	1	Allergen PBZ	7:06 AM	3:30 PM	506	3.00	Butcher Table	<50	Breaking the crab and throwing it onto the conveyor	There was some crab waste on the filter casing, again. Unsure if any of it got inside.
10	2	Allergen PBZ	7:13 AM	3:30 PM	500	3.00	Holding Room	<50	Stacking crab crates, icing the crab, feeding the crates to the butchers.	
11	8	Allergen PBZ	7:20 AM	3:44 PM	510	3.00	Cooker Room	<50	The cooking process of the crab.	
12	3	Allergen PBZ	7:27 AM	3:54 PM	511	3.00	Quality Control	222	In the Process Room office for a good part of the day.	
13	4	Allergen PBZ	7:32 AM	3:29 PM	480	3.00	Section Packer (End of Line)	748	Taking sections of crab and packing them together to be weighed.	She had to leave early because she wasn't feeling well. Found the pump in the office still running. Not sure what time she left it there.
14	5	Allergen PBZ	7:35 AM	4:20 PM	???	3.00	Section Packer (Start of Line)	950*	Taking sections of crab and packing them together to be weighed.	Update: she said that she felt when the pump shut off (vibrations) and turned it back on, herself. Therefore, time should be pretty accurate from July 11. Had problems with the pump again, today. She kept turning it back on, though. Again, unsure of the elapsed time.
15	6	Allergen PBZ	7:38 AM	4:55 PM	562	3.00	Weigher	672	Weighs the crab that come from the section packing table.	
16	7	Allergen PBZ	8:01 AM	4:45 PM	527	3.00	Freezer Area	222		* - volume (m^3) unknown, used 1m^3

1

Table 3: Tabulated plant 2 air sampling results from year 1

								Nanograms/m3		
Sample #	Pump #	Sample Type	Time On	Time Off	Elapsed Time (min)	Flow Rate (lpm)	Area	Results	Operations Monitored	Remarks/Conditions
1	1	Allergen Area	2:40 PM	4:40 PM	120		Office in the Processing Area	170		
2	2	Allergen Area	2:46 PM	4:46 PM	120		Weigher in the Processing Area	243		
3	1	Allergen Area	4:45 PM	6:45 PM	120		Office in the Processing Area	160		
4	2	Allergen Area	4:48 PM	6:48 PM	120		Weigher in the Processing Area	212		
Date: July 12, 2001										
								Nanograms/m3		
Sample #	Pump #	Sample Type	Time On	Time Off	Elapsed Time (min)	Flow Rate (lpm)	Area	Results	Operations Monitored	Remarks/Conditions
5	1	Allergen Area	8:38 AM	10:38 AM	120		Office in the Processing Area	80		
6	2	Allergen Area	8:40 AM	10:40 AM	120		Weigher in the Processing Area	217		
7	3	Allergen Area	8:49 AM	10:49 AM	120		Stairs in the Butcher Area	11		
8	1	Allergen Area	10:44 AM	12:44 PM	120		Office in the Processing Area	157		
9	2	Allergen Area	10:45 AM	12:45 PM	120		Weigher in the Processing Area	145		
10	3	Allergen Area	10:51 AM	12:51 PM	120		Stairs in the Butcher Area	3		
11	1	Allergen Area	12:48 PM	2:48 PM	120		Office in the Processing Area	167		
12	2	Allergen Area	12:49 PM	2:49 PM	120		Weigher in the Processing Area	256		
13	3	Allergen Area	12:54 PM	2:54 PM	120		Stairs in the Butcher Area	<2		
14	1	Allergen Area	2:52 PM	4:52 PM	120		Office in the Processing Area	163		
15	2	Allergen Area	2:53 PM	4:53 PM	120		Weigher in the Processing Area	218		

Table 4: Tabulated plant 2 air sampling results from year 1

Plant 2, Allergen Personal Samplers July 18, 2002. Sampler: Brad Pelley										
Calibrated by: Brad Pelley **On:** July 18, 2002										
Sample #	Pump #	Sample Type	Time On	Time Off	Elapsed Time (min)	Flow Rate (lpm)	Area	Ng/m^3 Results	Operations Monitored	Remarks/Conditions
26	1	Allergen PBZ	7:15 am	1:45 pm	360	3.00	Sorting and Brushing	1346	Taking sections of crab and packing them together to be weighed.	Cooking in progress
27	2	Allergen PBZ	7:30 am	2:00 pm	275	3.00	Packing	886	Boxing crab, off-loading, putting crab in Cold Storage.	Cooking in progress
28	4	Allergen PBZ	7:30 am	11:35 am	245	3.00	Box Room	133	Make boxes for packing	Cooking in progress
29	5	Allergen PBZ	7:00 am	1:30 pm	370	3.00	Cooker	68	Cooking Process	Cooking in progress
30	6	Allergen PBZ	6:51 am	1:30 pm	370	3.00	Butcher	55	Butchering Process	Cooking in progress
31	7	Allergen PBZ	7:30 am	1:45 pm	375	3.00	Weights	202	Weighs the crab that come from the section packing table.	Cooking in progress
32	8	Allergen PBZ	6:56 am	1:35 pm	379	3.00	Cooling	302	Monitors crab in brine cooler	Cooking in progress
Date: July 19th , 2002 - **Sampler:** Brad Pelley										
Calibrated by: Brad Pelley **On:** July 19, 2002										
Sample #	Pump #	Sample Type	Time On	Time Off	Elapsed Time (min)	Flow Rate (lpm)	Area	Ng/m^3 Results	Operations Monitored	Remarks/Conditions
33		Allergen PBZ	8:00 am	1:37 pm	337	3.00	Weights (Static)	327	Weighs the crab that come from the section packing table.	Cooking in progress
34		Allergen PBZ	8:05 am	1:37 pm	332	3.00	Grader (Static)	598	Grading crab for weighing	Cooking in progress
35		Allergen PBZ	7:21 am	1:05 pm	312	3.00	Cooker	154	Cooking Process	Cooking in progress
36		Allergen PBZ	7:40 am	1:42 pm	329	3.00	End of Cooler	342	Area located at the end of the Pre Chill Cooler, workers load crates.	Cooking in progress
37		Allergen PBZ	7:21 am	1:05 pm	312	3.00	Butcher	64	Butchering Process	Cooking in progress
38		Allergen PBZ	7:43 am	1:35 pm	352	3.00	Cold Storage	69	Entrance to cold storage room	Cooking in progress
39		Allergen PBZ	7:40 am	2:00 pm	349	3.00	Sorting and Brushing	1322	Taking sections of crab and packing them together to be weighed.	Cooking in progress

Table 1: Plant 2, Allergen Personal Samplers

Table 5: Tabulated plant 2 air sampling results from year 2

Plant 2, Allergen Personal Samplers July 21st, 2002. Sampler: Brad Pelley										
Sample #	Pump #	Sample Type	Time On	Time Off	Elapsed Time (min)	Flow Rate (lpm)	Area	Ng/m³ Results	Operations Monitored	Remarks/Conditions
40	1	PBZ	2:00 pm	5:25 pm	205	3.0	Sorting/Brushing (Static)	792	Taking sections of crab and packing them together to be weighed.	Cooking in progress
42	4	PBZ	1:00 pm	5:00 pm	240	3.0	Cooker	60	Cooking process	Cooking in progress
43	5	PBZ	1:00 pm	5:00 pm	???	3.0	Butcher	N/A	Butchering process	It was off when it was retrieved, no idea how long.
44	6	PBZ	1:30 pm	5:30 pm	240	3.0	Freezer/Cold Storage	775	Entrance to cold storage room	Worker moved between cold storage and weights.
45	7	PBZ	2:05 pm	5:20 pm	195	3.0	Cooling (Static)	356	Cooling process	Cooking in progress
46	8	PBZ	1:15 pm	5:26 pm	251	3.0	Grader	568	Grading crab for weighing	Cooking in progress
Plant 2, Allergen Personal Samplers July 22nd, 2002. Sampler: Brad Pelley										
								Ng/m³		
Sample #	Pump #	Sample Type	Time On	Time Off	Elapsed Time (min)	Flow Rate (lpm)	Area	Results	Operations Monitored	Remarks/Conditions
47	1	PBZ	7:35 am	2:20 pm	405	3.0	Saws (Static)	338	Sawing operations	Cooking in progress
48	2	PBZ	7:40 am	2:20 pm	400	3.0	Grader (Static)	552	Grading crab for weighing	Cooking in progress
49	4	PBZ	7:55 am	2:35 pm	400	3.0	Old packing/Brine Freezer (Static)	218	Between Brine Freezer and Old Packing Line.	Cooking in progress
50	5	PBZ	7:02 am	2:15 pm	433	3.0	Cooker	96	Cooking process	Cooking in progress
51	6	PBZ	7:10 am	2:02 pm	387	3.0	Cooling	394	Cooling process	Cooking in progress
52	7	PBZ	7:05 am	2:35 pm	450	3.0	Butcher	27	Butchering process	Cooking in progress
53	8	PBZ	7:15 am	2:02 pm	382	3.0	Sorting and Brushing	1218	Taking sections of crab and packing them together to be weighed.	Cooking in progress

Table 2: Plant 2, Allergen Personal Samplers

Table 6: Tabulated plant 2 air sampling results from year 2

Plant 2, Area Allergen Samples July 18th, 2002 Sampler: Brad Pelley Pumps Calibrated by Brad Pelley										
Sample #	Pump #	Sample Type	Time On	Time Off	Elapsed Time (min)	Flow Rate (lpm)	Area	Ng/m³	Operations Monitored	Remarks/Conditions
1		Allergen Area	8:30 am	10:35 am	125	150	Butcher Room on Floor	14	Butchering process	Cooking in progress
2		Allergen Area	8:35 am	10:45 am	130	150	Top of Cooker	90	Cooking progress	Cooking in progress
3		Allergen Area	8:45 am	11:50 am	125	150	Cooler, beginning of Drum	9	Beginning of drum, next to cooling tank	Cooking in progress
4		Allergen Area	9:00 am	11:00 am	120	150	Top Old Packing Line	138	End of Brine Freezer and beginning of packing line	Cooking in progress
5		Allergen Area	10:35 am	12:50 pm	135	150	Butcher Room on Floor	6	Butchering process	Cooking in progress
6		Allergen Area	10:45 am	12:50 pm	125	150	Top of Cooker	43*	Cooking process	Flow rates at the end were approx 100 l/min.
7		Allergen Area	10:50 am	1:00 pm	130	150	Cooling, beginning of Drum	5*	Beginning of drum, next to cooling tank	Flow rates at the end were approx 100 l/min.
8		Allergen Area	10:55 am	1:00 pm	125	150	Top Old Packing Line	50	End of Brine Freezer and beginning of packing line	Cooking in progress
Plant 2, Area Allergen Samples July 19th, 2002 Sampler: Brad Pelley Pumps Calibrated by Brad Pelley										
								Ng/m³		
Sample #	Pump #	Sample Type	Time On	Time Off	Elapsed Time (min)	Flow Rate (lpm)	Area	Results	Operations Monitored	Remarks/Conditions
9	1	Allergen Area	8:30 am	10:50 am	140	150	Butcher	23	Butchering process	Cooking in progress
10	2	Allergen Area	8:30 am	10:50 am	140	150	Cooker	17	Cooking process	Cooking in progress
11	A/C	Allergen Area	8:45 am	11:10 am	140	150	Top of Old Packing Line	42	End of Brine Freezer and beginning of packing line	Cooking in progress
12	3	Allergen Area	9:40 am	11:40 am	145	150	Behind Grader table, end of drum.	584	End of Drum behind grader table	Cooking in progress
13	1	Allergen Area	11:30 am	1:15 pm	105	150	Butcher	66*	Butchering process	Cooking in progress
14	2	Allergen Area	10:50 am	1:00 pm	130	150	Cooker	418*	Cooking process	Cooking in progress
15	A/C	Allergen Area	11:15 am	1:20 pm	125	150	Top of Old Packing Line	142	End of Brine Freezer and beginning of packing line	Cooking in progress
16	3	Allergen Area	11:40 am	1:48 pm	128	150	Behind Grader table, end of drum.	193	End of Drum behind grader table	Cooking in progress

Table 3: Plant 2, Area Samplers

Table 7: Tabulated plant 2 air sampling results from year 2

Plant 2, Allergen Area Samplers July 21st, 2002. Sampler: Brad Pelley

Sample #	Pump #	Sample Type	Time On	Time Off	Elapsed Time (min)	Flow Rate (lpm)	Area	Ng/m³ Results	Operations Monitored	Remarks/Conditions
17	2	Allergen Area	1:50 pm	3:52 pm	122	150	Cooker	32	Cooking Process	Cooking in progress
18	3	Allergen Area	1:49 pm	4:08 pm	139	150	Cold Storage	25	Cold Storage Entrance	Cooking in progress

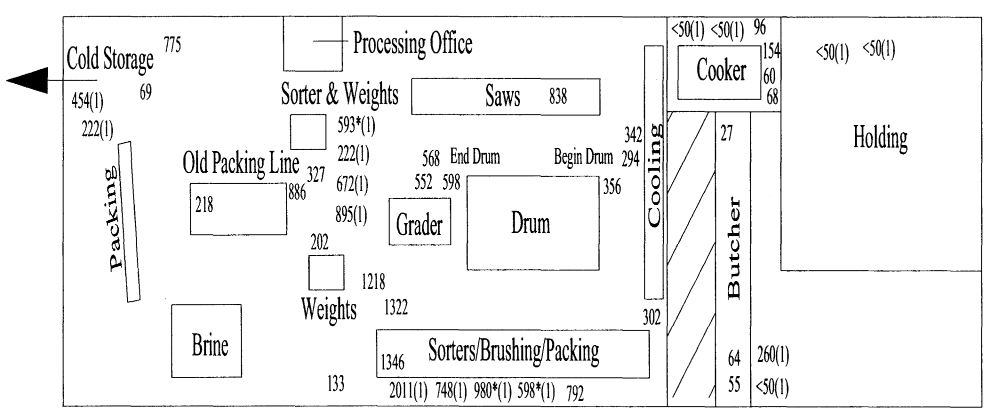
Plant 2, Allergen Personal Samplers July 22nd, 2002. Sampler: Brad Pelley

Sample #	Pump #	Sample Type	Time On	Time Off	Elapsed Time (min)	Flow Rate (lpm)	Area	Ng/m³ Results	Operations Monitored	Remarks/Conditions
19	3	Allergen Area	8:35 am	10:40 am	125	150	Holding Room	7	Holding room for crab.	Cooking in progress
20	2	Allergen Area	8:30 am	10:40 am	130	150	Cooker	24	Cooking Process	Cooking in progress
21	A/C	Allergen Area	8:48 am	10:54 am	126	150	Brine Freezer/Old Packing Line	26	Between Brine Freezer and Packing Area.	Cooking in progress
22	3	Allergen Area	10:50 am	12:50 pm	120	150	End of Drum	263	End of Drum behind grader table	Cooking in progress
23	2	Allergen Area	10:45 am	12:45 pm	120	150	Cooker (on floor)	218	Cooking Process	Cooking in progress
24	A/C	Allergen Area	10:55 am	12:52 pm	117	150	Brine Freezer/Old Packing Line	28	End of Brine Freezer and beginning of packing line	Cooking in progress

Table 4: Plant 2, Allergen Personal Samplers

Table 8: Tabulated plant 2 air sampling results from year 2

Plant 2 - PBZ Samples Year 1&2



* means averaged flow volumes were used.

Figure 3: Plant 2 air sampling results from year 2

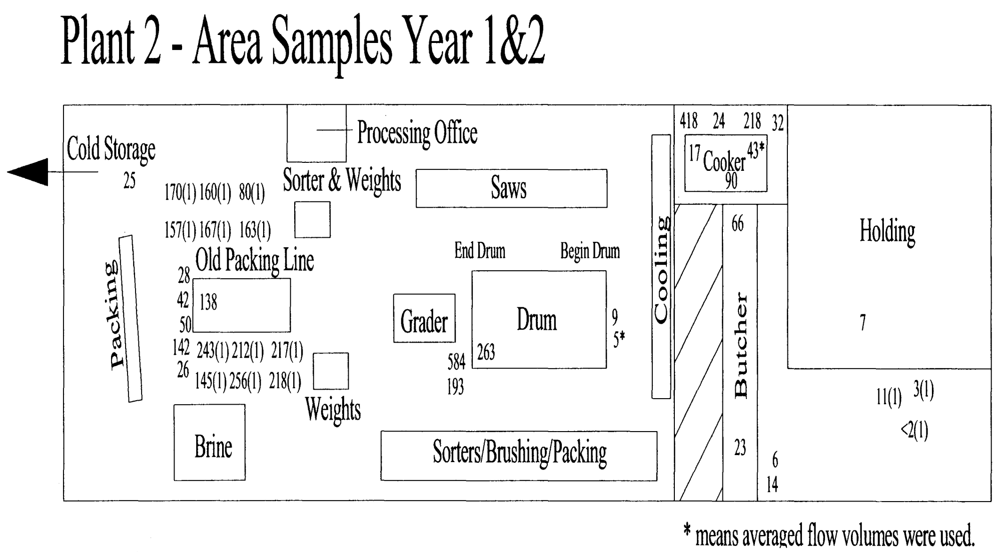


Figure 4: Plant 2 air sampling results from year 2

Appendix C

Plant 3 Sample Results

Air sampling results for plant 3 have been tabulated and presented in the following tables.

Sample #	Pump #	Sample Type	Time On	Time Off	Elapsed Time (min)	Flow Rate (lpm)	Area	Nanograms/m³ Results	Operations Monitored	Remarks/Conditions
Calibrated by: Jason Callahan **On:** August 6, 2001 (includes pumps # 1 to # 8)										
1	3	Allergen PBZ	8:00 AM	4:55 PM	471	3.00	Start of Cooker	74	Takes the crates of crab off of the Sorting Line and puts them into the Cooker.	
2	7	Allergen PBZ	8:01 AM	5:17 PM	~ 420	3.00	Caging Area	169	After being weighed, he loads the crates into cages and hoists the cages into the Pre-Chill Tank.	Pump was off when he turned it in for lunch. I don't think it was off for too long. There was a bit of mess on the filter casing. I turned it back on at 1:04 PM, after lunch. Checked pump at 1:40 PM and it was off again ??? Turned it on again. Was alright for the afternoon (213 min. elapsed).
3	1	Allergen PBZ	7:58 AM	4:55 PM	473	3.00	Butcher Area	<50	The crab comes from the boat or holding room and he cracks the crab, brushes them, and sends them on to be graded and sorted.	In the afternoon, the filter came off and fell in the water chute on the butchering line. He picked it up and put it on again. When I collected the pumps at end of day the filter paper inside looked wet and ruined. Looks useless.
4	5	Allergen PBZ	8:03 AM	4:56 PM	397	3.00	Weigher	183	After the Cooler, the crabs are weighed to specific amounts by her and sent to be caged and chilled.	At 11:08 AM, I had to restart the pump. The elapsed time then was 137 minutes. At the end of the day, the elapsed time was 260 minutes. Therefore, total was 397 minutes.
5	6	Allergen PBZ	8:05 AM	4:58 PM	474	3.00	End of Cooler	172	Removes the crates of crab from the Cooler and sends them down on a conveyor belt to be weighed.	
6	4	Allergen PBZ	8:08 AM	4:56 PM	458	3.00	Caging Area	68	Helps to lower the crates of crab into the Pre-Chill Tank and transports the crab from the Pre-Chill Tank to the Brine Tank (crane).	I was told that he was at the end of the Cooker, but he is at the Caging Area. Trying to get the guy at the end of Cooker to wear the pump tomorrow (August 9).
7	2	Allergen PBZ	8:10 AM	4:57 PM	461	3.00	Sorting Area	<50	Sorts the crab and puts the crab into different sizes before the Cooker.	
Sampler: Jason Callahan - **Date:** August 9, 2001										
Calibrated by: Jason Callahan **On:** August 6, 2001 (includes pumps # 1 to # 8)										
Sample #	**Pump #**	**Sample Type**	**Time On**	**Time Off**	**Elapsed Time (min)**	**Flow Rate (lpm)**	**Area**	**Nanograms/m3 Results**	**Operations Monitored**	**Remarks/Conditions**
8	6	Allergen PBZ	7:55 AM	4:58 PM	490	3.00	End of Cooler	139	Removes the crates of crab from the Cooler and sends them down on a conveyor belt to be weighed.	
9	5	Allergen PBZ	7:57 AM	4:49 PM	472	3.00	Weigher	137	After the Cooler, the crabs are weighed to specific amounts by her and sent to be caged and chilled.	
10	4	Allergen PBZ	7:59 AM	4:58 PM	478	3.00	End of Cooker	244	Takes the crates of crab out of the Cooker and places them into the start of the Cooler.	This is the first day for X with the pump. Changed from Y to X due to closeness to Cooker and Cooler.
11	7	Allergen PBZ	8:00 AM	5:00 PM	???	3.00	Caging Area	<50	After being weighed, he loads the crates into cages and hoists the cages into the Pre-Chill Tank.	Checked pump at 9:24 AM and it was off. I restarterd it. Pump was off when he turned it in for lunch. I turned it back on at 1:00 PM. Checked pump at 2:00 PM and it was off again. I restarted it. Off again at 5:00 PM. Everytime the pump was found off, it didn't show elapsed time (it should). Not a good sample because totally unsure of time. M is next to T, so not a big loss.
12	1	Allergen PBZ	8:02 AM	4:59 PM	478	3.00	Butcher Area	<50	The crab comes from the boat or holding room and he cracks the crab, brushes them, and sends them on to be graded and sorted.	Some mess on the filter casing. Not much.
13	3	Allergen PBZ	8:03 AM	4:57 PM	471	3.00	Start of Cooker	68	Takes the crates of crab off of the Sorting Line and puts them into the Cooker.	
14	2	Allergen PBZ	8:04 AM	4:56 PM	472	3.00	Sorting Area	49	Sorts the crab and puts the crab into different sizes before the Cooker.	

Table 9: Tabulated plant 3 air sampling results from year 1

Sample #	Pump #	Sample Type	Time On	Time Off	Elapsed Time (min)	Flow Rate (lpm)	Area	Nanograms/m3 Results	*Operations Monitored*	Remarks/Conditions
August 8, 2001. Sampler: Jason Callahan. Calibrated by Mark Swanson										
1	1	Allergen Area	8:54 AM	10:54 AM	120		Behind Brine Tank	23		
2	2	Allergen Area	8:58 AM	10:58 AM	120		Next to Weigher	9		The pump got pretty wet. Filter seemed alright. Not sure, though. Can this pose a problem ???
3	3	Allergen Area	9:03 AM	11:03 AM	120		Behind Cooker	13		
4	1	Allergen Area	11:33 AM	1:33 PM	120		Behind Brine Tank	19		
5	2	Allergen Area	11:39 AM	1:39 PM	120		Next to Weigher	10		I moved the pump a little. Still got a bit wet, but not as much as last time.
6	3	Allergen Area	11:41 AM	1:41 PM	120		Behind Cooker	14		
7	1	Allergen Area	1:35 PM	3:35 PM	120		Behind Brine Tank	42		
8	2	Allergen Area	1:40 PM	3:40 PM	120		Next to Weigher	41		
9	3	Allergen Area	1:44 PM	3:44 PM	120		Behind Cooker	60		
Date: August 9, 2001										
Sampler: Jason Callahan										
Sample #	**Pump #**	**Sample Type**	**Time On**	**Time Off**	**Elapsed Time (min)**	**Flow Rate (lpm)**	**Area**	**Nanograms/m3 Results**	**Operations Monitored**	**Remarks/Conditions**
10	1	Allergen Area	8:17 AM	10:17 AM	120		Behind Brine Tank	61		
11	2	Allergen Area	8:20 AM	10:20 AM	120		Next to Weigher	122		
12	3	Allergen Area	8:23 AM	10:23 AM	120		Behind Cooker	25		
13	1	Allergen Area	10:19 AM	12:19 PM	120		Behind Brine Tank	47		
14	2	Allergen Area	10:22 AM	12:22 PM	120		Next to Weigher	61		
15	3	Allergen Area	10:25 AM	12:25 PM	120		Behind Cooker	97		
16	1	Allergen Area	12:40 PM	2:40 PM	120		Behind Brine Tank	36		
17	2	Allergen Area	12:43 PM	2:43 PM	120		Next to Weigher	56		
18	3	Allergen Area	12:46 PM	2:46 PM	120		Behind Cooker	26		
19	1	Allergen Area	2:41 PM	4:41 PM	120		Behind Brine Tank	48		
20	2	Allergen Area	2:44 PM	4:44 PM	120		Next to Weigher	54		
21	3	Allergen Area	2:47 PM	4:47 PM	120		Behind Cooker	36		

Table 10: Tabulated plant 3 air sampling results from year 1

Sample #	Pump #	Sample Type	Time On	Time Off	Elapsed Time (min)	Flow Rate (lpm)	Area	Ng/m³ Results	Operations Monitored	Remarks/Conditions
Plant 3 Allergen Samples, PBZ Samples August 15th - Sampler: Brad Pelley										
Calibrated by: Brad Pelley On: August 15th, 2002										
54	1	Allergen PBZ	8:10am	3:00pm	341	3.00	Raw Sorter	53	Sorts the crab before it enters the cooker after it comes from the butcher room.	Cooking in progress
55	2	Allergen PBZ	8:12am	3:00pm	339	3.00	Packing	63	Packs crab in cardboard boxes and ship to cold storage.	Cooking in progress
56	4	Allergen PBZ	7:45am	3:00pm	373	3.00	Cooler	107	Monitors crab as it leaves the cooker.	Cooking in progress
57	5	Allergen PBZ	7:42am	3:00pm	372	3.00	Brine Freezer	168	Helps to lower the crates of crab into the Pre-Chill Tank and transports the crab from the Pre-Chill Tank to the Brine Tank (crane).	Cooking in progress
58	6	Allergen PBZ	7:51am	3:00pm	351	3.00	Grader	235	Removes the crates of crab from the Cooler and sends them down on a conveyor belt to be weighed.	Cooking in progress
59	7	Allergen PBZ	7:40am	3:00pm	376	3.00	Butcher	66	The crab comes from the boat or holding room and he cracks the crab, brushes them, and sends them on to be graded and sorted	Cooking in progress
60	8	Allergen PBZ	7:54am	3:25pm	451	3.00	Cooker			
61	3	Allergen PBZ	8:20am	???	???	3.00	Varies			
Sam										
Calibrated by: Brad Pelley On: August 16, 2002										
Sample #	**Pump #**	**Sample Type**	**Time On**	**Time Off**	**Elapsed Time (min)**	**Flow Rate (lpm)**	**Area**	**Ng/m³ Results**	**Operations Monitored**	**Remarks/Conditions**
62		Allergen PBZ	7:54am	3:07pm	371	3.00	Butcher	<13	The crab comes from the boat or holding room and he cracks the crab, brushes them, and sends them on to be graded and sorted.	Cooking in progress
63		Allergen PBZ	10:20am	3:26pm	274	3.00	Cooler	147	Monitors crab as it leaves the cooler	Cooking in progress
64		Allergen PBZ			Nil	3.00			Not used	Not used
65		Allergen PBZ	8:45am	3:30pm	405	3.00	Midway Grader	120	Static PBZ midway on automatic grader line	Cooking in progress
66		Allergen PBZ	8:06am	3:06pm	336	3.00	Brine Freezer	138	Helps to lower the crates of crab into the Pre-Chill Tank and transports the crab from the Pre-Chill Tank to the Brine Tank (crane).	Cooking in progress
67		Allergen PBZ	8:07am	3:06pm	353	3.00	Packing	65	Packs crab in cardboard boxes and ship to cold storage.	Cooking in progress
68		Allergen PBZ	8:36am	3:06pm	323	3.00	Raw Sorter	34	Sorts the crab before it enters the cooker after it comes from the butcher room.	Cooking in progress
69		Allergen PBZ	8:12am	3:43pm	364	3.00	Cooker	247	Monitors the crab as it moves through the cooker.	Cooking in progress

Table 1: Plant 3, Allergen PBZ Samples

Table 11: Tabulated plant 3 air sampling results from year 2

Plant 3 Allergen Samples, PBZ Samples August 18th - Sampler: Brad Pelley										
Calibrated by: Brad Pelley On: August 18th, 2002										
Sample #	Pump #	Sample Type	Time On	Time Off	Elapsed Time (min)	Flow Rate (lpm)	Area	Ng/m^3 Results	Operations Monitored	Remarks/Conditions
70	1	Allergen PBZ	1:02pm	5:12pm	250	3.00	Packer	60	Packs crab in cardboard boxes and ship to cold storage.	Cooking process
71	2	Allergen PBZ	1:07pm	5:00pm	233	3.00	Raw Sorter	77	Sorts the crab before it enters the cooker after it comes from the butcher room.	Cooking process
72	3	Allergen PBZ	1:08pm	5:00pm	232	3.00	Cooker	40	Monitors the crab as it moves through the cooker.	Not sure what time this pump cut out but it was off when I checked near the end of the shift.
73	5	Allergen PBZ	1:10pm	5:02pm	232	3.00	Butcher	57	The crab comes from the boat or holding room and he cracks the crab, brushes them, and sends them on to be graded and sorted.	Cooking process
74	6	Allergen PBZ	1:20pm	5:02pm	222	3.00	Grader (static)	95	Removes the crates of crab from the Cooler and sends them down on a conveyor belt to be weighed	Cooking process
75	7	Allergen PBZ	1:10pm	5:03pm	233	3.00	Cooler	209	Monitors crab as it leaves the cooker.	Cooking process
76	8	Allergen PBZ	1:30pm	5:30pm	240	3.00	Brine Freezer	72	Helps to lower the crates of crab into the Pre-Chill Tank and transports the crab from the Pre-Chill Tank to the Brine Tank (crane).	Cooking process

Table 2: Plant 3, Area Allergen Samples

Table 12: Tabulated plant 3 air sampling results from year 2

Plant 3, Area Allergen Samples										
August 14th, 15th, 16th 2002 Sampler: Brad Pelley Calibrated: Brad Pelley										
Sample #	Pump #	Sample Type	Time On	Time Off	Elapsed Time (min)	Flow Rate (lpm)	Area	Ng/m^3 Results	Operations Monitored	Remarks/Conditions
1(14th)	2	Allergen Area	7:15pm	9:05pm	110	150	Top of Cooker	42	On top of cont. cooker	Cooking in progress
2(15th)	A/C	Allergen Area	9:20am	11:50am	140	150	Holding Room	<3	Crab Holding Room	Cooking in progress
3(15th)	2	Allergen Area	9:00am	10:30am	90	150	Butcher	17	Butchering Room	Cooking in progress
4(15th)	3	Allergen Area	8:45am	10:15am	90	150	Top of Cooker	87	Cooking process	Cooking in progress
5(15th)	A/C	Allergen Area	12:10pm	2:10pm	120	150	Holding Room	<3	Crab holding room	Cooking in progress
6(15th)	2	Allergen Area	10:30am	12:30pm	120	150	Butcher	15*	Butchering process	*Based on estimated collection volumes
7(15th)	3	Allergen Area	10:15am	12:15pm	120	150	Top of Cooker	83*	Cooking process	*Based on estimated collection volumes
8(16th)	2	Allergen Area	1:30pm	3:30pm	120	150	Grader, 8' off floor	46	8ft off floor, top grader	Cooking in progress
9(16th)	3	Allergen Area	1:30pm	3:30pm	120	150	Brine Freezer	72*	Top of brine tank, packing end	*Based on estimated collection volumes
Date: August 17th,18th , 2002										
Sampler: Brad Pelley										
Sample #	Pump #	Sample Type	Time On	Time Off	Elapsed Time (min)	Flow Rate (lpm)	Area	Ng/m^3 Results	Operations Monitored	Remarks/Conditions
10(17th)	A/C	Allergen Area	11:00am	1:00pm	120	150	End of Brine Tank	4	Nil	No work today
11(17th)	2	Allergen Area	11:10am	1:10pm	120	150	Top of Cooker	8	Nil	No work today
12(17th)	3	Allergen Area	11:05am	1:05pm	120	150	Weights	<3	Nil	No work today
13(18th)	2	Allergen Area	1:30pm	3:30pm	120	150	Cooker	30	Nil	No work today
14(18th)	3	Allergen Area	1:30pm	3:30pm	120	150	Pre Cooler	34	Nil	No work today
15(18th)	2	Allergen Area	3:30pm	5:30pm	120	150	Cooker	56	Nil	No work today
16(18th)	3	Allergen Area	3:30pm	5:30pm	120	150	Mid Brine Freezer	69	Nil	No work today

Table 3: Plant 3, Area Allergen Samples

Table 13: Tabulated plant 3 air sampling results from year 2

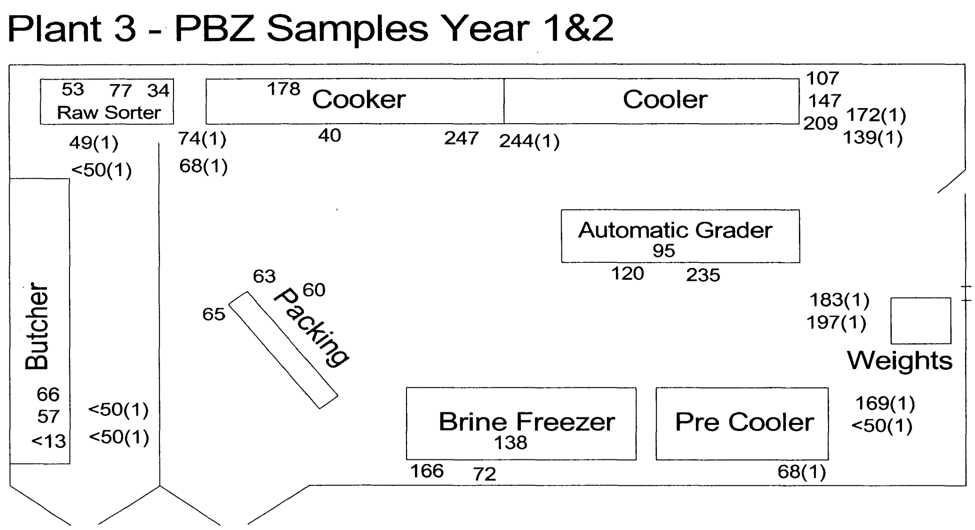


Figure 5: Plant 3 air sampling results from year 2

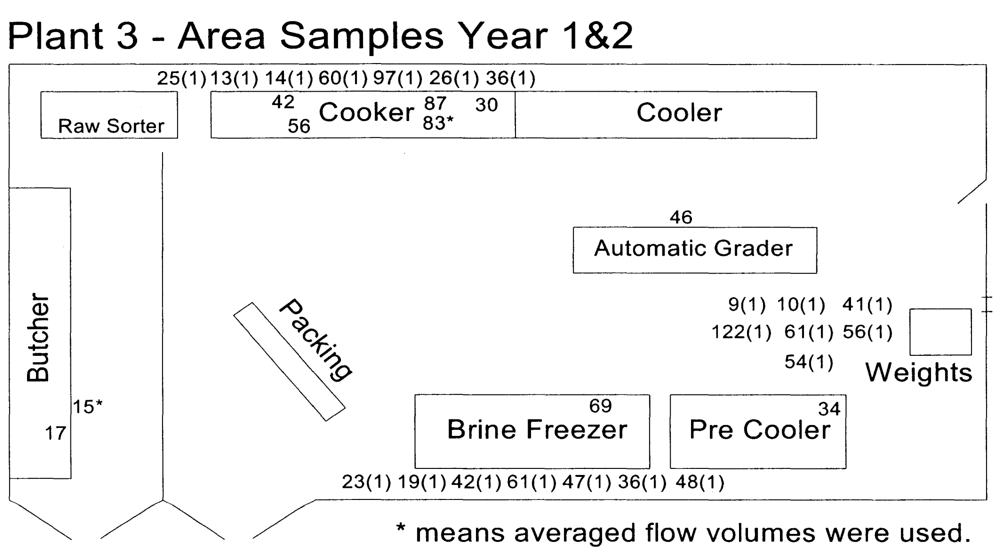


Figure 6: Plant 3 air sampling results from year 2

Appendix D

Plant 4 Sample Results

Air sampling results for plant 4 have been tabulated and presented in the following tables.

Plant 4, Allergen Personal Samplers June 10th , 2002. Sampler: Brad Pelley										
Calibrated by: Brad Pelley On: June 9th, 2002										
Sample #	Pump #	Sample Type	Time On	Time Off	Elapsed Time (min)	Flow Rate (lpm)	Area	Ng/m^3 Results	Operations Monitored	Remarks/Conditions
8	7	Allergen PBZ	8:12am	1:15pm	276	3.00	Butcher	19	Butchers the crab when it is brought in from the holding room.	Cooking in progress
9	2	Allergen PBZ	8:25am	12:55pm	300	3.00	Cooker	158	Cooks the crab in a sectioned off room in batch cookers.	Cooking in progress
10	6	Allergen PBZ	9:00am	1:00pm	240	3.00	Ice Loader (outside)	125	Shovels Ice into crates for use in the cooking room to cool the crab down.	Cooking in progress
11	4	Allergen PBZ	10:18am	3:15pm	272	3.00	Packing	300	Boxing crab for Cold Storage.	Cooking in progress
12	1	Allergen PBZ	8:32am	1:00pm	268	3.00	Saws	749	Removes crab from sorting line and brings it to the saws line.	Cooking in progress
14	5	Allergen PBZ	10:15am	3:10pm	280	3.00	Saws	918	Scores(saws) the crab legs	Cooking in progress
13	8	Allergen PBZ	10:28am	3:22pm	280	3.00	Brine Freezer	465	Puts crab in Brine cooler before it gets packed and sent to storage.	Cooking in progress
Date: June 18th Sampler: Brad Pelley										
Calibrated by: Brad Pelley On: June 17th , 2002										
Sample #	Pump #	Sample Type	Time On	Time Off	Elapsed Time (min)	Flow Rate (lpm)	Area	Ng/m^3 Results	Operations Monitored	Remarks/Conditions
22	1	Allergen PBZ	9:25am	2:04pm	279	3.00	Saws	2869	Scores(saws) the crab legs	Cooking in progress
23	2	Allergen PBZ	10:00am	1:45pm	225	3.00	Everywhere	77	Moved throughout the plant	Brad Pelley wore the PBZ while moving throughout the plant.
24	4	Allergen PBZ	7:04am	12:00pm	296	3.00	Butcher	53	Butchers the crab when it is brought in from the holding room.	Cooking in progress
25	8	Allergen PBZ	7:05am	11:15pm	250	3.00	Cooker	195	Cooks the crab in a sectioned off room in batch cookers.	Cooking in progress

Table 1: Plant 4, Allergen Personal Samplers

Table 14: Tabulated plant 4 air sampling results from year 1

Sample #	Pump #	Sample Type	Time On	Time Off	Elapsed Time (min)	Flow Rate (lpm)	Area	Results	Operations Monitored	Remarks/Conditions
Plant 4, Area Allergen Samples June 10th, 2002 Sampler: Mark Swanson Calibrated by :Mark Swanson										
								Ng/m³		
21		Allergen Area	11:00am	1:00pm	120	150	Cooker	105	Cooks the crab in a sectioned off room in batch cookers.	Cooking in progress
22		Allergen Area	11:00am	1:00pm	120	150	Saws	233	Scores(saws) the crab legs	Cooking in progress
23		Allergen Area	11:00am	1:00pm	120	150	Sorting/Grading/Saws	182	Moves crab from sorting table to saws table	Cooking in progress
24		Allergen Area	11:00am	1:00pm	120	150	Butcher	57	Butchers the crab when it is brought in from the holding room.	Cooking in progress
25		Allergen Area	11:00am	2:20pm	200	150	Box Washer	13	Washes crab crates	Cooking in progress
26		Allergen Area	1:00pm	2:50pm	110	135	Cooker	47	Cooks the crab in a sectioned off room in batch cookers.	Cooking in progress
27		Allergen Area	1:00pm	2:50pm	110	150	Saws	602	Scores(saws) the crab legs	Cooking in progress
28		Allergen Area	1:00pm	1:30pm	30	150	Sorting/Grading/Saws	487	Moves crab from sorting table to saws table	Cooking in progress
29		Allergen Area	1:00pm	2:50pm	110	150	Sorting/Grading	175	Grading crab and packing into crates	Cooking in progress
30		Allergen Area	1:00pm	2:20pm	80	150	Boat Hold	6	Unloading crab from boat	Sampler placed in Boat Hold with 6000lbs crab.
Plant 4, Area Allergen Samples June 18th, 2002 Sampler: Mark Swanson Calibrated by :Mark Swanson										
								Ng/m³		
Sample #	**Pump #**	**Sample Type**	**Time On**	**Time Off**	**Elapsed Time (min)**	**Flow Rate (lpm)**	**Area**	**Results**	**Operations Monitored**	**Remarks/Conditions**
50		Allergen Area	10:00am	12:00pm	120	150	Outdoors, N end, downwind	124	Sampling outside the plant	Sampler was put outside at the North end of the plant.
51		Allergen Area	10:00am	12:30pm	150	150	Cooker	181	Cooks the crab in a sectioned off room in batch cookers.	Cooking in progress
52		Allergen Area	10:00am	12:00pm	120	150	Saws	316	Scores(saws) the crab legs	Cooking in progress
53		Allergen Area	10:00am	12:40pm	160	150	Holding Room	22	Crab is stored for butchering	Cooking in progress
54		Allergen Area	10:00am	12:00pm	120	150	Cooker	61	Cooks the crab in a sectioned off room in batch cookers.	Cooking in progress
55		Allergen Area	10:00am	1:00pm	180	150	Holding Room	10	Crab is stored for butchering	Cooking in progress
57		Allergen Area	10:00am	11:15am	75	150 2	Saws	77	Scores(saws) the crab legs	Cooking in progress

Table 15: Tabulated plant 4 air sampling results from year 1

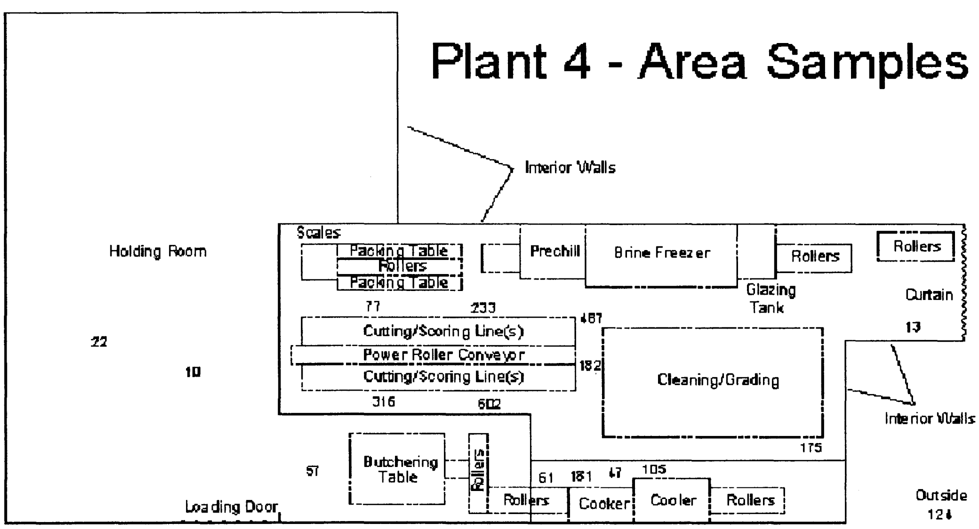


Figure 7: Tabulated plant 4 air sampling (Area) results from year 1

Plant 4, Raw Crab Experiment Allergen Personal Samplers July 21st, 2003. Sampler: Brad Pelley										
Calibrated by: Brad Pelley On: July 21st, 2003										
Sample #	Pump #	Sample Type	Time On	Time Off	Elapsed Time (min)	Flow Rate (lpm)	Area	Ng/m^3 Results	Operations Monitored	Remarks/Conditions
1	1	Allergen PBZ	7:00am	2:34pm	424	3.00	Saws	1589	Scores (saws) the crab legs	Cooking in progress
2	2	Allergen PBZ	6:50am	2:26pm	426	3.00	Saws/Packing	663	Worker moved between packing and sawing.	Cooking in progress
3	3	Allergen PBZ	6:10am	1:50pm	420	3.00	Cooker	648	Cooks the crab in the batch cooker.	Cooking in progress
4	4	Allergen PBZ	9:45am	2:30pm	255	3.00	Saws	3188	Scores (saws) the crab legs	Cooking in progress
5	5	Allergen PBZ	7:25am	2:23pm	388	3.00	Packing	673	Grading and cleaning crab and packing into crates	Cooking in progress
6	6	Allergen PBZ	8:00am	3:50pm	443	3.00	Brine Freezer	365	Puts crab in Brine cooler before it gets packed and sent to storage	Cooking in progress

Table 1: Plant 4, Allergen Personal Samplers

Table 16: Tabulated plant 4 air sampling (PBZ) results from year 2

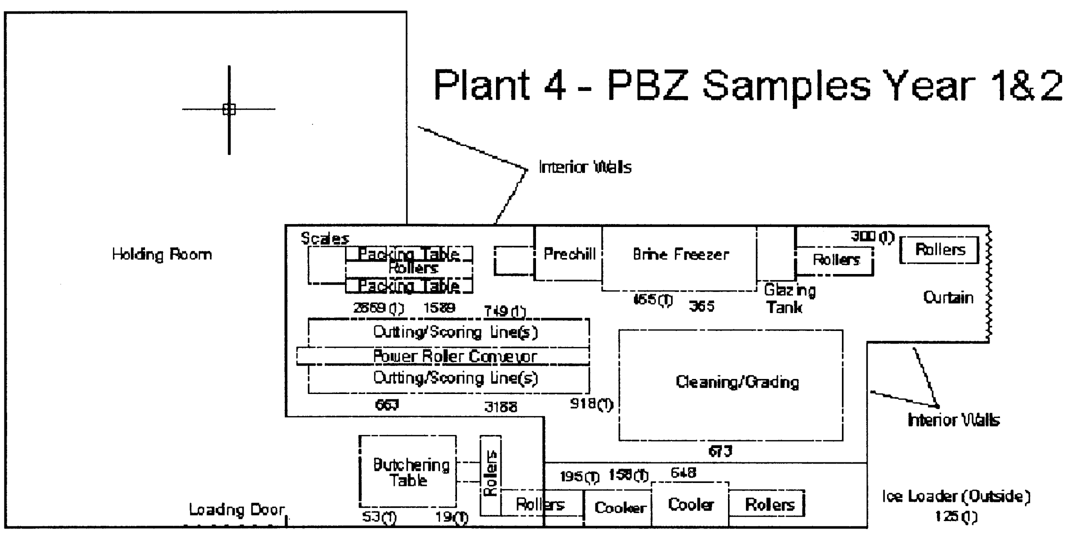


Figure 8: Plant 4 air sampling results from year 2

Appendix E

Plant 1 Results

Temperature and humidity results for plant 1 are shown in the following figures.

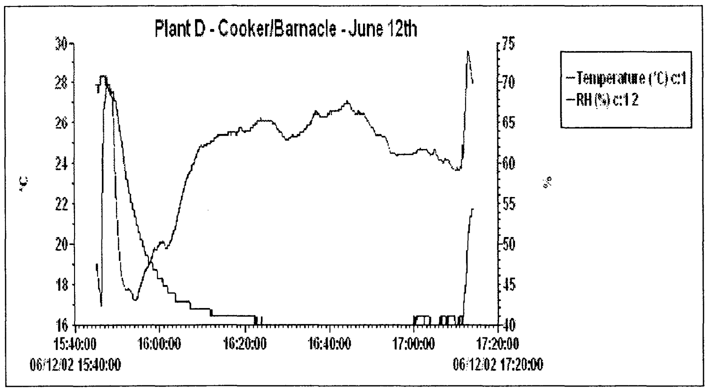


Figure 9: Year 1 Temperature and Humidity Measurements (Cooking Room and Barnacle Table Area)

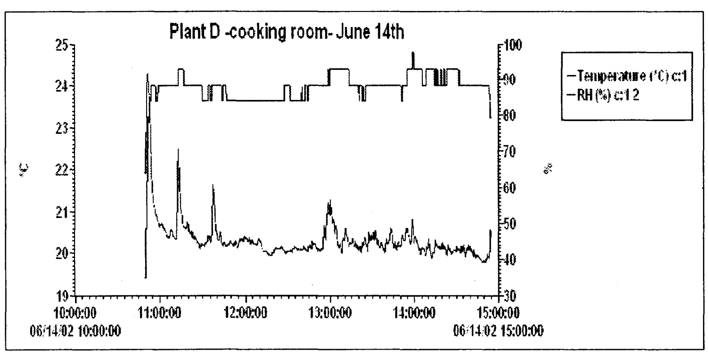


Figure 10: Year 1 Temperature and Humidity Measurements (Cooking Room)

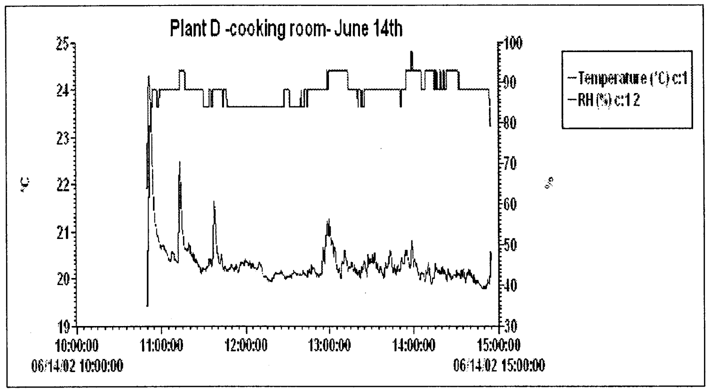


Figure 11: Year 1 Temperature and Humidity Measurements (Cooking Room)

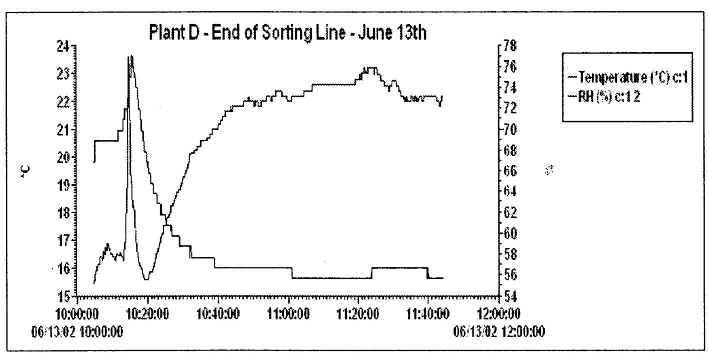


Figure 12: Year 1 Temperature and Humidity Measurements (Sorting and Packing Area)

Appendix F

Plant 2 Results

Temperature and humidity results for plant 2 are shown in the following figures.

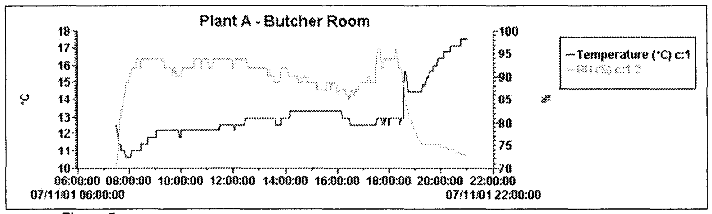


Figure 5

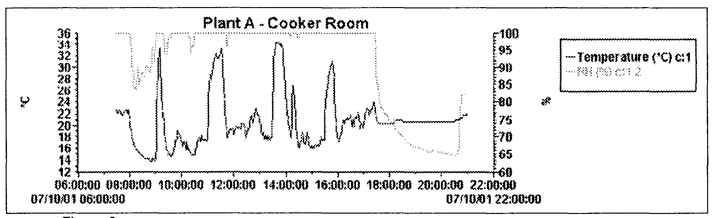


Figure 6

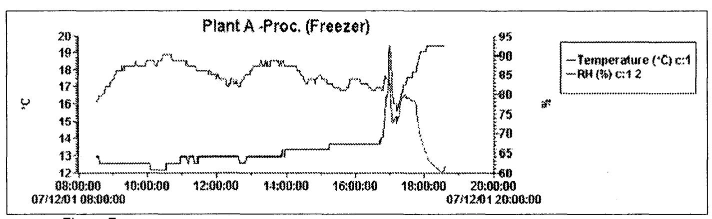


Figure 7

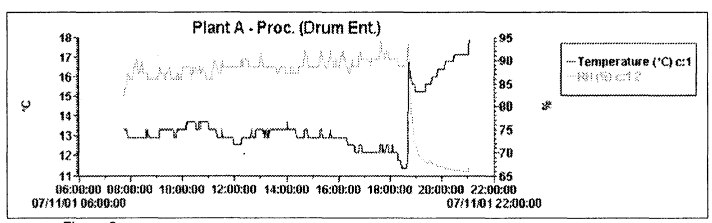


Figure 8

Figure 13: Year 1 Temperature and Humidity Measurements (All Areas)

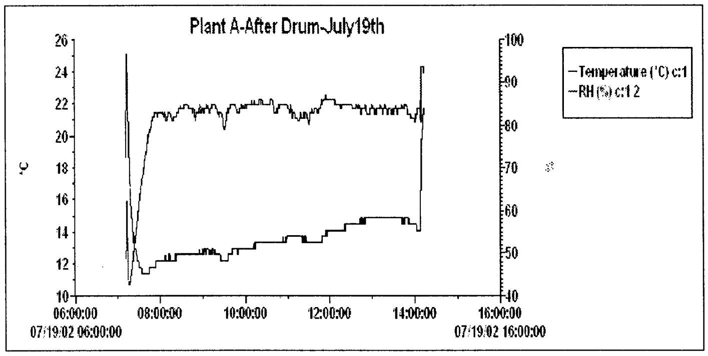


Figure 14: Year 2 Temperature and Humidity Measurements (Drum Area)

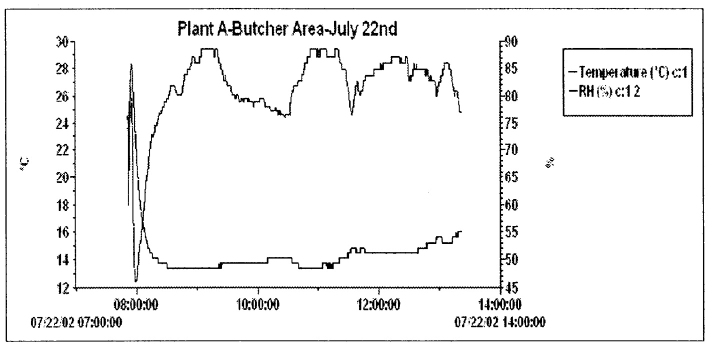


Figure 15: Year 2 Temperature and Humidity Measurements (Butcher Area)

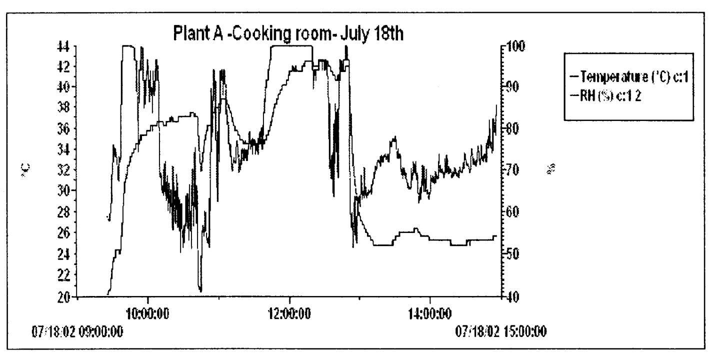


Figure 16: Year 2 Temperature and Humidity Measurements (Cooking Room)

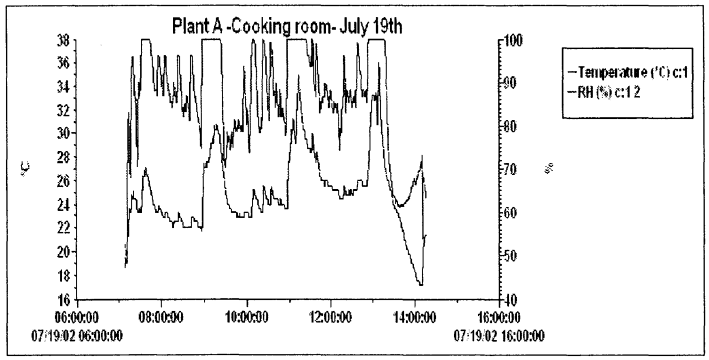


Figure 17: Year 2 Temperature and Humidity Measurements (Cooking Room)

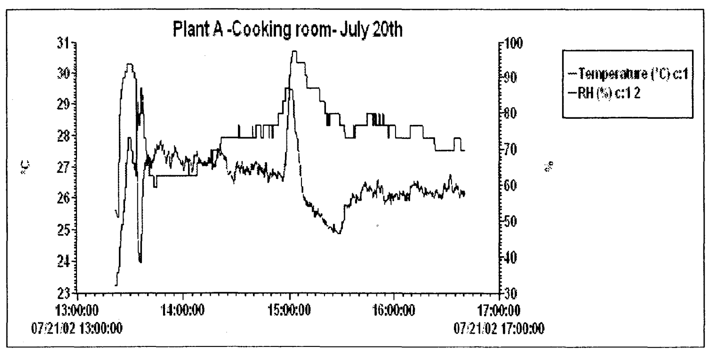


Figure 18: Year 2 Temperature and Humidity Measurements (Cooking Room)

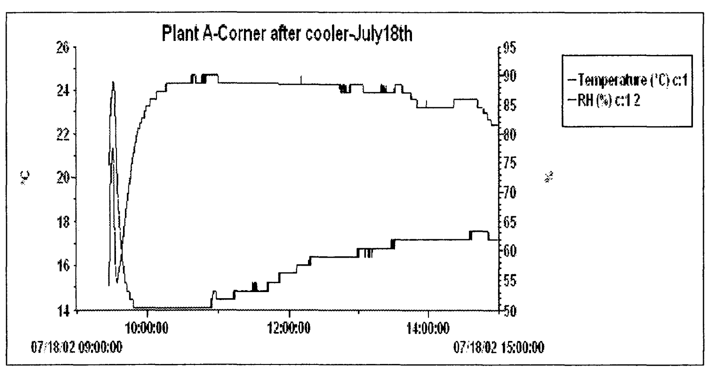


Figure 19: Year 2 Temperature and Humidity Measurements (Cooling Area)

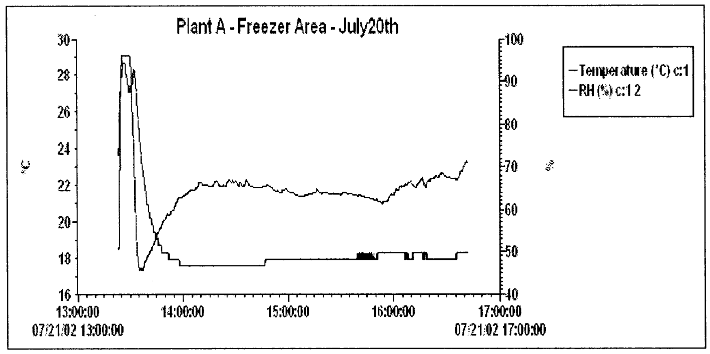


Figure 20: Year 2 Temperature and Humidity Measurements (Freezer Area)

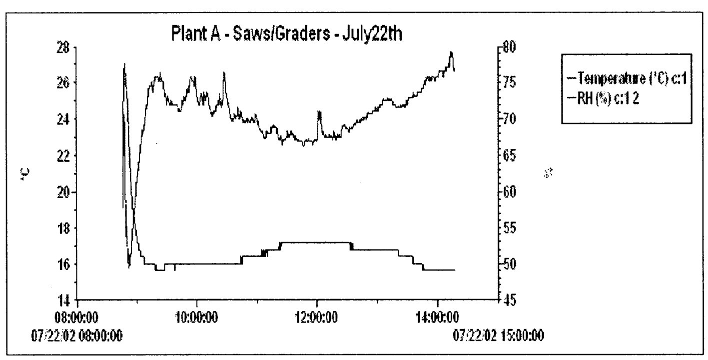


Figure 21: Year 2 Temperature and Humidity Measurements (Sawing and Grading Area)

Appendix G

Plant 3 Results

Temperature and humidity results for plant 3 are shown in the following figures.

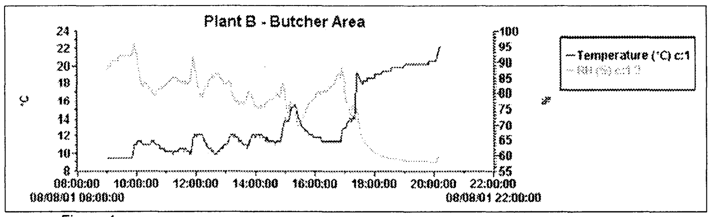


Figure 4

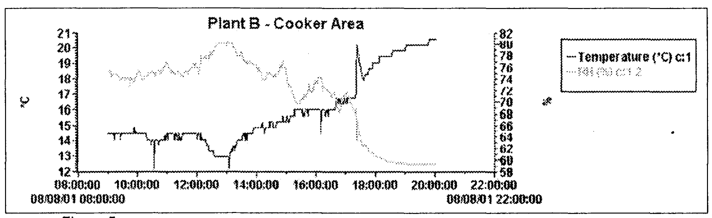


Figure 5

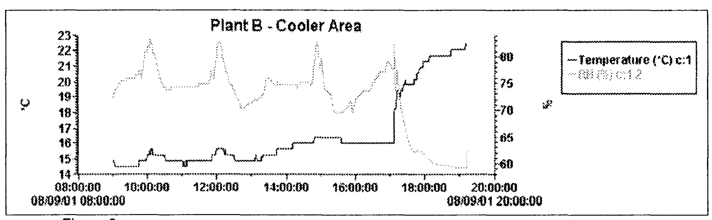


Figure 6

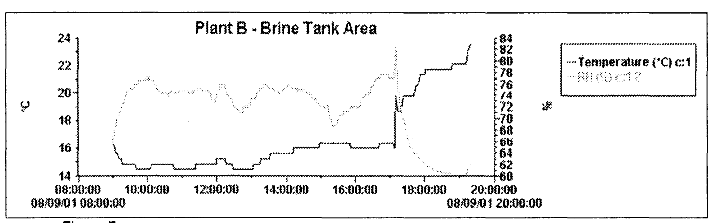


Figure 7

Figure 22: Year 1 Temperature and Humidity Measurements (All Areas)

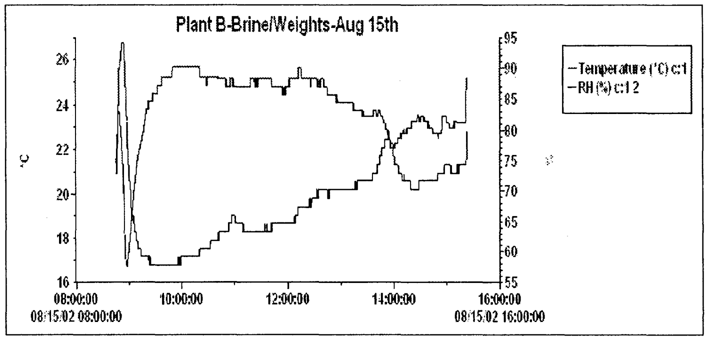


Figure 23: Year 2 Temperature and Humidity Measurements (Brine Tank/Weights Area)

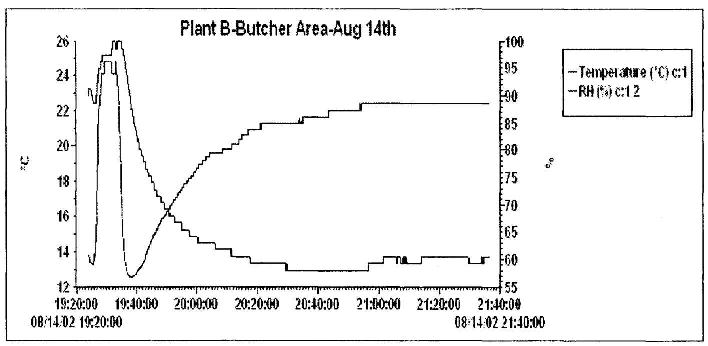


Figure 24: Year 2 Temperature and Humidity Measurements (Butcher Area)

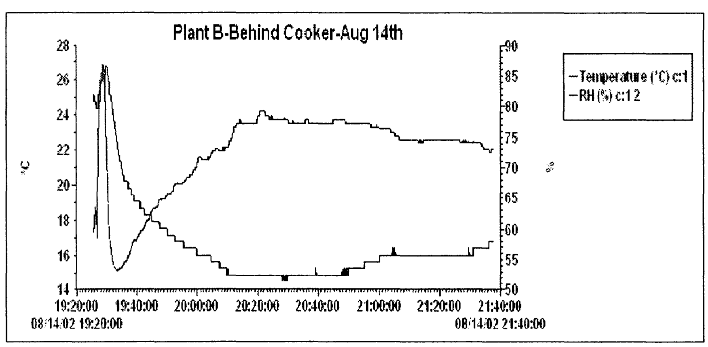


Figure 25: Year 2 Temperature and Humidity Measurements (Cooking Room)

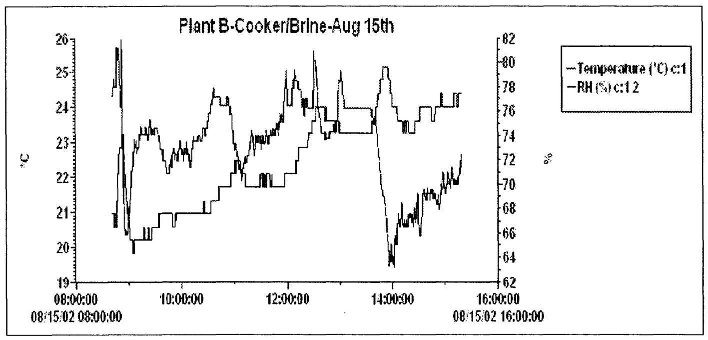


Figure 26: Year 2 Temperature and Humidity Measurements (Cooker/Cooling Area)

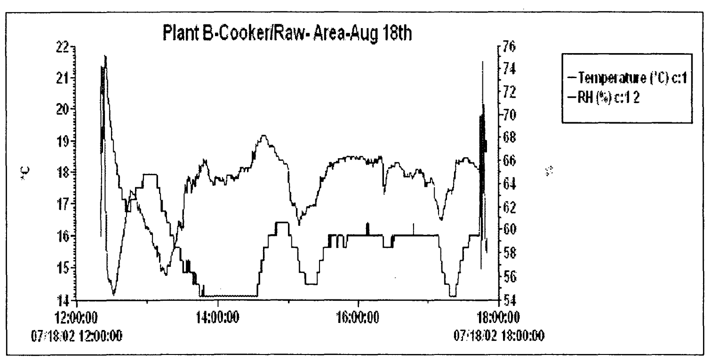


Figure 27: Year 2 Temperature and Humidity Measurements (Cooker/Raw Sorting Area)

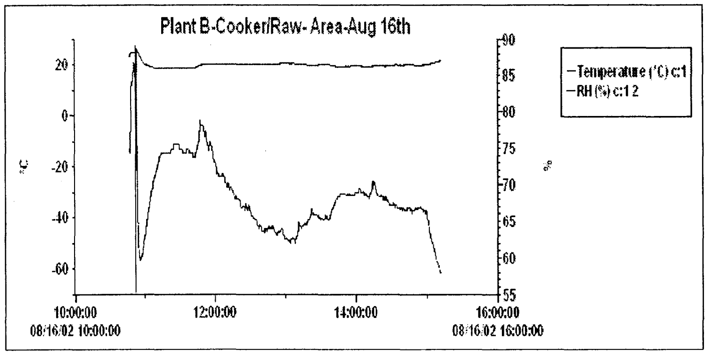


Figure 28: Year 2 Temperature and Humidity Measurements (Cooker/Raw Sorting Area)

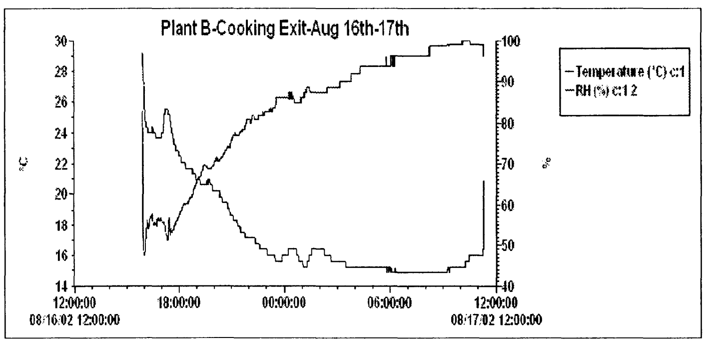


Figure 29: Year 2 Temperature and Humidity Measurements (Cooling Tank Area)

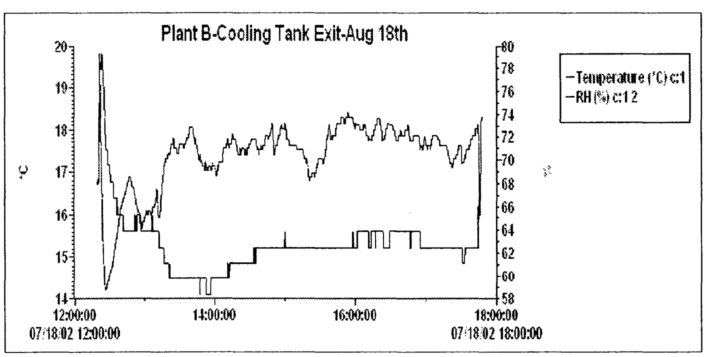


Figure 30: Year 2 Temperature and Humidity Measurements (Cooling Tank Area)

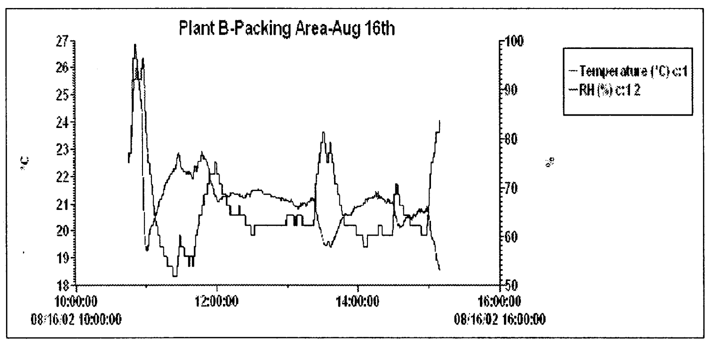


Figure 31: Year 2 Temperature and Humidity Measurements (Packaging Area)

Appendix H

Plant 4 Results

Temperature and humidity results for plant 4 are shown in the following figures.

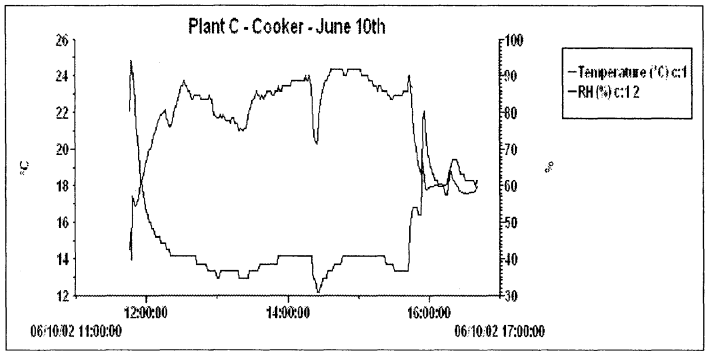


Figure 32: Year 1 Temperature and Humidity Measurements (Cooking Room)

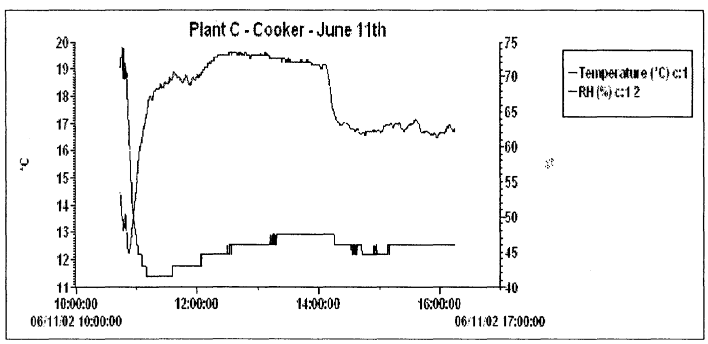


Figure 33: Year 1 Temperature and Humidity Measurements (Cooking Room)

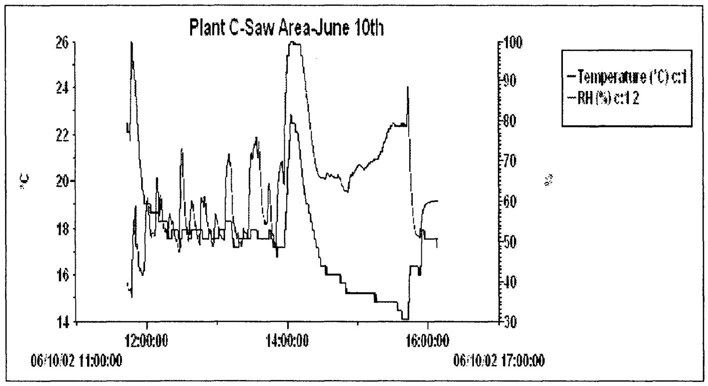


Figure 34: Year 1 Temperature and Humidity Measurements (Sawing Area)

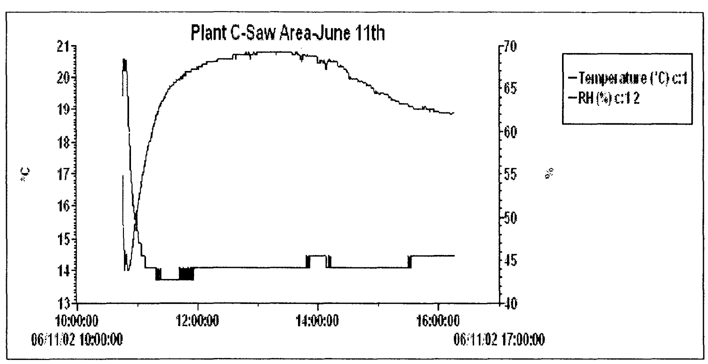


Figure 35: Year 1 Temperature and Humidity Measurements (Sawing Area)