FIELD AND LABORATORY STUDIES OF MIXING TUBES FOR MARINE OUTFALLS

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Field and Laboratory Studies of Mixing Tubes for Marine Outfalls

by

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Abstract

Increase in land costs due to urbanization has led many coastal communities towards marine outfalls as a convenient means of disposing of domestic and non toxic wastes. It has been common practice to use submerged outfalls for small discharges to take advantage of the immediate dilution available as the effluent rises to the surface. The prime objective of the marine outfall installation is to maximize the total dilution of the waste and to minimize impact on the marine environment. Jet pumps or mixing tubes may be used to improve the initial dilution and to promote plume submergence in small outfalls. Theoretical and experimental studies have been carried out but field trials have been very limited.

Studies have shown that very limited improvement in dilution is obtained with conventional mixing tubes. The basic reason for this is that the combination of increased flow and increased diameter of the mixing tube modify the values of density difference, relative depth and densimetric Froude number. Due to these changes less mixing takes place between the end of the mixing tube and the surface than would have taken place in the original jet discharged without a mixing tube. The combination of increased dilution within the mixing tube and decreased dilution in the buoyant jet has been found to limit the improvement factor of overall dilution to a factor of about two.

In this thesis experiments on a novel shape of mixing tube are described. This was designed to overcome the problems discussed above and used a transition from a square section at entry to a two dimensional slot at the exit. The study showed that better performance can be acheived at low values of the Froude number. The improvement of overall dilution with a slot mixing tube compared to the circular mixing tube was however, fairly limited.

Little information is available to describe the field performance of mixing tubes. This lack was rectified by a field study run parallel to the laboratory work. In this study a circular mixing tube was built and installed on a small outfall located at Spaniards bay on the east coast of the island of Newfoundland. Dye studies were done at this installation to check the dilution achieved in the field. Comparisons were made between the performance of a horizontal jet with and without the mixing tube but little improvement in overall dilution was acheived with the mixing tube. It was found that the mixing tubes performed better in the field than was theoretically predicted.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

As land costs continue to escalate due to increased urbanization, more and more coastal communities are turning to marine outfalls as a convenient means for disposing of domestic and non toxic industrial wastes. The process involves some pretreatment onshore to remove suspended solids and floating materials followed by discharge offshore at a depth well below low water. The prime objective of the marine outfall is to maximise physical dilution of the waste to protect the quality of the marine environment. Following dilution and dispersion, organic wastes are stabilized by natural processes which, with proper design, occur without environmental or aesthetic damage to the environment.

Comparisons between the performance of land based secondary treatment plants and ocean outfalls are often made as if they were comparisons between full treatment and total lack of treatment. This approach to the problem is misleading and irrational because the primary difference between the two lies in the location and not in the manner of treatment. In a secondary treatment plant sewage wastes are stabilized by the action of bacteria and other micro-organisms in enclosed basins. In the sea the same result is obtained by essentially similar processes (albeit natural) but the size of the treatment zone is increased while the concentration of pollutants is reduced. One major difference is the degree of control exerted over the two types of treatment. Land treatment plants have closely controlled purification processes whereas the only control over the natural treatment which occurs in the ocean lies in the choice of the outfall site, the design of the outfall and the permissible loading. Thus, dilution is very important in the design of ocean outfalls. Not only does it decrease the concentration of wastes, it also provides an ambient source of dissolved oxygen so that aerobic bacteria and higher forms of life flourish without depleting the dissolved oxygen concentration. It has been documented that under suitable wind, wave and current conditions, ocean outfalls provide favourable reduction in BOD at less cost (Clough and Cannon, 1981) and at less damage to the environment (Allen and Sharp, 1987) than land based treatment plants.

It is often assumed, for example, that land treatment provides a pure effluent with no side effects. However liquid wastes following treatment are usually rich in nutrients and, when discharged to the sea, the relatively clear outflow conceals the food immediately available for algae growth. This is not the case when effluent is discharged through an outfall. Under these conditions the organic matter is widely dispersed and breaks down slowly. The same total amount of nutrient is available but this is released slowly over a wide area. Ocean outfalls seem to be particularly suitable to small, remote, coastal communities where domestic sewage constitutes the major part of the effluent. In addition an outfall is an alternative because most of the cost is for capital works and the system needs very little maintenance when compared to a secondary treatment plant. The simplest system of disposing of effluent, common in the case of small discharges, consists of head work and a long pipe which runs from the shore line to well below the low water mark. The effluent is discharged through a circular nozzle at the end of the pipe. The head work usually consists of grit chambers to remove suspended solids and a pump chamber. Automatic pumps with float operated swithes are used to pump the collected sewage at a regular interval of time. For larger flows it is common to use a multiport diffuser in which effluent is discharged through a series of ports located along the length of the diffuser pipe. This method has been used successfully for decades but, there has also been considerable interest in the development of other devices which, by some means of premixing, increase the dilution even more than can be achieved by multiport diffusers.

Various types of baffles and obstructions to the flow have been tried in an effort to increase dilution above that which can be obtained by a simple jet discharge. Jet-pumps, or mixing tubes, have also been advocated on various occasions (Silvester 1967, Argaman, et al.,1975, Agg, et al., 1974). These operate with effluent being discharged from a nozzle into a larger diameter pipe, the mixing tube, in such a way that receiving water is entrained at entry thus diluting the effluent within the mixing tube itself. However, it has been shown both theoretically (Sharp, 1978) and experimentally (Argaman, et al., 1975) that the increase in dilution caused by use of these mixing tubes is limited to a factor of about two. This is because, pre-dilution changes the characteristics of the jet such that subsequent dilution between the mixing tube and the surface is less than the dilution which could be obtained without the tube. The gain in dilution within the tube is thus offset by a reduction in dilution between the tube and the surface.

This thesis describes field and laboratory studies related to the use and effectiveness of mixing tubes. Despite some previous theoretical and laboratory work on cylindrical mixing tubes, no field data has been collected or reported to show whether laboratory results can be scaled up for use in the field. To remedy this lack, cylindrical mixing tubes were designed and installed on a small outfall on the east coast of Newfoundland. Dye studies were undertaken to determine whether dilutions measured in the field were the same as those which could be predicted from previously reported laboratory studies. The tubes were left in place over the winter months and were then examined to determine whether the design was adequate to withstand the winter weather. Alongside this fieldwork a laboratory study was undertaken for a novel shape of mixing tube. This was designed to overcome the problems which were responsible for limiting the improvement of a cylindrical mixing tube to a factor of about 2.0. Two different shapes of mixing tube were studied in the laboratory and measurements were made of the pre dilution obtained within each tube. The tubes were designed to convert the flow from a circular jet entering the tube into a two dimensional flow from a slot at the end of the tube. Previous studies of two dimensional jets then made it possible to calculate the overall dilution which could be obtained. It should be emphasized however that the primary intention of this study was to determine whether the shape chosen represented a feasible alternative to the more common cylindrical tube rather than to provide a detailed design for practical use.

Chapter 2

Literature Review

2.1 Jets, plumes and buoyant jets

2.1.1 General

When fluid is discharged from a circular nozzle into another fluid, the resulting flow may be described as a pure (or momentum) jet, a buoyant plume or a buoyant jet. When no density difference exists between the two fluids the resulting flow is that of a pure jet. The trajectory is a straight line in the direction of the nozzle axis and mixing occurs because of the initial momentum given to the flow as it leaves the nozzle. If a density difference exists, but there is no initial momentum, the resulting flow is called a buoyant plume. This is unusual in practice because some initial momentum is almost always present. However the flow of heated air from a warm point source (eg. a cigarette end) or of melting water from a fresh water glacier submerged in sea water would be very plume like. In a true plume the flow is vertical. When density difference and initial momentum are both present the flow is termed a buoyant jet. Momentum dominates near the discharge nozzle and the flow in this region is similar to that of a pure jet. However, as the initial momentum is dissipated, buoyancy becomes more important. The flow passes through a stage where both momentum and buoyancy are important but as distance from the nozzle increases buoyancy becomes more and more dominant. With sufficient depth the initial momentum may be completely dissipated and the fluid then rises under the action of buoyancy alone. In this region the flow is similar to that of a buoyant plume.

This thesis relates primarily to the effect of mixing tubes on ocean outfalls discharging effluent with buoyancy and momentum. The literature survey will therefore concentrate on buoyant jets and mixing tubes. Plumes and momentum jets will be considered only in so far as their understanding impacts on an understanding of buoyant jets.

2.1.2 Buoyant jet

When a buoyant effluent flows into still water from the end of a horizontal pipe, it is immediately acted upon by a buoyant force, the magnitude of which depends on the density difference between the effluent and the receiving water. This causes the jet of effluent to be deflected and accelerated towards the surface. As shear stresses are set up between the rising jet and the surrounding water, turbulence is generated and mixing takes place, first around the periphery of the jet and finally throughout the whole column. With continued mixing, the density difference between the jet of effluent and the surrounding water decreases in proportion to the amount of mixing.

Since mixing is most pronounced around the edges of the rising column, it is this part of the column which is decelerated most rapidly, thus setting up secondary shear stresses and causing turbulent mixing throughout the entire column.

The earliest experiments on buoyant jets were conducted by Rawn and Palmer (1930) who cantilevered a nozzle from a raft in Los Angeles harbour and collected dye samples at the boil of the jet. Measurements of surface dilution were made and some empirical formulae were derived. It was later found that the empirical formulae were not universally applicable.

The data collected by Rawn and Palmer were re-analyzed by Rawn, Bowerman and Brooks (1960) who calculated the densimetric Froude number, F_Δ, the Reynolds number, R_e, and the relative depth Y_o/d for each test. Using partial analysis they showed that

$$S_o = \phi\left(F_\Delta, R_e, \frac{Y_o}{d}\right) \tag{2.1}$$

S_o = dilution of the jet fluid defined as the ratio of concentration of the jet fluid at any point to the concentration of the jet fluid at the discharge point
F_Δ = densimetric Froude number defined as $Q/\frac{\pi}{4}\sqrt{g'd^5}$
R_e = Reynolds number defined as $Q/\frac{\pi}{4}\nu d^3$
Q = rate of discharge from the jet
ν = kinematic viscosity
g' = $g\frac{\Delta\rho}{\rho}$
g = gravitational acceleration
$\Delta\rho$ = difference in density between the discharging fluid and the surrounding fluid
ρ = density of the receiving fluid

By careful analysis of the samples Rawn et al., were able to show that the Reynolds number had no significant influence on the dilution, provided the jet flow was fully turbulent. Because the Reynolds number calculated using Rawn's data was always greater than 5000 making the flow to be fully turbulent, it was concluded that Reynolds number had no appreciable significance on the initial surface dilution S_o. Thus the basic equation namely, (Equation 2.1) reduced to

$$S_o = \phi\left(F_\Delta, \frac{Y_o}{d}\right) \tag{2.2}$$

A graphical solution (Figure 2.1) for the available data was developed to determine the surface dilution S_o.

Measurements for centre line dilution were made by Cederwall (1963) by means of a conductivity probe placed within a salt water jet injected to fresh water. Maximum concentration was observed along the axis of the jet. Comparisons of these dilutions with Rawn, Bowerman and Brooks showed that at large densimetric Froude numbers the predicted dilutions of Rawn et al. (1960), were greater than the measured minimum centre-line dilution.

Frankel and Cumming (1965) carried out a series of experiments on buoyant jets in a still receiving water. A graphical solution for concentrations within the jet was developed with the aid of non dimensional relationships. It was found that the distribution across the jet closely approximate the gaussian distribution. Various angles of jet discharge were also tested and it was found that the horizontal jet was the most efficient and the vertical jet least efficient. Frankel and Cumming

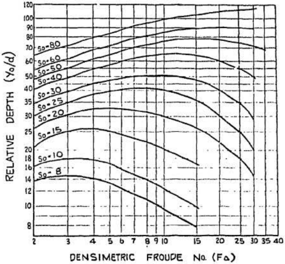


Figure 2.1: Initial Solution after Rawn, Bowerman and Brooks, (1960)

also studied the effect of surface proximity on mixing in the surface transition zone. Measurements of concentration were taken on the surface and at some depth below it. They concluded that the effective diluting depth to diameter ratio is considerably less than the available surface depth to diameter ratio. As a result, the dilution at the centre-line of the plume cannot be calculated solely as a function of the depth of nozzle below the surface. They estimated the effective mixing depth to be as little as two thirds of the available depth in some instances.

A comprehensive study of buoyant jet phenomena was done by Abraham (Abraham, 1963, 1965). He assumed that the velocity and buoyancy profiles were of a gaussian nature. Empirical relations for velocity distribution and distribution of tracer concentration at any cross section of the jet were developed,namely

$$\frac{U_r}{U_o} = e^{-k(r/s)^2} \tag{2.3}$$

$$\frac{C_r}{C_o} = e^{-\mu k(r/s)^2} \tag{2.4}$$

where

U_o = centre line velocity of the jet
U_r = velocity at a distance r from the centre line
C_o = centre line concentration
C_r = concentration at a distance r from the centre line
r = radial distance measured from the centre line
s = axial distance of the plane from the nozzle
μ, k = dimensionless coefficients

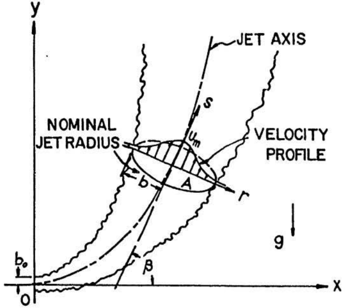


Figure 2.2: Cross sectional profile of a buoyant jet (Abraham, 1963)

A typical sketch showing all the above parameters is shown in Figure 2.2.

The flow establishment for pure jets as outlined by Albertson, et., al., (1956) was used to explain the flow pattern. Figure 2.3 shows the Zone of flow establishment and the zone of established flow. It was found that the length of the zone of flow establishment was equal to 6 times the diameter of the jet. The analysis was based on the assumption that the buoyant jet had jet like characteristics in the zone of flow establishment and plume like characteristics in the zone of established flow. Values for the constants k and μ were given by the relation

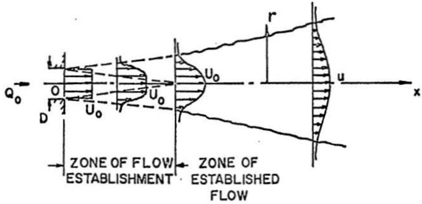


Figure 2.3: Zone of flow establishment and zone of established flow (Albertson et al., 1956)

$$k = -304(\frac{\beta}{\pi})^3 + 228(\frac{\beta}{\pi})^2 + 77 \tag{2.5}$$

$$\mu = 0.96(\frac{\beta}{\pi})^3 - 0.72(\frac{\beta}{\pi})^2 + 0.80$$

where β was defined as the angle the jet axis makes with the horizontal at any point distance 's' along the axis of the jet (Figure 2.2). The rate of entrainment was represented as a function of the axial distance of the jet axis. The theoretical solutions developed were verified by experimental results. A graphical solution (Figure 2.4)was developed for the prediction of the surface dilution.

Comparison of Abraham's predicted dilutions with Rawn and Palmer (1930) showed that there was considerable agreement at lower densimetric Froude numbers but, at large values, Abraham's dilutions were lower than Rawn and Palmer. This was discussed by Sharp (Sharp, 1968) who stated that this may be due to the perfect still water conditions of Abraham's measurements when compared to field measurements of Rawn and Palmer. It would also be difficult to accurately locate the point of minimum dilution during the sampling done by Rawn and Palmer, again resulting in an overestimate of dilution.

Improvements on these theoretical solutions were made by Fan and Brooks (1966). They assumed that the rate of entrainment was proportional to the local characteristic velocity U_m and the local characteristic radius of the jet or plume 'b' and by following the technique used successfully by Morton et al. (1956) they presented,

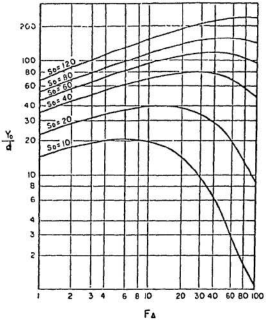


Figure 2.4: Prediction of surface dilution of a buoyant jet after Abraham (1963)

$$\frac{dQ}{ds} = \frac{d}{ds}(\pi U_r b^2) = 2\pi \alpha b U_r \tag{2.6}$$

where α = a dimensionless constant of proportionality.

The velocity and concentration profiles were presented in a slightly different form than that of Abraham's equation namely Equation (2.3) and (2.4) as

$$\frac{U_r}{U_o} = e^{-(r/b)^2} \tag{2.7}$$

$$\frac{C_r}{C_o} = e^{-(r/\lambda b)^2} \tag{2.8}$$

Here λ is a dimensionless spread ratio and 'b' is the half width of the jet.

A set of four ordinary differential equations namely Continuity , Momentum, Buoyancy flux and the geometry of the jet were developed based on the rate of increase in volume flux (Equation 2.6). One principle advantage of the entrainment equation over Abraham's approach is that it is more flexible and can be used for a variety of problems such as those involving buoyant jets and plumes in a stratified environment. This is because the plume width and the distance 's' need not be specified in advance but can be derived from equations of motion and continuity.

In 1968 Cederwall (1968) developed a set of analytical equations to predict dilution achieved in a horizontal buoyant jet, namely

$$S_o = 0.54 F_\Delta \left[\frac{(Y_o/d)}{F_\Delta}\right]^{7/16} \qquad for \;\; Y_o/d < 0.5 F_\Delta \tag{2.9}$$

and

$$S_o = 0.54F_\Delta\left[0.38\frac{(Y_o/d)}{F_\Delta} + 0.66\right]^{5/3} \qquad for \;\; Y_o/d > 0.5F_\Delta \qquad (2.10)$$

A generalised chart (Figure 2.5) was developed by Liseth (1970) combining the work of various workers. He found that the field data predicts a higher degree of dilution than shown by analytical results The reason for this is due to lateral mixing within the transition zone which tends to increase the dilution. He also found that the selected dimensionless parameter in his figure would show less scatter than plotting with other dimensionless parameters.

The later work in this area has tended to deal with refinements of the mathematical models of Fan and Abraham and has generally confirmed the validity of the solutions shown in Figure 2.5. More recent work, which will be presented later, has dealt with the effects of currents, stratification and waves.

2.1.3 Vertical buoyant jet

Studies on buoyant plumes were done by Morton, Taylor and Turner (Morton et al., 1956) using the following assumptions

1. The entrainment at any cross section is related to some characteristic velocity at that section.
2. The velocity and buoyancy profiles across the plume are of similar form at different heights.

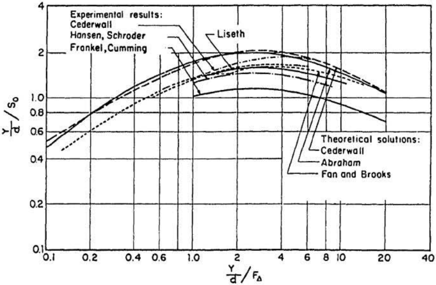
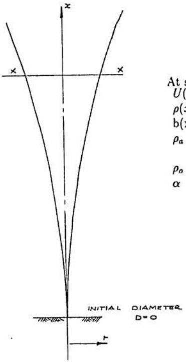


Figure 2.5: Generalised chart of various workers for surface dilution of a buoyant jet (Liseth, 1970)



At section x - x :-
$U(x,r)$ = U = Vertical velocity
$\rho(x,r)$ = ρ= Density of the Plume
b(x) = b = Radius of the plume
ρ_a = Density of ambient Fluid
= outside Plume
ρ_o = Initial density of plume
α = Constant relating inflow velocity at edge of plume to vertical velocity inside the plume

Figure 2.6: Flow parameters involved in the theoretical analysis of buoyant plume (Morton et al., 1956)

3 Local variations in density are small in comparison to the density of the ambient fluid at the source.

Using the notation shown in Figure 2.6 they were able to show that,

By principle of Conservation of volume

$$\frac{d}{dx}(\pi b^2 u) = 2\pi b\alpha u$$

by principle of conservation of mass

$$\frac{d}{dx}(\pi b^2 u^2 \rho) = \pi b^2 g(\rho_a - \rho)$$

and by the principle of conservation of density difference

$$\frac{d}{dx}(\pi b^2 u(\rho_o - \rho)) = 2\pi b\alpha u(\rho_o - \rho_a)$$

where

u = vertical velocity
b = radius of the plume
ρ = density of plume
ρ_a = density of ambient fluid outside plume
ρ_o = initial density of plume
α = constant relating inflow velocity at edge of plume to vertical velocity inside plume

These equations were derived with an assumption that velocity and buoyancy force across the plume were constant. Expressions for velocity and dilution along the jet axis were derived by rearranging the above equations to give

$$u = \frac{5}{6\alpha}\left(\frac{9}{10}\alpha Q\right)^{1/3} x^{-1/3} \tag{2.11}$$

and

$$g\frac{(\rho_o - \rho)}{\rho} = \frac{5Q}{6\alpha}\left(\frac{9}{10}\alpha Q\right)^{1/3} x^{-5/3} \tag{2.12}$$

Where Q=constant

This solution was compared with experimental results and also with results provided by Schmidt (1941) and Rouse et al. (1952) The proportionality constant α was found to have a value of 0.093 and the vertical velocity and concentration distributions were shown to be gaussian and given by

$$u = u_m exp\left[-80(\frac{r}{x})^2\right] \tag{2.13}$$

$$c = c_m exp\left[-80(\frac{r}{x})^2\right] \tag{2.14}$$

Where

u_m = vertical velocity on axis of jet at distance x from origin
c_m = concentration on axis of jet at distance x from origin

$$c_m = \frac{\rho_a - \rho}{\rho_a - \rho_o}$$

u and c are the vertical velocity and concentration at a point distance r from the axis and a distance x from the origin.

Abraham (1963) analyzed jet diffusion in a liquid of greater density and suggested that the factor x in the above equations should be replaced by (x+2d) for a jet of finite initial diameter D and velocity U_o . He also states that the value of Q in both equations is given by

$$Q = \frac{\pi}{4}d^2u_o\frac{(\rho_a - \rho_o)}{\rho_o} \tag{2.15}$$

because the densimetric Froude number is given by

$$F_\Delta = \frac{Q}{\frac{\pi}{4} d^2 \left(g \frac{(\rho_a - \rho_o)}{\rho_o d} \right)^{1/2}} \tag{2.16}$$

Equations 2.11 and 2.12 were rewritten as:-

$$\frac{u_m}{u_o} = 3.65 F_\Delta{}^{-2/3} \left(\frac{x}{d+2} \right)^{-1/3} exp \left[-80 (\frac{r}{x})^2 \right] \tag{2.17}$$

$$\frac{c_m}{c_o} = 9.7 F_\Delta{}^{-2/3} \left(\frac{x}{d+2} \right)^{-5/3} exp \left[-80 (\frac{r}{x})^2 \right] \tag{2.18}$$

Where u_o and c_o are initial velocity and concentration of the jet as it leaves the nozzle.

Velocity and concentration on the axis of the jet can be calculated using equations 2.17 and 2.18 and at any other point on the jet by using equations 2.13 and 2.14.

A recent analysis makes use of the concept of characteristic lengths (Fischer et al., 1979), an approach which seems to be becoming more popular than the traditional dimensional analysis based on the individual variables involved. The basic parameters which determine the flow in a jet or a plume are considered to be the are initial fluxes of volume, momentum and buoyancy represented as $Q, M,$ and$B$ respectively. The distance 'z' along the axis of the jet is included as a basic parameter. For a vertical jet of diameter d discharging with a velocity of w into a receiving fluid with a density difference of $\Delta\rho$, the initial fluxes of volume, momentum and buoyancy

Thus we can write any flow variable (non dimensionalized) as a function of these variables. Hence velocity of the buoyant jet 'w_m' can be written as

$$w_m \frac{Q}{M} = f\left[\frac{M^{1/2}z}{Q}, \frac{M^{3/4}}{B^{1/2}}\right] \tag{2.21}$$

Considering the limiting conditions where flow has both momentum M and buoyancy B, but no initial volume flux Q, the above solution for a round jet would take the form

$$w_m \frac{M^{1/4}}{B^{1/2}} = f\left[\frac{B^{1/2}z}{M^{3/4}}\right] \tag{2.22}$$

Fischer (1979) showed that equation 2.22 could be developed to give

$$w_m \frac{M^{1/4}}{B^{1/2}} \rightarrow c_1 \left[\frac{M^{3/4}}{B^{1/2}z}\right] for \quad z \ll \frac{M^{3/4}}{B^{1/2}} \tag{2.23}$$

and

$$w_m \frac{M^{1/4}}{B^{1/2}} \rightarrow c_2 \left[\frac{M^{3/4}}{B^{1/2}z}\right]^{1/3} for \quad z \gg \frac{M^{3/4}}{B^{1/2}} \tag{2.24}$$

where c_1 and c_2 are emperical constants. The ratio $\left[M^{3/4}/B^{1/2}\right]$ is defined as a charecteristic length l_m. For $z \ll l_m$ the flow is like a jet and for $z \gg l_m$ the flow is like a plume.

The dilution of a vertical buoyant jet (S_o) may be calculated using the dimensionless values (Fischer, et al., 1979) of the volume flux ($\bar{\mu}$) and distance from the jet orifice (ζ) as are given as

$$Q = \frac{\pi}{4} d^2 w \qquad M = \frac{\pi}{4} d^2 w^2 \qquad B = g(\frac{\Delta\rho}{\rho_2})Q$$

where

g = gravitational acceleration
d = diameter of the jet
$\Delta\rho$ = $\rho_2 - \rho_1$
ρ_2 = density of the receiving fluid
ρ_1 = density of the fluid being discharged

Thus the dimensions of Q, B, and M will be

$$[Q] = \frac{L^3}{T}, \quad [M] = \frac{L^4}{T^2}, \quad [B] = \frac{L^4}{T^3}, \quad [z] = L$$

The basic equation of the variables involved in vertical buoyant jet phenomena can then be written as

$$\phi(Q, M, B, z) = 0 \tag{2.19}$$

For the above basic equation the non dimensional equation can be written as

$$\phi\left(\frac{M^{1/2}z}{Q}, \frac{M^{3/4}}{B^{1/2}}\right) = 0 \tag{2.20}$$

The first of these parameters includes momentum and volume flux and is important in the analysis of momentum jets, while the second includes the efffect of buoyancy.

$$S_o = \frac{\mu}{Q} = \bar{\mu}\left(\frac{R_p}{R_o}\right) \tag{2.25}$$

where

R_p = plume Richardson number equal to 0.557
R_o = jet Richardson number for a round jet defined as
= $\left(\frac{\pi}{4}\right)^{1/4}\frac{1}{F_\Delta}$
F_Δ = densimetric Froude number

the dimensionless value of volume flux is given (Fischer et al., 1979) as a function of ζ as

$$\bar{\mu} = \zeta \qquad for \ \ \zeta \ll 1 \tag{2.26}$$

$$\bar{\mu} = \zeta^{5/3} \qquad for \ \ \zeta \gg 1 \tag{2.27}$$

where ζ is given by

$$\zeta = \frac{c_p z}{R_p l_m}$$

c_p = plume coefficient equal to 0.25 (Fischer et al., 1979)
R_p = plume Richardson number equal to 0.557

2.1.4 Two dimensional buoyant jet

A theoretical solution for the case of a two dimensional horizontal buoyant jet in stagnant, homogeneous water has been presented by Abraham (Abraham 1965). This approach assumes that the lateral velocity and buoyancy profiles are approximately gaussian. The similarity profiles for velocity and concentration for horizontal two dimensional buoyant jets were presented as

$$\frac{U_r}{U_o} = e^{-k(r/s)^2} \tag{2.28}$$

$$\frac{C_r}{C_o} = e^{-\mu k(r/s)^2} \tag{2.29}$$

where

U_o = centre line velocity of the jet
U_r = velocity at a distance r from the centre line
C_o = centre line concentration
C_r = concentration at a distance r from the centre line
r = distance measured from the axis of the jet
s = axial distance of the plane from the nozzle
μ, k = dimensionless coefficients

the value of dimensionless coefficients were given by the empirical equations namely

$$k = 32\left(\frac{\beta}{\pi}\right)^3 + 24\left(\frac{\beta}{\pi}\right)^2 + 50 \tag{2.30}$$

$$\mu = -2.4(\frac{\beta}{\pi})^3 - 1.8(\frac{\beta}{\pi})^2 + 0.50$$

where β was defined as the angle the jet axis makes with the horizontal at the required point (Figure 2.2). The theory is based on empirical functions for the spread of mass and momentum where the rate of spread is introduced as a function of the local angle of inclination of the jet trajectory.

The following equations have been solved:
Two momentum flux equations, namely

Horizontal momentum flux;

$$\left(\frac{\pi}{2k}\right)^{1/2} \rho_o {U_r}^2 s cos\beta = \beta \rho_o {U_o}^2$$

Vertical momentum flux;

$$\left(\frac{\pi}{2k}\right)^{1/2} \rho_o {U_r}^2 s sin\beta = M_e sin\beta_e + g \int_{s_e}^{s} (\rho_s - \rho_o) \left(\frac{\pi}{2k}\right)^{1/2} C_r s ds$$

where

s = axial distance of the plane from the nozzle
s_e = length of flow establishment
β_e = β at $s = s_e$
M_e = $\int_A \rho u^2 dA$ at $s = s_e$
M_o = $\int_A \rho u^2 dA$ at $s = 0$
B = depth of the jet

Geometric relations for the jet trajectory, namely

$$\frac{x}{B} = \int_o^{s/B} cos\beta d\frac{s}{B} \; and \; \frac{y}{B} = \int_o^{s/B} cos\beta d\frac{s}{B}$$

Continuity equation, namely

$$\left(\frac{\pi}{k(1+\mu)}\right)^{1/2} U_r C_r s = BU_o C_o$$

A numerical solution to this system of equations was presented based on the Bousinesq approximation, that is, that density differences can be ignored in all terms except the gravity term. A general solution was developed for design purposes and the dilution along the axis of the jet (S_d), was plotted as a function of Froude number (F) and relative depth (y/B) as shown in Figure 2.7.

Improvement of Abraham's theory for diffusion of a two dimensional buoyant jet in uniform and linearly stratified environment was done by Fan and Brooks (1969). The theory was based on the principle of entrainment, first proposed by Morton et al., (1956) which was advocated by Fan and Brooks as more simple and more logical from physical point of view. The equations solved in this theory were Continuity equation, namely

$$\frac{d}{ds}(ub) = 2\alpha u/\sqrt{\pi}$$

Two momentum flux equations

horizontal momentum;

$$\frac{d}{ds}\left(\frac{u^2 b}{\sqrt{2}} cos\theta\right) = 0$$

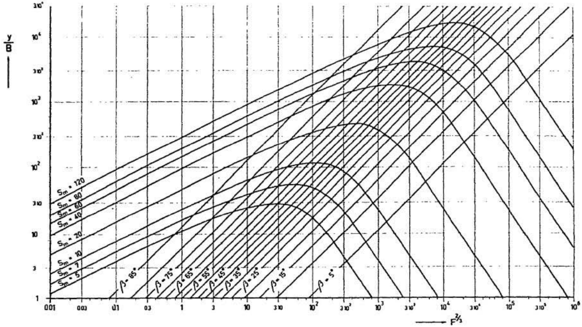


Figure 2.7: General solution for two dimensional buoyant jet Abraham (1965)

vertical momentum ;

$$\frac{d}{ds}\left(\frac{u^2 b}{\sqrt{2}} cos\theta\right) = g\lambda b \frac{\rho_o - \rho}{\rho_o}$$

Geometric relations for the jet trajectory namely

$$\frac{dx}{ds} = cos\theta$$
$$\frac{dy}{ds} = sin\theta$$

Numerical integration was carried out using Runge-kutta-gill method. The centre line dilution for a horizontal buoyant jet was plotted as a function of Froude number and relative depth and is shown in Figure 2.8.

Experiments were conducted by Cederwall (Cederwall ae al., 1971) to verify the above theories of horizontal two dimensional buoyant jet in stagnant environment. The graphical representation of the theoretical centre line dilution and comparison with experimental data is shown in Figure 2.9

2.2 Factors affecting dilution

2.2.1 Effect of current

Any turbulence or disturbance caused in the receiving water will increase the dilution of the ocean outfall. Two different types of approaches, namely mathematical and empirical approaches exist for determining the effect of current on the dilution. Morton et al., (1956) originated the integral momentum technique for single jet

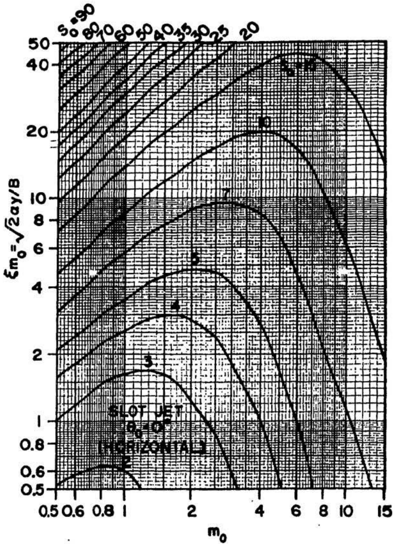


Figure 2.8: Dilution of slot buoyant jets in stagnant uniform environments (Fan and Brooks, 1969)

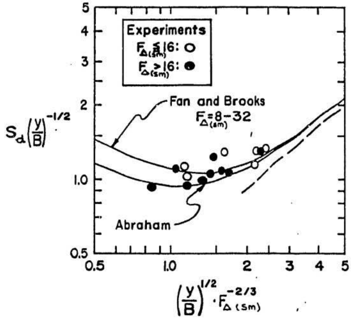


Figure 2.9: Graphical representation of centre-line dilution for two dimensional buoyant jet in stagnant environment and comparison with experimental data (Cederwall, 1971)

discharges. Fan (1967) followed the integral technique devised by Morton et al., (1956) and developed a set of first order differential equations which could be numerically integrated using the Runge-Kutta-Gill method. Assumptions were made that flow was incompressible and turbulent, that the density difference was small and that longitudinal convection was much larger than longitudinal turbulent transport. Velocity profiles were considered to be similar at all cross sections normal to the axis and the entrainment coefficient was assumed constant. Alam et al., (1982) compared three Environmental Protection Agency (EPA) models (PLUME, OUTPLM, and DKHPLM) and models of Fan and Brooks, Abraham and Roberts. He concluded that OUTPLM was of little use, perhaps because it had initially been developed for cooling towers plume analysis. The models developed by Fan and Brooks and PLUME model gave good results for still water while DKHPLM gave consistently lower values than measured in both still and moving water. Results from Abraham's model varied depending on the current magnitude and Robert's model significantly under predicted dilutions.

Using data collected at five marine outfalls around the coast of England, Agg and Wakeford (1972) developed an equation for minimum centre line dilution as

$$S_m/S_o = 7.526(U_a/U_j)^{0.938} \tag{2.31}$$

Where

S_m = minimum centre line dilution at the surface
S_o = still water dilution under identical conditions of depth and density difference
U_a = velocity of ambient current
U_j = velocity of jet at outfall

Based on the studies conducted on the long sea outfall at Hastings on the south coast of England, Bennett (1981, 1983) developed an empirical relationship for the ratio of moving water to still water dilution. He used Cederwall's equation for the still water dilution and presented his correction factor as:-

$$log_{10}CF = 1.554 + 0.684log_{10}U_a - 0.467log_{10}V - 0.297log_{10}Y_o \qquad (2.32)$$

where

S_m = moving water dilution
S_o = still water dilution
CF = correction factor (S_m/S_o) applied to still water dilution
U_a = current velocity
V = velocity of the jet
Y_o = depth of receiving water

He also used linear regression to obtain the measured moving water dilution directly as a function of U_a, Y_o and U_j or Q, the discharge. This gave the equation:-

$$S_m = 55.59({U_a}^{0.682}/{U_j}^{0.955}){Y_o}^{1.183} \qquad (2.33)$$

He recommended this formula in preference of Equation(2.31) for practical design use.

Using the complete data base, comprising both sets of data namely Agg and Wakeford's and Bennett's, an effort was made by Sharp and Moore (Sharp and Moore 1987) to develop a new equation. A number of forms of equations were considered and after some preliminary analysis, they adopted a form based on Cederwall's still-water dilution and presented their equation as:-

$$S_m = S_o + 1.57\left(\frac{U_a}{V}\right)^{0.359} \tag{2.34}$$

where

S_m = moving water dilution
S_o = still water dilution
U_a = current velocity
V = velocity of the jet
Y_o = depth of receiving water

Comparisons of all these different empirical equations were later done and they concluded that best predictions for the set of field data was from Equation (2.34) with Agg and Wakeford's Equation (2.31) providing generally similar results with slightly increased accuracy but decreased precision. they found that Bennet's modified equation significantly less accurate and less precise than either of the others. The updated EPA models namely UOUTPLM, UDKHPLM, UMERGE were chosen for comparison by Sharp and Moore (1989) who concluded that each of the models tended to over predict dilution. They suggested that the increase in dilution due to a current should be looked on as a bonus to improve the performance of the outfall and that designers should not rely entirely on the effect of a current to prove the acceptability of an outfall.

2.2.2 Effect of waves

The effects of waves have received much less attention than those of currents. Some quantitative work has been carried out in order to develop an understanding of the phenomenon and some predictor equations have been developed. Generally wave effects have been shown to depend strongly on the type of the wave, deep water wave effects being significantly different from those of shallow water.

Early studies were done by Shuto and Ti (1974) who developed empirical equations, based on equations previously developed for jets discharged into a cross current and modified on the basis of experiments carried out with small jets discharged under standing waves in a 0.5 m wide wave channel. They found that surface dilution, S_w could be described by

$$S_w = 1.27\frac{\alpha^2}{F}(\frac{H}{D})(\frac{Y_o}{D})^{3/2} \tag{2.35}$$

where

Y_o = depth of discharge
H = wave height
F = discharge Froude number= $U_j/(gD)^{1/2}$
D = diameter of the jet
g = gravitational acceleration
α = entrainment coefficient dependent primarily on wave condition
U_j = velocity of the jet

Ger (1979) proposed a somewhat more complex arrangement identical with a different entrainment coefficient. This equation gave centre line dilutions as a linear function of the horizontal co-ordinate, X,at the point of measurement. Thus,

$$S_w = 1.15[1 + 2.24\alpha\frac{X}{D}] \tag{2.36}$$

where α is given in terms of the wave and jet velocities.

Qualitative experiments were conducted by Sharp (1986) who showed that the jet structure under shallow waves was quite different from that experienced with deep waves. In particular, under shallow wave action the jet broke into two distinct clouds of effluent whereas in deep water waves the structure was somewhat similar to that experienced in still water. This suggested that a single theory could not be valid for all wave types.

Recently Chin (Chin, 1987) used dimensional analysis with a length scale approach based on Fischer's work (Fischer et al., 1979) to identify the relevant length scales. He presented the functional relationship

$$S_w/S = 1 + 6.15(U_{max}/U_j) \tag{2.37}$$

where S_w is the average surface dilution with waves and S is the average surface dilution without waves. U_{max} is the maximum horizontal wave-induced velocity at the discharge point given in terms of the wave parameters; H=wave height, L=wave length, Y_o= depth, T= wave period, g= gravitational acceleration.

$$U_{max} = \frac{gT(H/L)}{2Cosh(\frac{2\pi Y_o}{L})} \tag{2.38}$$

2.3 Methods of increasing dilution

2.3.1 General

To maximise the performance of an ocean outfall, designers pay particular concern to the dilution which will be experienced by the effluent after discharge. The overall dilution depends on the initial mixing that takes place in the rising column of the buoyant jet and the turbulent mixing that takes place when the plume is carried and dispersed by ocean currents. Because adequate initial dilution is so important in the design of a marine outfall various efforts have been made to increase dilution without significantly increasing the cost of the operation. Much attention has been devoted to improving the initial dilution by changing the geometry of the discharging jet.

Rawn et al.,(1960) looked at how dilution could be increased by changing the design parameters and showed the effects of these changes in a simplified version of their dilution chart. This simplified version is shown in Figure 2.10. To alter the dilution it is necessary to change either the relative depth, Y_o/d, or the densimetric Froude number, F_Δ. However, because the density difference at the site is fixed by the site conditions (approximately equal to that between fresh water and sea water), variation in the value of F_Δ can only be achieved by varying the discharge or the outfall diameter. In general, the discharge is fixed, at least to the extent that it is

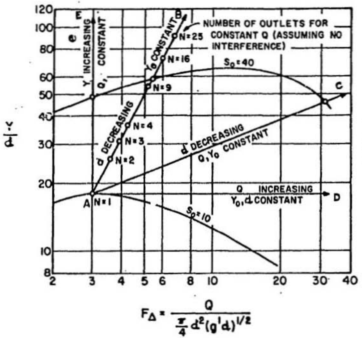


Figure 2.10: Basic methods of increasing the surface dilution of buoyant jet (Rawn et al., 1960)

limited between the lower and upper limits of the discharge flow. However it would be possible to modify the discharge to some extent by discharging at a constant rate over a carefully selected period of time. This would require construction of storage ponds, either to hold back the effluent while the outfall is not discharging or to balance out the flow so that the effluent could be discharged at a constant rate. However this would involve excessive costs in building the storage ponds and the smell nuisance because of the storage. This alternative which is practiced in many places is shown in Figure 2.10 as line AD. Increasing dilution by changing the depth and diameter are limited due to economic considerations. Increased depth can be obtained only by running the outfall further offshore with resulting cost increases due to the extra length of outfall required. Decreasing the diameter increases head losses and results in increased pumping costs. These alternatives are shown as line AE and AC respectively in Figure 2.10.

2.3.2 Multi-port diffusers

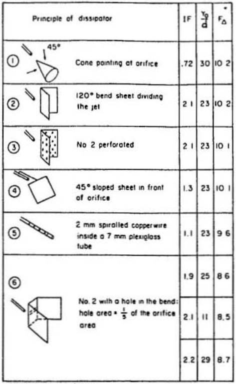
Various methods have been devised to procure higher dilutions than would be obtained by discharging effluent through a single nozzle located at the downstream end of the sewer. The most common approach is to use a multi-port diffuser in which the effluent is discharged through a series of ports located on either side along the length of the diffuser pipe. The holes are placed so that jets discharge horizontally and are separated by distances large enough to ensure that that the jets will not mix with each other. By doing this a simple discharge is converted to a number of separate discharges each at a larger Y_o/d and at a different value of F_Δ The increase in dilution can be seen by the line AB in Figure 2.10. The use of a multiport diffuser is a common approach in large outfalls. Sometimes it is also common to bury the outfall pipe and discharge through ports located on vertical risers. This is particularly true for outfalls designed to cope with large flow rates from cooling water systems of thermal or nuclear power stations.

2.3.3 Baffles

Various attempts have been made to increase dilution by promoting additional turbulence in the jet after the effluent has been discharged. Baffles and other devices to obstruct the flow, or alter the flow pattern, were reported by Hansen (Hansen and Schroder, 1968) and advocated by Snook (Snook, 1969). The devices reported are illustrated in Figure 2.11 together with test details. Among all the devices tested, items 2 and 3, (Figure 2.11) in which the flow is divided into two or more components by placing the obstructions, doubled the level of dilution. Spiral' inserts in the end section of the pipe showed little improvement and increased the head loss in the system. One device tested was actually detrimental and reduced dilution.

2.3.4 Buoyant wall jet

When a buoyant effluent is discharged to the marine environment, it rises and mixes with the receiving fluid due to the formation of turbulent eddies. However, if the jet is discharged very close to horizontal solid boundary, it will be subjected to the coanda effect which causes it to cling to the boundary for some distance before rising. This type of jet is called a buoyant wall jet. A preliminary study of the buoyant wall jet was done by Sharp (1975) and Sharp and Vyas (1977) to measure the increase in dilution achieved when compared to that of a horizontal jet. Experimental work showed that the surface dilution of such a jet was approximately twice that obtained in an equivalent free jet.



Principle of dissipator		IF	y_o/D	$\dot{F}_\Delta$
①	Cone pointing at orifice	.72	30	10.2
②	120° bend sheet dividing the jet	2.1	23	10.2
③	No 2 perforated	2.1	23	10.1
④	45° sloped sheet in front of orifice	1.3	23	10.1
⑤	2 mm spiralled copperwire inside a 7 mm plexiglass tube	1.1	23	9.6
⑥	No. 2 with a hole in the bend: hole area = $\frac{1}{5}$ of the orifice area	1.9	25	8.6
		2.1	11	8.5
		2.2	29	8.7

IF = Improvement factor

Figure 2.11: Improvement Factors of surface dilution using Dissipators (Snook, 1969)

2.4 Methods of pre dilution

2.4.1 Venturi effect

Pre dilution devices operate by disturbing the flow pattern of the jets issuing from the outfall or by drawing receiving water into the pipe thereby diluting the effluent before it is discharged. Most of the ideas presented have not been detailed further than the experimental stages. The earliest and simplest method employed was the venturi principle advocated by Nece (1966). In this method the diameter was restricted over a section of the outfall pipe. Due to the increase in velocity and reduction in pressure at the reduced section the ambient fluid was sucked through the ports located in the conduit wall . Results indicated that the concentration in the outfall pipe was reduced by 50%. No measurements were made for the subsequent dilution between outfall and surface but the general effect of pre-dilution can be estimated from Figure 2.4. A decrease in concentration of 50% implies that the discharge is doubled and that the density difference is halved. This therefore represents an increase(by a factor of $\sqrt{2}$) in the discharge densimetric Froude number. This increase in densimetric Froude number will have relatively little effect but may be detrimental. Thus pre-dilution within the outfall may be, to some extent, offset by a reduction in subsequent dilution between the discharge point and the surface. The device involved substantial head losses and would be probably not be suitable for this reason alone.

2.4.2 Pre-dilution devices

Six possible designs for devices to achieve pre-dilution of sewage before being discharged from a submerged outfall were studied by Agg and White (Agg and White, 1974). Of the methods investigated for inducing mixing and dilution, the most useful was a device with a shape of a truncated cone. Average dilution factors, within the mixing device, were found to be about 11 for low effluent flows and between 4 and 6 at higher discharge rates. An assesment of overall dilution that could be achieved using this mixing device under field conditions was done using the data of. Agg and Wakeford (1972). An overall improvement in dilution of approxomately two was obtained in shallow water, but at larger depths the advantage of the device was less marked.

2.4.3 Mixing tubes

Research on mixing tubes at the University of Western Australia was done by Silvester. Dilutions of more than two were obtained within the mixing tubes (Silvester, 1967) using relatively high velocity jets and with the receiving water at rest. Model tests were also conducted by Silvester and Patarapanich (1972) for the use of jet pumps in ocean outfalls. It was recommended that the length of the mixing tube must be seven times the diameter of the mixing tube and that the discharging nozzle should be placed at least one diameter from the mixing tube. Water was used in the model experiments but, although the results have been interpreted in relation to sewage discharged from submerged outfalls, no account seems to have been taken of the possible effect of density difference on the mixing mechanism.

The maximum overall dilution factor appeared to be less than two although the experimental results for vertical jets suggested that the predictions were conservative. Analytical comparisons were made for outfalls with and without mixing tubes and it was observed that the overall dilution between the outfall jet and the surface was improved by a factor of no more than two.

Only one field installation of a mixing tube has been reported but few details were given (Anon 1966). This device was installed at a small outfall discharging sewage from Surfer's paradise into the Nerang River in south East Queensland and was designed to pre-dilute the effluent by a factor of 2.5 prior to discharge. The system worked satisfactorily, the only disadvantage being a slight increase in head on the discharge pipe.

Laboratory tests were conducted by Argaman (1975) both in uniform and stratified receiving fluids with a mixing tube having the geometry shown in the Figure 2.12.

The purpose of these tests was to measure the the primary dilution achieved within the mixing tube. Based on these experiments a linear relationship was developed to predict the primary dilution achieved in a mixing tube having a circular cross section. This was given as

$$n = K_1 + (D/d)K_2 \tag{2.39}$$

n = primary dilution within the mixing tube
D = diameter of the mixing tube
d = diameter of the nozzle

The non dimensional constants K_1 and K_2 were determined from the experimental results to be 0.8 and 0.7 respectively. The subsequent dilution achieved between

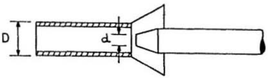


Figure 2.12: Circular mixing tube (Argaman et al., 1975)

the outlet of the mixing tube and the surface was calculated using the Cederwall's equations 2.9 and 2.10. Argaman also combined the equation for initial dilution (Equation 2.39) with the Cederwall's equation (1968) to provide a simplified equation to calculate the overall dilution as :-

$$S_m = 0.54 F_\Delta \left[\frac{(Y_o/d)}{F_\Delta}\right]^{0.437} \left(\frac{K_1 \frac{D}{d} + K_2}{\frac{D}{d}}\right)^{1.845} \quad for \ \frac{Y_o}{dF_\Delta} < 0.5\left(K_1 + K_2 \frac{d}{D}\right)^{1.5} \tag{2.40}$$

$$S_m = 0.54 F_\Delta \left(\frac{K_1 \frac{D}{d} + K_2}{\frac{D}{d}}\right)^{2.5} \left[0.38 \frac{(Y_o/d)}{F_\Delta} \left(\frac{K_1 \frac{D}{d} + K_2}{\frac{D}{d}}\right)^{-1.5} + 0.66\right]^{1.67} \quad for \ \frac{Y_o}{dF_\Delta} > 0.5\left(K_1 + K_2 \frac{d}{D}\right)^{1.5} \tag{2.41}$$

in which S_m = overall dilution obtained with a mixing tube and F_Δ = densimetric Froude number of flow through nozzle. Improvement factors were calculated for

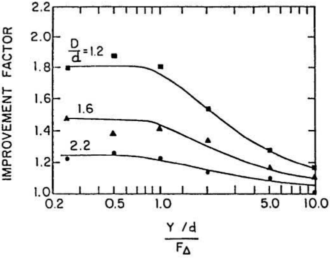


Figure 2.13: Improvement factors for overall dilution using a circular mixing tube (Argaman et al, 1975)

different D/d ratios. Here, the improvement factor (IF) is defined as the ratio of the overall dilution achieved with a mixing tube to the overall dilution achieved without a mixing tube attached under the same experimental or field conditions. The depth parameter $Y/d(F_\Delta)$ and the improvement factor IF were plotted for different D/d ratios (Figure 2.13. The improvement factor increased with the reduction of D/d ratios and depth factor $Y/d(F_\Delta)$.

2.4.4 Limitations of pre-dilution devices and mixing tubes

Experimental studies to improve the overall dilution using pre-dilution devices have been reported. The earlier studies were undertaken by Silvester who did experimental studies on a circular mixing tube. The maximum improvement achieved by his device was again limited to a factor of two. Later studies with different shapes of mixing devices were done by Agg and White (1974) who were able to achieve initial average dilution of 11 within the mixing device but the overall dilution between the discharge nozzle and the water surface was limited to a factor of approximately two. They also found that the overall improvement reduces with the depth of water. Laboratory tests on circular mixing tubes based on Silvester's design was done by Argaman (1975). The effect of mixing tubes on overall dilution was examined by comparing the dilutions obtained by a simple outlet with and without, a mixing tube. From Figure 2.13 it was concluded that the mixing tube improvement factor increases with decrease in the diameter ratio D/d of the mixing tube to the discharging nozzle. They also found that the improvement is greatest as D/d approaches 1.0. The maximum improvement factor that was reported was approximately two.

Reasons for the experimentally observed limitations on the maximum value of Improvement factor were studied theoretically by Sharp (Sharp, 1978). Using equations developed by Albertson et al., (1956) Liseth (1970) and Cederwall (1968) to describe the dilution of jets and plumes, he concluded that the improvement factor due to pre-dilution lies in the range

$$\left(\frac{n}{p}\right)^{0} < IF < \left(\frac{n}{p}\right)^{5/2} \tag{2.42}$$

Where

n = factor by which the effluent is pre-diluted before being discharged from the mixing tube
p = factor by which the diameter increases
IF = improvement factor

This indicated that the pre-dilution device should be operated with as small a value of p as is practically possible. This agreed with the conclusions reported by Argaman et al. (1975) in the experimental studies of mixing tubes. Tables of improvement factors were presented based on the different types of jets (Table 2.1).

This limitation of the improvement factor can be explained using Figure 2.4 which is the relationship between dilution S_o, densimetric Froude number F_Δ, and depth to diameter ratio Y_o/d. Due to the entrainment of the surrounding water into the mixing tube, there is an increase in discharge and a considerable decrease in the density of the mixed fluid. Increase in the diameter of the mixing tube, when compared to the discharging nozzle, combined with the reduction in density difference between the discharge fluid from the mixing tube and the surrounding fluid increases the densimetric Froude number and reduces the depth and diameter ratio. Thus the improvement achieved in the mixing tube is partly lost in the buoyant jet from the mixing tube to the surface thereby limiting the value of improvement factor to a factor between two and three.

The suggestion was then made that future research should be oriented towards devices which change the basic structure of the outfall jet, since the arguments presented in the previous literature suggested that the application of pre-dilution devices which do not radically alter the flow patterns is limited.

$\frac{n}{p}$	$\frac{Y_o/d}{F_\Delta}$	$IF = \frac{C_{m1}}{C_{m2}}$	Comment
2.0	1.0	3.61	Momentum case, F_Δ large, $(n/p)^{5/2} = 5.66$
2.0	10.0	1.49	Intermediate
2.0	20.0	1.26	Intermediate
2.0	100.0	1.05	Buoyancy case, F_Δ small
3.0	10.0	2.24	Intermediate
3.0	20.0	1.62	Intermediate
3.0	100.0	1.12	Buoyancy case, F_Δ small

Type	IF	Comment
Momentum jet $F_\Delta = \infty$	$\frac{n}{p}$	Density difference zero
Buoynat plume $F_\Delta \to 0, Y_o/d \to \infty$	$\left(\frac{n}{p}\right)^0 = 1.0$	Initial velocity approaches zero or very large depth
Buoyant jet $Y_o/d < 0.5F_\Delta$	$\left(\frac{n}{p}\right)^{1.84} = 1.0$	Intermediate case F_Δ large, Y_o/d small
Buoyant jet $Y_o/d > 0.5F_\Delta$	$1.0 < IF < \left(\frac{n}{p}\right)^{5/2}$	Intermediate case, lower limit for buoyancy dominant,upper limit for momentum dominant and $\frac{n}{p} \to \infty$

Table 2.1: Theoretical improvement factors for $Y_o/d < 0.5F_\Delta$ (Sharp, 1978)

Chapter 3

Field Studies of an Existing Ocean Outfall

3.1 Introduction

The Spaniards bay outfall was installed in 1987 by the provincial government of Newfoundland and Labrador to discharge the sewage wastes from the town of Tilton and the town of Spaniards bay. A monitoring study was undertaken by the government (Sharp, 1989) to investigate the performance of the outfall. Part of this investigation involved a dye study to estimate the amount of dilution in the outfall and this was extended to investigate the field performance of cylindrical mixing tubes. The study was done by injecting red dye solution into the sewage at the pumping station and tracing it after it left the outfall nozzles. Samples were collected both at the pumping chamber and at sea. The dilution achieved at the site was then calculated based on the difference in dye concentrations between the samples collected in the pump chamber and those collected at sea. Following initial work to determine the dilution achieved by the outfall as it was designed mixing tubes were installed and the process was repeated to determine the effect of the mixing tubes.

3.2 Spaniards Bay Outfall

3.2.1 Outfall design

Spaniards bay outfall was designed to handle a normal flow rate of 3347 cubic meters per day in 1987 rising to 4426 cubic meters per day in 2006 A.D. The outfall consists of a 200 mm diameter pipe extending 100 meters offshore. Sewage waste is discharged through two nozzles of 100 mm diameter placed in a depth of approximately 5.0 meters of water(Figures 3.1 to 3.3). The outfall was designed for horizontal nozzles, but during installation an error was made and the nozzles were installed vertically.This error was only discovered during the first dye study.

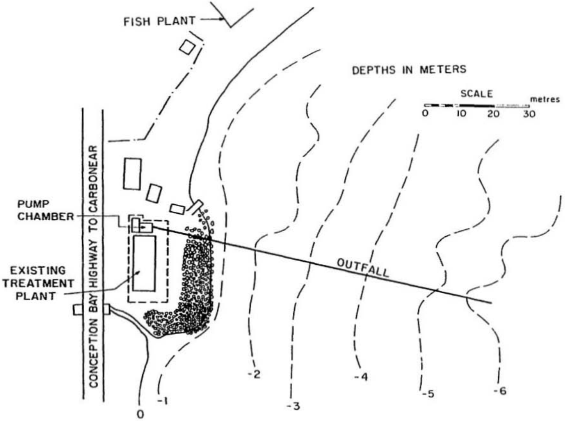


Figure 3.1: Location of Spaniards bay outfall

3.2.2 Pump chamber

Onshore arrangements for discharging the sewage effluent utilize the collecting tank of the existing, no longer useful, treatment plant. From there sewage is led into a pump chamber through a rectangular channel. A right angled V-notch is provided at the end of the channel to facilitate flow measurement. The sump chamber has a uniform rectangular cross-section of 2.6 m x 1.7 m over a distance of 1.4 meters from the top but, below this the cross-section reduces to 1.5 x 1.0 m at the bottom (Figure 3.4). Sewage is pumped into the bay by two pumps located at the bottom of the sump chamber. Grinder pumps were chosen to prevent large solids from being discharged into the bay.

Automatic float operated switches are used to operate the pumps (Figure 3.4). The lowest float 'A' switches off the pumps when the sewage falls to a level close to that at which the pumps would run dry. Float 'B', set at a higher level, switches on the first pump and, if the level continues to rise, the second pump is activated by the third float 'C'. The fourth float 'D', set at the highest level, activates a warning if the level of sewage in the chamber continues to rise when both pumps are in operation. This would provide a signal to the operator warning him about the rising trend and the possibility of pump failure. A switch board is provided outside the pump chamber to allow manual operation of the pumps.

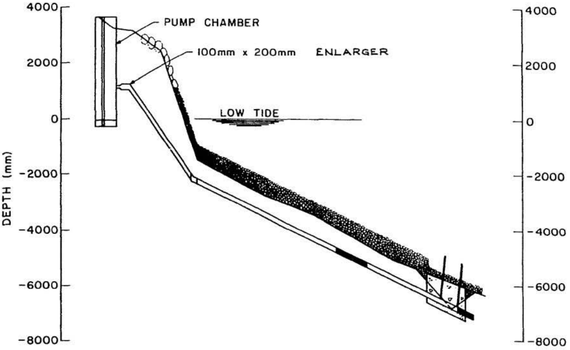


Figure 3.2: Cross section showing the depth of the outfall

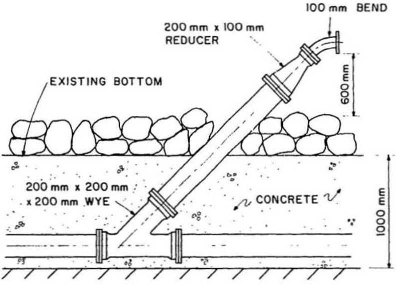


Figure 3.3: Cross section showing the details of the discharging nozzles at the outfall

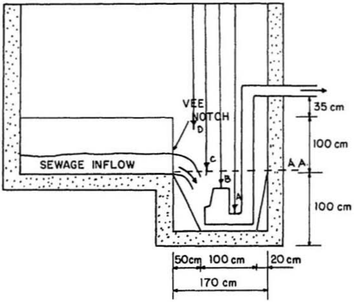


Figure 3.4: Cross section of pump chamber along with automatic float operated switches

3.3 Preliminary preparation for field work

3.3.1 Site visit

Two weeks prior to the study, a visit was made to the outfall site to inspect the pump chamber and to estimate sewage flows. As indicated previously, sewage was led to the pump chamber through a rectangular channel. The channel was provided with a right angled V-notch at its end and a linear scale attached to its side wall. This had been installed for flow measurement but, due to the excessive sediment build up in the channel, the V-notch weir proved ineffective. The flow rate was therefore calculated by inactivating the pumps and measuring the time taken for a known rise in sewage level in the rectangular section of the pump chamber. The rate of inflow was thus found to be approximately equal to 10 litres per second.

3.3.2 Planning of dye study

The main intention of the dye study was to measure the dilution achieved between the discharge nozzle and the sea surface and then to install a mixing tube to measure its performance in the field. Another purpose was to determine the movement of the effluent as it dispersed away from the outfall. It was planned to inject a known concentration of the dye solution to the inlet channel, in order to obtain well mixed, dyed, sewage in the pump chamber. The dyed sewage would be pumped to the sea by inactivating float switches and operating one pump by manual switching. During pumping, samples would be collected from the pump chamber and the sea. These samples would be later measured in the laboratory for dye concentration.

Differences in dye concentrations between the samples collected in the chamber and the sea would then provide the dilution achieved in the outfall.

3.3.3 Selection of dye

It was decided to use Rhodamine-B (m/s Aldrich, USA) as the red dye in powdered form for preparing the dye solution. The main reasons for selecting this dye were that the dye had no deleterious environmental effect (Douglas et al., 1983) and gave a bright red colour when mixed with water, thus making it easy to identify . Other criteria were its cost and easy availability in the market.

3.3.4 Spectrophotometer

Because of accuracy and convenience the decision was made to analyze samples using a spectrophotometer (manufactured by Pye Unicam Ltd., Series S18-100) available in the biochemistry department of Memorial University. A Spectrophotometer is an instrument used to measure the relative concentration of any solution. It works on the principal that the amount of light absorbed is directly proportional to the concentration of the solution. Relative concentration is measured by comparing the amount of light absorbed by the dyed solution and by the basic solution (ie. the liquid in which the dye is to be dissolved). To determine the dye concentration, the dyed solution and the basic solution are placed in the two glass cells of the spectrophotometer. The instrument passes two beams of light through the glass cells and compares the amount of light absorbed by the two solutions. A numerical value is displayed depending on the comparison. The relative dye concentration corresponding to the numerical value is calculated using a calibration chart. Tests undertaken at a variety of concentrations showed that the measurable range of the instrument was between 1 x $10^{-5} g/cm^3$ and 1 x $10^{-8} g/cm^3$ for the dye chosen at a wavelength of 550 nm. with no filters attached.

3.3.5 Preliminary arrangements

Arrangements were made to have fresh water for the preparation of the dye solution available on site by connecting a hose pipe to a fire plug near the outfall. Sample bottles and a sampling device were borrowed from Environment Canada. A boat was hired for the study to collect samples from the sea. Because the red dye would be injected to the bay care was taken to inform the council of Spaniards bay during the week prior to the test to ensure that local residents would not be unduly alarmed.

3.4 First Field Study

3.4.1 Initial preparation

It was decided to do one pumping cycle during a morning session and four cycles during an afternoon session. Throughout the study the float switches were inactivated and pumping was done by manual operation. The duration of each pumping cycle was measured by noting the time taken to fill the pump chamber up to the maximum level 'AA' (Figure 3.4) and also the time to empty it using a single pump. During the morning session, the duration of each cycle was found to be 12 minutes.

The rate of inflow was also measured in order to calculate the rate of dye injection. As mentioned earlier, excessive sediment build up in the inlet channel made the V-notch weir ineffective for measuring the flow rate. The flow rate was therefore calculated by measuring the time taken for a known rise in the level of sewage in the rectangular portion of the pump chamber. The rate of inflow during the morning session was thus found to be 10.62 litres per sec. (Table 3.1). The dye solution was injected into the inlet channel at a constant rate in order to obtain an approximately uniform concentration of dye in the pump chamber. The amount of dye injected to the channel was based on the inflow rate and the expected dye concentration at sea. To ensure that the dye concentration was within the measurable limits of the instrument, it was decided that the expected dye concentration above the outfall should be of the order of 1 x $10^{-6} g/cm^3$. The dilution achieved between the discharge nozzle and the sea surface was expected to be about 30, as given in the design data. The required dye concentration in the pump chamber was then calculated as follows,

Design dilution of the outfall = 30
Expected dye concentration in the sea = 1 x $10^{-6}\ g/cm^3$
Required dye concentration in the chamber = $30(1 \times 10^{-6})$
= 3 x $10^{-5} g/cm^3$

The amount of dye to be added to the channel with a flow rate of 10.62 litre/s (920 cubic meters per day) to get a dye concentration of 3 x $10^{-5} g/cm^3$ in the pump chamber was then calculated, Thus:

$$\begin{aligned}
\text{Rate of inflow in the channel} &= 10.62 \text{ x } 10^3 cm^3/s \\
\text{Expected concentration in the chamber} &= 3 \text{ x } 10^{-5} g/cm^3 \\
\text{Amount of dye to be injected} &= (10.62 \text{ x } 10^3)(3 \text{ x } 10^{-5}) \\
&= 0.32 \text{ g/s}
\end{aligned}$$

3.4.2 Test set up at outfall site

At the outfall site, the experimental arrangements for injecting the dye solution were set up as shown in Figure 3.5. A cylindrical aluminum tank, T , having a diameter of 82 cm and a height of 120 cm was placed on the roof of the pump chamber. A control valve 'A' was provided at the bottom of the tank T . A smaller tank S, with two control valves B and C, was placed immediately above the inlet channel. The two tanks T and S were linked by a hose pipe connecting valves A and B.

3.4.3 Rate of dye injection

It was decided to prepare a dye solution sufficient for three pumping cycles. The duration of each cycle was taken as 12 minutes and the amount of dye required, at a rate of 0.32 g/s, for three pumping cycles was calculated to be 691.2 grams. As mentioned earlier pumps were operated manually and it was necessary to operate the pump once every 12 minutes to stop overflooding. Thus it was decided to have 12 minute cycle for dye injunction and sample collection though it seems a little short for the receiving water to reach steady state conditions. It was found easier to inject a highly concentrated dye solution at a low rate than to inject a low con-

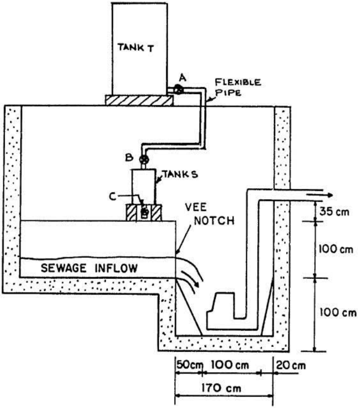


Figure 3.5: Test set-up at the outfall site

centrated dye solution at a higher rate. Hence, it was decided to mix 600 grams of dye with 250 litres of water to achieve a dye concentration of 2.4 x $10^{-3}g/cm^3$. The rate of injection of the dye solution to give a uniform dye concentration of 3 x $10^{-5}g/cm^3$ in the chamber was calculated as follows.

$$\begin{aligned}
\text{Concentration of dye solution} &= 2.4 \times 10^{-3} g/cm^3 \\
\text{Amount of dye to be injected} &= 0.32\ \text{g/s} \\
\text{Rate of inflow of dye solution} &= 0.32/2.4 \times 10^{-3} \\
&= 133.3\ cm^3/s
\end{aligned}$$

3.4.4 Initial adjustment of test set-up

In the test set-up(Figure 3.5, the valve B was used to maintain the level in the small tank S and valve C was used to adjust the rate of dye injection. It was thus necessary to adjust valve C by trial and error to achieve an inflow rate of 134 cm^3/s. Initially, all valves were closed and the tank T was filled with 250 litres of water(48 cm depth of water). Valves A and B were opened fully and the water was allowed to fill the tank S. Valve C was opened when the water level reached the upper mark SS of the tank S. The water level in the tank S was maintained at SS by adjusting valve B. This provided a fairly constant head and hence an approximately uniform flow of dye. Using a measuring jar and stop watch, valve C was then adjusted to discharge at an approximate rate of 134 cm^3/s. The number of turns required to close the valve C was noted. Valve A was closed, valve C was opened and the water was emptied from the set-up.

3.4.5 Preparation of dye solution

All the valves A,B and C were closed and the dye solution was prepared in the aluminium tank by mixing 600 grams of Rhodamine-B with 250 litres of water(48 cm depth of water). Valves A and B were opened fully and the small tank was allowed to fill. When the level of the dye solution reached the upper mark SS, valve B was closed.

3.4.6 Pumping cycle

Five men participated in the dye study. One person was stationed at the switch board to operate the pumps and to signal the men in the boat to notify them regarding starting and stopping the pumping operation. Two men were stationed on the boat to collect samples at the sea, during pumping. The collection of dye samples from the pump chamber and the maintenance of an approximately constant level in the tank S was done by two men stationed near the inlet channel.

The test was started by emptying the pump chamber until the level of sewage dropped to the lowest level where the pump would run dry. At this instant valve C was given the known number of turns to achieve a rate of injection of approximately 134 cm^3/s and valve B was opened and controlled to maintain a constant head at level SS. Dyed sewage was allowed to fill the chamber and once the level reached the upper mark AA, (see Figure 3.4) one pump was switched-on. Samples were not collected during the first pump out, due to a storage of 3140 litres in the 100 m long, 200 mm diameter outfall pipe. Pumping was stopped when the level fell down to the lowest level where the pumps would run dry. During the second pumping cycle, two samples were collected from the pump chamber, one before pumping and another midway through pumping. These samples were necessary to permit accurate measurement of dye concentration in the sump chamber. Five samples at the boil above the outfall were collected at intervals of approximately 25 seconds. Efforts were made to collect samples from the centre of the boil, but this was not always possible because of the difficulty, partly due to wind, in stationing the boat accurately. Throughout the sampling period measurements were made for the time of rise and fall of sewage level in the rectangular part of the sump chamber. These measurements were used to determine inflow and outflow rates.

Testing was resumed in the afternoon with the same procedure. It was decided to run four test pumping cycles in addition to the first pumping cycle required to fill the outfall pipe. During the afternoon session the rate of inflow of sewage was found to be 8.2 litre/sec. It was decided to prepare a dye solution by mixing 1 Kg of dye in 500 litres of water. The resulting solution, therefore, would have a dye concentration of 2×10^{-3} g/cm^3. The rate of injection was calculated as before and was equal to 123 cm^3/s. Initial adjustments were made and the number of turns that had to be given to valve C to achieve a flow rate of approximately of 123 cm^3/s was noted. The dyed sewage was pumped out four times following the first pump out to fill the pipe. During each pumping cycle, two samples were collected from the chamber and five samples from the sea. The samples were collected in the same sequence as in the morning session.

3.5 Analysis of samples

The collected samples were analyzed in the spectrophotometer previously mentioned. It was, however, first necessary to prepare a calibration chart to interpret the numerical values given by the spectrophotometer in order to determine the concentration of the samples. To prepare the calibration chart. a dye solution was prepared by mixing 5 mg of Rhodamine-B with 200 ml of distilled water. The resulting dye solution had a concentration of 2.5 x 10^{-5} g/cm^3. Initial adjustments were made as given in the users manual of the instrument. A wavelength plot was run to determine the wave length at which the test had to be conducted. Procedures listed in the users manual of the spectrophotometer were followed to run the plot for the dye used in the study and the instrument was adjusted corresponding to the peak value of the wave length plot. The prepared dye solution was tested for dye concentration and the numerical value displayed by the instrument was noted. This numerical value therefore corresponded to the dye concentration of 2.5 x 10^{-5} g/cm^3. Calibration was continued by reducing the dye concentration of the prepared solution by 50% and again noting down the numerical value displayed by the instrument. This procedure was continued and the numerical values corresponding to different dye concentrations were noted. Distilled water was used to dilute the sample to acheive different dye concentrations. The calibration chart which correlates the numerical value, displayed by the instrument with the dye concentration of samples was then prepared (Table 3.2, Figure 3.6). It was found that the calibration curve was linear to a concentration of 1.5 x 10^{-5} g/cm^3 and was nonlinear beyond that. Since, the concentrations to be measured were always less than 1.5 x

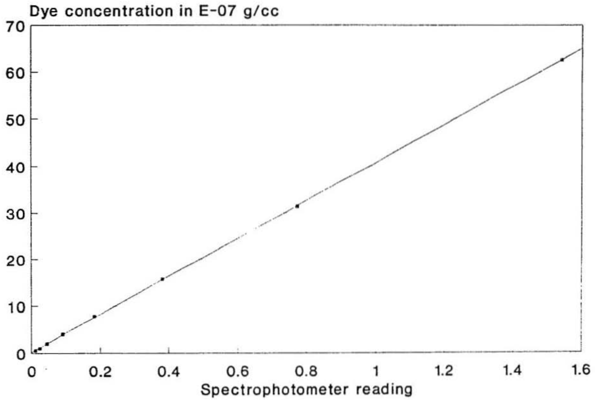


Figure 3.6: Calibration chart of spectro photometer used during first and second field studies

$10^{-5}\ g/cm^3$ the calibration curve was taken as linear throughout the relevant range.

Samples collected at sea were first analyzed. These were highly diluted and, as expected, the dye concentration of the samples fell within the measurable range of the instrument. (Measured concentration ranged from 2.1×10^{-7} to 14.1×10^{-7} g/cm^3. -see Table 3.3)

The numerical values displayed by the instrument for different samples were recorded and dye concentrations were calculated using the calibration chart. Due to the linearity of the calibration chart over the relevant range, the readings could be interpolated to calculate the dye concentration of the field samples. However, the samples collected in the pump chamber were much more concentrated than those collected in the sea. These were therefore diluted by a known quantity of water before the analysis. The dilution was done by mixing 5 ml of the sample with 20 ml of sea water. This reduced the dye concentration of the samples by a factor of five. These diluted samples were then tested and the numerical values were recorded. The dye concentrations calculated by these readings were multiplied by 5 to get the actual dye concentration in the pump chamber. To check the accuracy of the calculated dye concentration, 5 ml of the diluted samples were again diluted by adding 20 ml of sea water. This reduced the original dye concentration by 25 times. These, double, diluted samples were again tested and the resulting dye concentrations were multiplied by 25 to obtain the actual dye concentrations in the pump chamber. The results of this analysis are shown in Tables 3.3 and 3.4. Dilution achieved at the outfall was calculated by taking the ratio of dye concentration in the pumping chamber and dye concentration in the sea. The results are shown in Table 3.5.

The measured dilution varied between 18 and 50 for the set of samples collected at sea. Average dilution was calculated for each test and the variation was between 19 and 33, except for the dilution obtained during the afternoon test number 2 which showed a very high dilution of 42. Experimental scatter was considered to be due primarily to the difficulty in collecting samples exactly at the boil.

These values were of the same order as the dilution (namely 30) which had been predicted during the design of the outfall. However, the outfall had been designed for horizontal nozzles, whereas vertical nozzles had been installed in error. Also conditions experienced during the field study (eg. flow rates, depth, etc.) were not identical to those of the design data. In order to clarify the situation therefore theoretical calculations were performed using the actual values of field data recorded during the study.

3.6 Theoretical verification

The ocean outfall at Spaniards bay was designed for horizontal nozzles but, during installation, an error was made and the nozzles were installed vertically. Dilution achieved by a vertical buoyant jet placed at a depth z meters below the surface of the water was given earlier (Fischer, 1979) in equation (2.25) and is reproduced here as :-

$$S_o = \frac{\mu}{Q} = \bar{\mu}\left(\frac{R_p}{R_o}\right) \tag{3.1}$$

Where,

S_o = dilution achieved
Q = rate of Discharge through each nozzle
μ = dimensionless value of volume flux
R_o = Richardson number
R_p = Richardson number for simple plume,shown (Fischer, 1979) to be 0.557

The Richardson number R_o is dependent on the densimetric Froude number and is given by

$$R_o == \left(\frac{\pi}{4}\right)^{1/4} \frac{1}{F_\Delta}$$

Where,

F_Δ = densimetric Froude number
= $Q/\sqrt{g\frac{\Delta\rho}{\rho}d^5}$
d = diameter of the nozzle
g = gravitational acceleration
$\Delta\rho$ = difference in density of discharging and receiving water
ρ = density of receiving water

The dimensionless value of volume flux $\bar{\mu}$, is dependent on ζ, which is the ratio of dimensionless value of distance, defined as,

$$\zeta = \frac{c_p z}{R_p l_m} = c_p \frac{z}{l_Q} \left(\frac{R_o}{R_p}\right)$$

Where,

z = depth of the receiving water
c_p = plume coefficient equal to 0.25 (Fischer, 1979)
l_m = characteristic length of plume defined as l_Q / R_o
l_Q = characteristic length of the jet
= $\sqrt{\pi/4}(\mathrm{D})$
d = diameter of the nozzle

The non dimensional volume flux is represented as a function of ζ and is given as

$$\hat{\mu} = \zeta \qquad for \quad \zeta < 1 \tag{3.2}$$

or

$$\hat{\mu} = \zeta^{5/3} \qquad for \quad \zeta > 1 \tag{3.3}$$

Receiving water depths were calculated using the tide tables provided by Environment Canada. The depth of the outfall nozzle was measured and was found to be approximately 4.5 meters below the mean sea level (MSL). The tide level for the morning test on October 9, 1988 was 0.71 m above MSL and during the afternoon session it was 0.93 m above MSL. Thus the depth of receiving water for the morning session was 5.21 m and for the afternoon session was 5.43 m. As mentioned earlier the rate of inflow of sewage into the chamber was calculated by measuring the time taken to fill a known height of the sump chamber. The discharge velocity of the nozzle was calculated by measuring the total volume discharged during the pumping session. This, in turn, was determined by measuring the time taken to pump-out a known depth of sewage in the rectangular portion of the pump chamber (column 6 of Table 3.6)and adding the volume of sewage added by inflow during the pumping session(column 10 of Table 3.6). This total volume was divided by the duration of pumping to get the total discharge. This total discharge was divided by two due to the presence of two discharge nozzles.

Using equation 3.1 the theoretical dilutions for the vertical nozzle were calculated and are shown in Table 3.7. Theoretical dilutions for the flow conditions at site vary between about 27 and 33. This theoretical dilution is in reasonable agreement with the measured dilution, which varies between 19 and 33, except for the dilution measured during the afternoon test number 2. It is considered that this high value was probably caused by sampling at a point not quite at the centre of the boil.

3.7 Second field study

3.7.1 Initial preparation

As mentioned earlier, an error was made during installation of the outfall and the nozzles were originally fixed to discharge vertically instead of horizontally. This error was rectified after the first study by replacing the vertical nozzles by horizontal nozzles and the dye study was again done following the same procedure as before. This second dye study was necessary in order to obtain data on horizontal discharge before installing the mixing tubes. With the past experience the study was well organised and seven pumping cycles were done. Two cycles were done in the morning session and five cycles during the afternoon session.

The inflow rate of sewage was calculated as before, by measuring the time taken to fill a known height of the pumping chamber. During the morning session it was found to be 6.75 litre/s. As in the previous study (Section 3.4.1) the required dye concentration in the pump chamber, to get a dye concentration of 1 x10^{-6} g/cm^3 in the ocean, was calculated to be 3 x 10^{-5} g/cm^3.

The amount of dye to be added to the channel, with a flow rate of 6.75 litre/s, to achieve a dye concentration of 3 x 10^{-5} g/cm^3 in the pump chamber was then calculated as

Trial Number	cross Area of the pump chamber in m^2	Sewage level measurements				Rate of inflow Q Litres/sec	Rate of inflow Q m^3/day
		Initial depth in m.	Final depth in m.	Rise in level in m.	Time taken in sec.		
Morning Trial 1	4.4	1.40	0.97	0.43	179	10.60	915.84
Morning Trial 2	4.4	1.40	0.97	0.43	178	10.63	918.43
Afternoon Trial 1	4.4	1.40	0.97	0.43	228	8.30	717.12
Afternoon Trial 2	4.4	1.32	0.97	0.35	193	8.00	691.20

Table 3.1: Inflow rate of sewage into the pumping chamber

Vol. of previous dye solution in cc.	Vol of water to be added in cc.	concentration of dye solution in gram/cc.	Number on spectrophotometer
50	50	$2.50x10^{-5}$	8.000
50	50	$1.25x10^{-5}$	2.970
50	50	$6.25x10^{-6}$	1.540
50	50	$3.125x10^{-6}$	0.773
50	50	$1.56x10^{-6}$	0.381
50	50	$7.81x10^{-7}$	0.183
50	50	$3.90x10^{-7}$	0.091
50	50	$1.95x10^{-7}$	0.045
50	50	$9.75x10^{-8}$	0.025
50	50	$4.87x10^{-8}$	0.012

Table 3.2: Calibration table of spectro-photometer used during first and second field studies

Test Number	Sample Number	Number on Spectro-photometer	Concentration of Dye in gram/cc 1 x 10^{-7}
Morning Test 1	1	0.161	6.87
	2	0.212	8.93
	3	0.217	9.13
	4	0.342	14.06
	5	0.271	11.26
Afternoon Test 1	1	0.197	8.36
	2	0.238	9.95
	3	0.172	7.34
	4	0.147	6.28
Afternoon Test 2	1	0.132	5.64
	2	0.272	11.30
	3	0.112	4.90
	4	0.112	4.90
Afternoon Test 3	1	0.237	9.92
	2	0.343	14.10
	3	0.138	5.90
	4	0.175	7.47
	5	0.292	12.10
Afternoon Test 4	1	0.201	8.50
	2	0.232	9.72
	3	0.153	6.54
	4	0.298	12.3
	5	0.213	8.97

Table 3.3: Analysis of samples collected at the sea during the first field study

Test Number	Sample Number	Volume of Dye solution in cc.	Volume of water added in cc.	Reading on spectrophotmeter	Concentration of the dye 1×10^{-6} gram/cc.	Actual concentration of the sample 1×10^{-5} gram/cc.	Average Concentration of the sample 1×10^{-5} gram/cc.
1	2	3	4	5	6	7	8
Morning Test 1	1(a)	2.5	10	1.495	6.06	3.03	3.03
	1(b)	2.5	10	0.293	1.21	3.03	
	2(a)	2.5	10	1.244	5.04	2.52	2.55
	2(b)	2.5	10	0.246	1.02	2.55	
Afternoon Test 1	1(a)	2.5	10	1.272	5.16	2.58	2.62
	1(b)	2.5	10	0.255	1.06	2.65	
	2(a)	2.5	10	1.250	5.06	2.53	2.54
	2(b)	2.5	10	0.244	1.02	2.55	
Afternoon Test 2	1(a)	2.5	10	1.226	4.97	2.48	2.50
	1(b)	2.5	10	0.242	1.01	2.52	
	2(a)	2.5	10	1.223	4.96	2.48	2.48
	2(b)	2.5	10	0.237	0.99	2.48	
Afternoon Test 3	1(a)	2.5	10	1.058	4.28	2.14	2.16
	1(b)	2.5	10	0.207	0.87	2.18	
	2(a)	2.5	10	1.103	4.46	2.23	2.3
	2(b)	2.5	10	0.219	0.92	2.30	
Afternoon Test 4	1(a)	2.5	10	0.846	3.42	1.71	1.75
	1(b)	2.5	10	0.167	0.71	1.78	
	2(a)	2.5	10	0.821	3.32	1.66	1.63
	2(b)	2.5	10	0.152	0.64	1.60	

In column 7, the concentration of sample (a) shown in column 6 is multiplied by five and sample (b) is multiplied by twenty five, to get the concentration of the original sample. Column 8 is the average concentration of (a) and (b).

Table 3.4: Analysis of samples collected at the pump chamber during first field study

Test Number	Pump chamber reading for inflow		Volume of water in m^3	Rate of inflow in m^3/sec 1×10^{-3}	Pump chamber reading for outflow		Volume of water in m^3	Extra volume due to inflow in m^3	Total volume of outflow in m^3	Rate of outflow in the outfall in m^3/sec. 1×10^{-2}	Rate of outflow in each nozzle in LPS
	time in sec.	depth in m.			time in sec.	depth in m.					
Morning Test 1	228	0.432	1.90	8.34	125	0.432	1.90	1.04	2.94	2.35	11.77
Afternoon Test 1	193	0.432	1.90	9.85	133	0.432	1.90	1.31	3.21	2.41	12.07
Afternoon Test 2	179	0.432	1.90	10.62	185	0.432	1.90	1.96	3.86	2.09	10.45

Cross sectional area of the pumpchamber = $2.59 \times 1.70 = 4.4\ m^2$

Cross sectional area of the nozzle = $7.85 \times 10^{-3} m^2$

Table 3.6: Calculation of Inflow rate and Outflow rate of the outfall during first field study

Test Number	Dye concentration in the chamber 1×10^{-5} gram/cc.	Dye concentration in the sea 1×10^{-7} gram/cc.	Dilution achieved	Average dilution/ Standard deviation
Morning Test 1		6.87	44.10	29.87/ 9.04
	3.03	8.93	33.93	
		9.13	30.56	
	2.55	14.06	18.14	
		11.26	22.64	
Afternoon Test 1	2.62	8.36	31.34	33.08/ 7.14
		9.95	25.93	
	2.54	7.34	34.60	
		6.28	40.45	
Afternoon Test 2		5.64	44.30	41.91/ 11.71
	2.50	11.3	22.12	
	2.48	4.90	50.61	
		4.90	50.61	
Afternoon Test 3		9.92	21.77	24.93/ 8.21
	2.16	14.1	15.32	
		5.90	37.79	
	2.30	7.47	30.79	
		12.1	19.00	
Afternoon Test 4		8.50	20.58	19.17/ 4.10
	1.75	9.72	18.00	
		6.54	25.84	
	1.63	12.3	13.25	
		8.97	18.17	

Table 3.5: Measured dilution during first field study

Depth in m.	Q in litres/sec.	V in m/sec	F_Δ	μ	ζ	S_o
5.05	11.77	1.50	9.18	2.62	5.01	27.19
5.43	12.07	1.54	9.41	2.75	5.42	30.18
5.43	10.44	1.33	8.15	3.18	6.90	33.25

Depth = Depth of receiving water in meters
Q = Rate of discharge from the nozzle in LPS
V = Velocity of the jet in meter/sec.
F_Δ = Densimetric Froude number of the jet
S_o = Overall theoretical dilution
μ = Dimensionless value of distance
ζ = Dimensionless value of volume flux

Table 3.7: Calculated theoretical dilution for the vertical nozzle installed at the outfall during first field study

Rate of inflow in the channel = $6.75 \times 10^3\ cm^3/s$
Expected concentration in the chamber = $3 \times 10^{-5}\ g/cm^3$
Amount of dye to be injected = $(6.75 \times 10^3)(3 \times 10^{-5})$ During the
= 0.21 gram/sec

morning session, it was planned to run two pumping cycles in addition to the first cycle to fill the outfall pipe. Hence, it was decided to mix 500 grams of Rhodamine B with 250 litres of water(48 cm depth of water) to achieve a dye concentration of $2.0 \times 10^{-3}\ g/cm^3$. The rate of injection of the dye solution into the channel so as to result in a uniform dye concentration of $3 \times 10^{-5}\ g/cm^3$ in the chamber was calculated as

Concentration of dye solution = $2.0 \times 10^{-3}\ g/cm^3$
Amount of dye to be injected = 0.21 gram/sec
Rate of inflow of dye solution = $0.21/2.0 \times 10^{-3}$
= $105\ cm^3/s$

The same experimental set-up, explained in Section 3.4.2, was used during this study. Initial adjustments were done as explained in Section 3.4.4 and the system was adjusted to deliver a flow rate of 105 cm^3/s The dye solution was prepared as explained in Section 3.4.5.

3.7.2 Pumping cycle

Six people participated in the study . All were stationed in the same manner as in the previous study except that three people were present on the boat instead of two. The same procedures were followed to run the tests. Float switches were inactivated and the pumps were operated with manual control. However, to vary the flow rate, single and double pumps were used in alternating cycles to pump-out the sewage from the chamber. The rate of inflow as well as outflow was measured by recording the time taken respectively to fill and empty a known height of the pump chamber. During this study, the pumping cycle was stopped when the level in the pumping chamber reached the lower point of the rectangular portion instead of emptying the chamber as done in the previous study. This reduced the pumping duration and saved the dye solution to run more cycles. Two cycles were run in addition to the first cycle to fill the outfall pipe. Three samples were collected in the pump chamber at equal intervals and six samples were collected at the boil above the outfall in the sea during each cycle.

Testing was resumed in the afternoon with the same procedure. It was decided to mix one kilogram of dye with 500 litres of water to get a dye solution having a concentration of 2x 10^{-3} g/cm^3. The rate of injection of this dye solution into the channel, was calculated as 97 cm^3/s to give a uniform concentration of 3 x 10^{-5} g/cm^3. in the chamber. Preliminary adjustments were made as in the previous session and five cycles were run in addition to the first cycle to fill the outfall pipe. Three samples were collected from the chamber and six samples were collected above the boil at the outfall in the sea during each cycle.

The analysis of the samples was done as explained in Section 3.5. The same spectrophotometer used for the previous study was used to do the laboratory analysis. Results are tabulated in Tables 3.8 to 3.13. Tables 3.8 to 3.13 give details of the measured dilutions. Due to the difficulty of stationing the boat exactly over the boil there was a considerable variation in the measured dilution at the sea. Average dilution for each test was calculated and was found to vary from a minimum of 32 to a maximum of 40 throughout the whole study. For comparative purposes, the dilutions for horizontal nozzles for the existing field conditions during the study were calculated based on the theory developed for horizontal buoyant jets.

3.7.3 Theoretical verification

The theoretical dilution for a horizontal buoyant jet was calculated using Cederwall's (Cederwall, 1968) equations which are again reproduced here for completeness.

$$S_o = 0.54F_\Delta \left[\frac{(Y_o/d)}{F_\Delta}\right]^{7/16} \qquad for \;\; Y_o/d < 0.5F_\Delta \tag{3.4}$$

$$S_o = 0.54F_\Delta \left[0.38\frac{(Y_o/d)}{F_\Delta} + 0.66\right]^{5/3} \qquad for \;\; Y_o/d > 0.5F_\Delta \tag{3.5}$$

Where,
Q = discharge through each nozzle
Y_o = depth of receiving water
F_Δ = densimetric Froude number
= $Q/\frac{\pi}{4}\sqrt{g\frac{\Delta\rho}{\rho}D^5}$
d = diameter of the nozzle
g = gravitational acceleration
$\Delta\rho$ = difference in density of discharging and receiving water
ρ = density of receiving water

Receiving water depths were calculated using the tide tables provided by Environment Canada. The tide level during the morning session on June 28, 1989 was 0.85 meters and during the afternoon session was 0.93 meters above MSL. Thus the depth of water during the morning tests was 5.35 m and during afternoon was 5.43 m. Discharge rates were calculated as before (Section 3.6) and are tabulated in Table 3.14. Calculated dilutions for the horizontal buoyant jet were based on equations 3.4 and 3.5 and are given in Table 3.15. This shows that the theoretical dilution for a horizontal buoyant jet for the existing field conditions varied between 36 and 39 except for the low value of 28.9 associated with the larger Froude number obtained with both pumps in action. It is thus clear that the measured dilution shown in Tables 3.12 and 3.13 with a variation of average dilution between 32 and 40 is in reasonable agreement with the theoretical dilution varying between 36 and 39 as shown in Table 3.15. As mentioned in section 3.6 the measured dilution for a vertical nozzle varies between 19 and 33. These values are smaller than those obtained for horizontal jet and a small improvement in measured dilution can thus be seen for a horizontal nozzle. This was as expected.

3.8 Field study of mixing tubes

3.8.1 Design of mixing tubes

The third field study was done at the same site to test the performance of the circular mixing tubes. Two circular mixing tubes were designed based on the design criteria of Argaman (1975). As mentioned in section 3.2.1, the outfall consists of two nozzles of 100 mm in diameter for discharging the sewage at a depth of 4.5 m below mean sea level. Based on the design criteria of Argaman(1975) the best size of mixing tube for the existing 100 mm nozzles was considered to be a 125 mm (5 inches) diameter tube. This would provide a maximum feasible improvement factor of 1.25 when compared to a horizontal nozzle without a mixing tube attached (see equations 2.6 and 2.7). However 125 mm diameter tube was unavailable locally and 150 mm (6 inches) diameter tube was used instead. This would give a lower improvement factor of 1.1. Nevertheless, the main purpose of the study was to check the validity of the theory in the field and a 150 mm (6 inches) diameter pipe was acceptable for the purpose. Details of the mixing tube are shown in Figure 3.7.

It was decided to use PVC pipe instead of cast iron pipe in order to reduce the overall weight. These mixing tubes were supported with a framework (Figure 3.7) to place them in position. A flange was provided at one end of the tube to attach to the existing nozzle and a metal grid was fixed to the bottom of the framework in order to place rocks which would prevent movement. The actual mixing tube installed at the site is shown in the Figure 3.8.

Test Number	Sample Number	Number on Spectro-photometer	Concentration of Dye in gram/cc 1×10^{-7}
Morning Test 1	1	0.121	5.18
	2	0.228	9.57
	3	0.213	8.97
	4	0.180	7.68
	5	0.168	7.17
	6	0.168	7.17
Morning Test 2	1	0.241	10.00
	2	0.202	8.54
	3	0.118	5.05
	4	0.104	4.46
	5	0.178	7.59
Afternoon Test 1	1	0.131	5.60
	2	0.116	4.90
	3	0.172	7.34
	4	0.194	8.22
	5	0.221	9.28
Afternoon Test 2	1	0.197	8.34
	2	0.218	9.18
	3	0.164	7.00
	4	0.143	6.11

Table 3.8: Analysis of samples collected at the sea during the second field study

Test Number	Sample Number	Number on Spectro-photometer	Concentration of Dye in gram/cc 1×10^{-7}
Afternoon Test 3	1	0.206	8.69
	2	0.128	5.48
	3	0.156	6.67
	4	0.131	5.61
	5	0.213	8.97
Afternoon Test 4	1	0.193	8.18
	2	0.231	9.68
	3	0.256	10.67
	4	0.192	8.15
	5	0.176	7.51
Afternoon Test 5	1	0.141	6.03
	2	0.194	8.22
	3	0.114	4.89
	4	0.193	8.18
	5	0.130	5.56

Table 3.9: Analysis of samples collected at the sea during the second field study

Test Number	Sample Number	Volume of Dye solution in cc.	Volume of water added in cc.	Reading on spectro-photmeter	Concentration of the dye 1×10^{-6} gram/cc.	Actual concentration of the sample 1×10^{-5} gram/cc.	Average Concentration of the sample 1×10^{-5} gram/cc.
1	2	3	4	5	6	7	8
Morning Test 1	1(a)	2.5	10	1.204	4.88	2.24	2.51
	1(b)	2.5	10	0.269	1.11	2.77	
	2(a)	2.5	10	1.211	4.91	2.45	2.69
	2(b)	2.5	10	0.281	1.17	2.93	
	3(a)	2.5	10	1.372	5.57	2.78	3.15
	3(b)	2.5	10	0.342	1.41	3.53	
Morning Test 2	1(a)	2.5	10	1.045	4.23	2.12	2.17
	1(b)	2.5	10	0.211	0.89	2.22	
	2(a)	2.5	10	1 003	4.06	2.03	2.06
	2(b)	2.5	10	0.198	0.84	2.09	
	3(a)	2.5	10	0.953	3.86	1.93	1.96
	3(b)	2.5	10	0.189	0.80	2.00	
Afternoon Test 1	1(a)	2.5	10	1.256	5.09	2.54	2.65
	1(b)	2.5	10	0.267	1.11	2.77	
	2(a)	2.5	10	1.329	5.39	2.69	2.74
	2(b)	2.5	10	0.227	1.12	2.79	
	3(a)	2.5	10	1.306	5.30	2.65	2.77
	3(b)	2.5	10	0.279	1.16	2.89	
Afternoon Test 2	1(a)	2.5	10	1.290	5.23	2.61	2.64
	1(b)	2.5	10	0.257	1.07	2.67	
	2(a)	2.5	10	1.252	5.08	2.53	2.61
	2(b)	2.5	10	0.259	1.08	2.69	
	3(a)	2.5	10	1.352	5.48	2.74	2.67
	3(b)	2.5	10	0.250	1.04	2.61	

Table 3.10: Analysis of samples collected at the pump chamber during second field study

Test Number	Sample Number	Volume of Dye solution in cc.	Volume of water added in cc.	Reading on spectro-photmeter	Concen-tration of the dye 1×10^{-6} gram/cc.	Actual concen-tration of the sample 1×10^{-5} gram/cc.	Average Concen-tration of the sample 1×10^{-5} gram/cc.
1	2	3	4	5	6	7	8
Afternoon Test 3	1(a)	2.5	10	1.186	4.81	2.4	2.51
	1(b)	2.5	10	0.251	1.05	2.61	
	2(a)	2.5	10	1.252	5.07	2.54	2.59
	2(b)	2.5	10	0.255	1.07	2.65	
	3(a)	2.5	10	1.352	5.48	2.74	2.83
	3(b)	2.5	10	0.280	1.16	2.91	
Afternoon Test 4	1(a)	2.5	10	1.273	5.16	2.58	2.66
	1(b)	2.5	10	0.265	1.10	2.75	
	2(a)	2.5	10	1.451	5.88	2.94	3.00
	2(b)	2.5	10	0.297	1.23	3.07	
	3(a)	2.5	10	1.402	5.69	2.84	2.91
	3(b)	2.5	10	0.287	1.19	2.97	
Afternoon Test 5	1(a)	2.5	10	0.934	3.78	1.89	1.96
	1(b)	2.5	10	0.192	0.81	2.03	
	2(a)	2.5	10	0.970	3.93	1.97	2.02
	2(b)	2.5	10	0.195	0.83	2.06	
	3(a)	2.5	10	1.040	4.21	2.10	2.15
	3(b)	2.5	10	0.208	0.88	2.19	

In column 7, the concentration of sample (a) shown in column 6 is multiplied by five and sample (b) is multiplied by twenty five, to get the concentration of the original sample. Column 8 is the average concentration of (a) and (b).

Table 3.11: Analysis of samples collected at the pump chamber during second field study

Test Number	Dye concentration in the chamber 1 x 10^{-5} gram/cc.	Dye concentration in the sea 1 x 10^{-7} gram/cc.	Dilution achieved	Average dilution/ Standard deviation
Morning Test 1		5.18	48.45	37.92/ 8.07
	2.51	9.57	26.25	
		8.97	29.98	
	2.69	7.68	35.02	
		7.17	43.93	
	3.15	7.17	43.93	
Morning Test 2	2.17	10.00	21.7	31.97/ 9.66
		8.54	25.4	
	2.06	5.05	40.79	
		4.46	46.18	
	1.96	7.59	25.82	
Afternoon Test 1	2.65	5.6	47.32	40.37/ 9.01
		4.9	54.08	
	2.74	7.34	37.32	
		8.22	33.33	
	2.77	9.28	29.84	
Afternoon Test 2	2.64	8.34	31.65	35.34/ 5.71
		9.18	28.75	
	2.61	7.00	37.28	
	2.67	6.11	43.69	

Table 3.12: Measured dilution during second field study

Test Number	Dye concentration in the chamber 1×10^{-5} gram/cc.	Dye concentration in the sea 1×10^{-7} gram/cc.	Dilution achieved	Average dilution/ Standard deviation
Afternoon Test 3	2.51	8.69	30.37	38.85/ 7.79
		5.48	47.90	
	2.59	6.67	39.13	
		5.61	47.06	
	2.83	8.97	29.77	
Afternoon Test 4	2.66	8.18	32.52	32.74/ 4.51
		9.68	27.47	
	3.00	10.67	28.1	
		8.15	36.81	
	2.91	7.51	38.74	
Afternoon Test 5	1.96	6.03	32.5	32.20/ 7.08
		8.22	23.86	
	2.02	4.89	41.31	
		8.18	24.69	
	2.15	5.56	38.67	

Table 3.13: Measured dilution during second field study

Test Number	Pump chamber reading for inflow		Volume of water in m^3	Rate of inflow in m^3/sec 1×10^{-3}	Pump chamber reading for outflow		Volume of water in m^3	Extra volume due to inflow in m^3	Total volume of outflow in m^3	Rate of outflow in the outfall in m^3/sec. 1×10^{-2}	Rate of outflow in each nozzle in LPS
	time in sec.	depth in m.			time in sec.	depth in m.					
Morning Test 1	233	0.356	1.566	6.72	316	0.356	1.566	2.12	3.686	1.16	5.80
Morning Test 2	121	0.178	0.782	6.46	290	0.356	1.566	1.87	3.436	1.18	5.90
Afternoon Test 1	230	0.356	1.566	6.8	268	0.356	1.566	1.822	3.388	1.126	5.63
Afternoon Test 2	212	0.280	1.232	5.8	180	0.356	1.566	1.792	2.61	1.145	5.79
Afternoon Test 3	253	0.356	1.566	6.18	290	0.356	1.566	1.792	3.358	1.158	5.79
Afternoon Test 4	250	0.356	1.566	6.26	74	0.318	1.399	0.463	1.862	2.50	12.5
Afternoon Test 5	195	.356	1.566	8.03	308	0.356	1.566	2.47	4.039	1.311	6.55

Cross sectional area of the pumpchamber = $2.59 \times 1.70 = 4.4\ m^2$

Cross sectional area of the nozzle = $7.85 \times 10^{-3} m^2$

Table 3.14: Calculation of Inflow rate and Outflow rate of the outfall during second field study

Depth z	Q	V	F_Δ	$\frac{z}{d \cdot F_\Delta}$	$S_{o(jet)}$
5.35	5.80	0.74	4.52	11.82	37.54
5.35	5.90	0.75	4.60	11.62	37.25
5.43	5.63	0.72	4.39	12.37	38.95
5.43	5.72	0.73	4.46	12.17	38.65
5.43	5.79	0.74	4.52	12.03	38.45
5.43	12.50	1.59	9.75	5.57	28.90
5.43	6.55	0.84	5.11	10.63	36.39

z = Depth of receiving water in meters
Q = Rate of discharge from the nozzle in LPS
V = Velocity of the jet in meters/sec.
F_Δ = Densimetric Froude number of the jet
d = diameter of the nozzle
$S_{o(jet)}$ = overall theoretical dilution

Table 3.15: Calculated theoretical dilution for the horizontal nozzle installed at the outfall during second field study

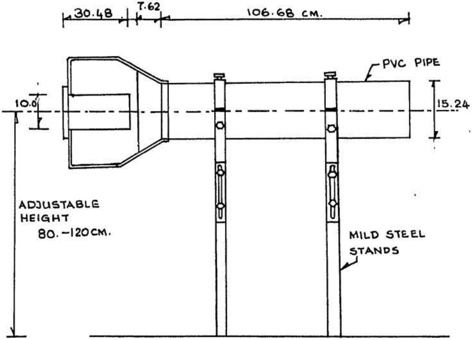


Figure 3.7: Dimensions of the circular mixing tube installed during third field study

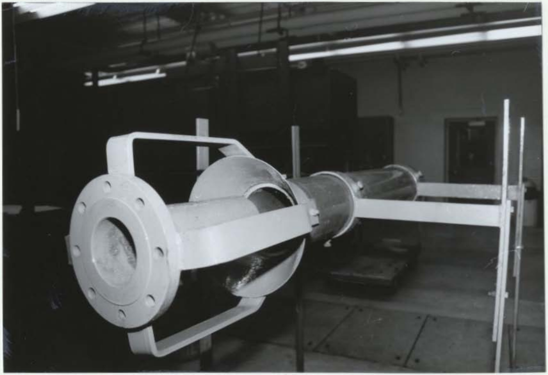


Figure 3.8: Photograph of the actual Mixing Tube installed at Spaniards bay

3.8.2 Third field study

Divers were employed to place these mixing tubes in position at the site during the first week of October 1989. The field study was done on 11 October, 1989 with the same number of people as in the second field study. With the past experience the study was well run and eight pumping cycles were completed. Three cycles were completed during the morning session and five cycles during the afternoon session.

The same procedures were followed to calculate the inflow rate of sewage as in the previous field studies. During the morning session the inflow rate was found to be 9.55 litre/s. As explained in section 3.4.1 the required dye concentration in the pump chamber was determined to be 3 x 10^{-5} g/cm^3. The amount of dye to be added to the channel, with a flow rate of 9.55 litre/s, to achieve a dye concentration of 3 x 10^{-5} g/cm^3 in the pump chamber was then calculated as

Rate of inflow in the channel = $9.55 \times 10^3\ cm^3/s$
Expected concentration in the chamber = $3 \times 10^{-5}\ g/cm^3$
Amount of dye to be injected = $(9.55 \times 10^3)(3 \times 10^{-5})$
= 0.3 gram/sec

During the morning session 500 grams of Rhodamine-B were mixed with 250 litres of water (48 cm depth of water in the dye tank) to achieve a dye concentration of 2.0 x 10^{-3} g/cm^3. The rate of injection of dye solution into the inlet channel so as to result in a uniform dye concentration of 3 x 10^{-5} g/cm^3 in the chamber was calculated as

Concentration of dye solution = $2.0 \times 10^{-3}\ g/cm^3$
Amount of dye to be injected = 0.30 gram/sec
Rate of inflow of dye solution = $0.30/2.0 \times 10^{-3}$
= $150\ cm^3/s$

The experimental set-up, described in Section 3.4.2, was used during this study. Initial adjustments were done as explained in Section 3.4.4 and the system was adjusted to deliver a flow rate of 150 cm^3/s The dye solution was prepared as explained in Section 3.4.5.

Tests were run following the same procedures explained in section 3.7.2. During the afternoon session it was decided to run five cycles. Red dye solution was prepared by mixing one kilogram of Rhodamine B with 500 litres of water to get a dye concentration of $2 \times 10^{-3}\ g/cm^3$. The rate of injection into the inlet channel, so as to get a uniform concentration of $3 \times 10^{-5}\ g/cm^3$. in the chamber, was calculated as 120 cm^3/s. Five cycles were run after making the same preliminary arrangements done for the previous studies. Three samples were collected from the chamber and six samples were collected above the boil at the outfall in the sea during each cycle.

The spectrophotometer described in section 3.3.4 was again used to analyze the samples and the procedures described in section 3.5 were followed during the analysis. Results are tabulated in Tables 3.17 to 3.22.

The dilution achieved in the sea with the mixing tube attached to the existing nozzles varied between 42 and 51. A considerable improvement in the measured dilution was seen with the mixing tube when compared to vertical and horizontal nozzles which had a variation in measured dilution from 19 to 33 and from 31 to

40 respectively. To examine the validity of the theory of mixing tubes in the field, theoretical dilutions were calculated with measured field conditions.

3.8.3 Theoretical verification

The theoretical dilution for a circular mixing tube installed to a horizontal jet was calculated using a combination of Cederwall's and Argaman's equations (Argaman, et.al., 1975). These were introduced in Chapter 2 and are reproduced here:

$$S_m = 0.54F_\Delta\left[\frac{(Y_o/d)}{F_\Delta}\right]^{0.437}\left(\frac{K_1\frac{D}{d}+K_2}{\frac{D}{d}}\right)^{1.845} \quad for \ \frac{Y_o}{dF_\Delta} < 0.5\left(K_1+K_2\frac{d}{D}\right)^{1.5} \qquad (3.6)$$

$$S_m = 0.54F_\Delta\left(\frac{K_1\frac{D}{d}+K_2}{\frac{D}{d}}\right)^{2.5}\left[0.38\frac{(Y_o/d)}{F_\Delta}\left(\frac{K_1\frac{D}{d}+K_2}{\frac{D}{d}}\right)^{-1.5}+0.66\right]^{1.67} \quad for \ \frac{Y_o}{dF_\Delta} > 0.5\left(K_1+K_2\frac{d}{D}\right)^{1.5} \qquad (3.7)$$

in which S_m = overall dilution obtained with jet pump. K_1 and K_2 are the constants whose values were found to be 0.8 and 0.7 respectively (Argaman, et al., 1975). F_Δ = Froude number of flow through nozzle.

Receiving water depths were calculated using the tide Tables provided by Environment Canada. On the test date October 11 1989, the tide levels were 0.81 meters above mean sea level (MSL) during the morning session and 0.92 meters above MSL during the afternoon session. The depth of water above the discharging jet was thus 5.31 m for morning tests and 5.42 m for afternoon tests. Discharge rates were calculated as before (section 3.6) and are tabulated in Table 3.23. Calculated dilutions for the horizontal circular mixing tubes are given in Table 3.24.

In Table 3.24, $S_{o(jet)}$ corresponds to the calculated dilution for a horizontal jet and $S_{o(cm)}$ shows the calculated dilution for a horizontal jet with a circular tube attached to the existing outfall nozzle. The improvement factor, IF, is the increase in dilution achieved with the mixing tube. There was a considerable variation between the measured dilution at the field and the calculated dilution using equation 3.7 . The theoretical values varied between 33 and 35 but the measured dilution varied between 28 and 51. Out of eight tests done, six tests gave values between 42. and 47. One test resulted in a very low value (28) and one in a very high value (51). In general the measured dilution appeared to be always higher than the calculated dilution suggesting that the mixing tubes perform better in the field than is predicted by the theory.

3.8.4 Removal of mixing tubes

Mixing tubes were left in the field for the entire winter. The purpose of leaving them in place was to check the effect of winter weather on the tubes. Divers were hired to remove the tubes on May 8, 1990. Before removal an underwater video was taken to see the actual performance of the mixing tube in field. A red dye was injected into the pump chamber during filming so that it would be easier to see the buoyant jet from the mixing tube. Figure 3.9 shows a photograph of the mixing tube after being removed from the sea. It was found that there were no deposits on the mixing tube and no marine growths. The mixing tubes were in good condition when they were removed, which made clear that they were able to withstand the

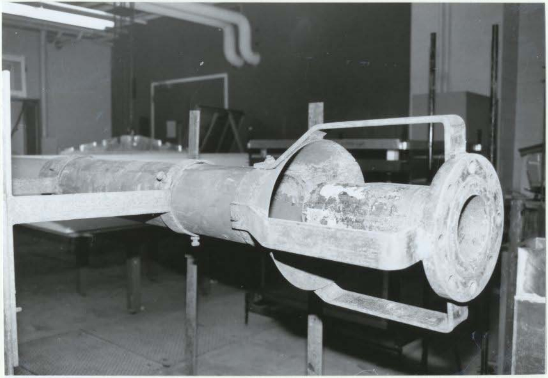


Figure 3.9: Photograph of the mixing tube after being removed from the sea

winter weather. The pipe which was made of PVC was in good condition. There was a little corrosion on the metal parts of the mixing tube; namely the supporting frame and the frame attached to the discharging nozzle. This was natural because mild steel was used for building the supporting frame and the attaching frame. If the tube was to be left in place on a long term basis it would be necessary to protect it against corrosion.

3.9 Discussion

The average initial dilution achieved at the outfall as initially installed was in reasonable agreement with the theoretical dilution calculated for a vertical buoyant jet. Dilution should be minimum at the boil and should increase in the radial direction from the boil. Variation in measured dilution from one test to another is partly due to changing site conditions (eg. flow rate) and partly due to experimental scatter. Due to the wind, it was difficult to station the boat exactly at the boil and this would cause some errors.

The dilution of the outfall was increased by replacing the vertical jet by a horizontal jet. This is clear from Tables 3.5 and 3.12, 3.13 The measured dilution for the horizontal jet at the outfall is in reasonable agreement with the calculated dilution using Cederwall's equations (Cederwall. 1968).

A summary of the calculated and measured dilutions is shown in Table 3.25. It can be seen that there is more variation in the measured values than the calculated values. During the first study with vertical discharging nozzles, the measured dilution varied between 19 and 41 but the averages of measured and calculated dilutions were in good agreement. The error between the average value of measured and calculated dilution was found to be 1 percent. A close correlation was also found during the second series of tests with the horizontal nozzle. The percentage error between the measured and the calculated dilutions varied between ±14. This error was reduced to 1% with the average values. It is noticeable in both series of tests that there was no general tendency to overpredict or underpredict. Some individual tests were higher than calculated values and some lower. Despite the relatively large percentage error in individual tests the theoretical and measured values are of the same order of magnitude and are probably as close as can be expected. The test with a mixing tube showed higher variations between the calculated and measured values. The percentage error was always positive and typically in excess of 25%. Although the average error was +26% the individual errors varied from +22% to +48% with one atypical value of -13.5%. This implies that the mixing tube performed better than predicted by the theory. It was difficult to calculate the value of the improvement factor in the field because the field study relating to horizontal nozzles was not done under the same conditions as field study of the mixing tubes. However the final results might be influenced by the receiving water temperature and salinity, which were assumed to be same for all three field tests. It should also be noted that the stratification and velocity of the receiving water were also not taken into account during the calculation.

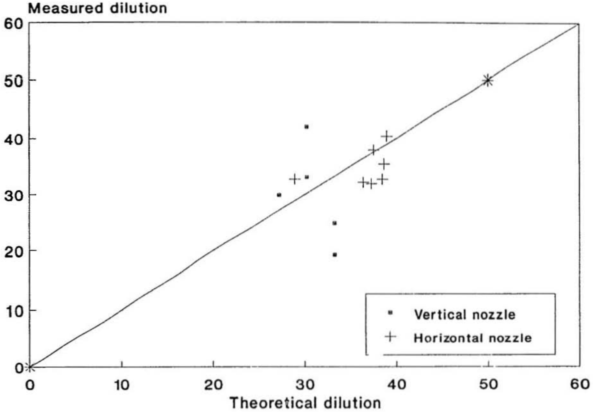


Figure 3.10: Experimental scatter in measured dilution when compared to calculated theoretical dilution for vertical and horizontal nozzles

Figures 3.10 and 3.11 show the scatter of the measured and theoretical dilution the for all three field tests. In conclusion it can be said that mixing tubes performed better in the field than theoretically predicted. For horizontal and vertical jets the theoretical dilutions are in reasonable agreement with the measured dilutions.

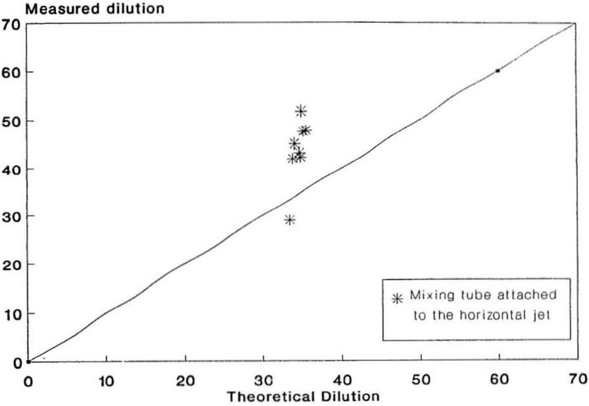


Figure 3.11: Experimental scatter in measured dilution when compared to calculated theoretical dilution for circular mixing tube

Vol. of previous dye solution in cc.	Vol of water to be added in cc.	concentration of dye solution in gram/cc.	Number on spectrophotometer
50	50	$1.25\text{x } 10^{-5}$	2.107
50	50	$6.75\text{x } 10^{-6}$	1.053
50	50	$3.125\text{x } 10^{-6}$	0.526
50	50	$1.56\text{x } 10^{-6}$	0.260
50	50	$3.9\text{x } 10^{-7}$	0.065
50	50	$1.95\text{x } 10^{-7}$	0.033
50	50	$9.76\text{x } 10^{-8}$	0.016

Table 3.16: Calibration table of spectro-photometer used during the third field study

Test Number	Sample Number	Number on Spectro-photometer	Concentration of Dye in gram/cc 1 x 10^{-7}
Morning Test 1	1	0.115	6.91
	2	0.138	8.27
	3	0.097	5.83
	4	0.142	8.51
	5	0.152	9.11
Morning Test 2	1	0.169	1.01
	2	0.101	6.01
	3	0.120	7.19
	4	0.143	8.57
	5	0.151	9.05
Morning Test 3	1	0.169	10.1
	2	0.186	11.1
	3	0.167	10.0
	4	0.143	8.57
	5	0.148	8.87
Afternoon Test 1	1	0.164	9.83
	2	0.127	7.62
	3	0.106	6.32
	4	0.141	8.45
	5	0.131	7.80
Afternoon Test 2	1	0.186	11.20
	2	0.160	9.59
	3	0.118	7.06
	4	0.099	5.89
	5	0.110	6.57

Table 3.17: Analysis of samples collected at the sea during the third field study

Test Number	Sample Number	Number on Spectro-photometer	Concentration of Dye in gram/cc 1×10^{-7}
Afternoon Test 3	1	0.123	7.37
	2	0.145	8.69
	3	0.127	7.62
	4	0.155	9.29
	5	0.155	9.29
Afternoon Test 4	1	0.119	7.13
	2	0.110	6.57
	3	0.124	7.44
	4	0.173	10.4
	5	0.138	8.27
Afternoon Test 5	1	0.089	5.27
	2	0.148	8.87
	3	0.103	6.14
	4	0.107	6.39
	5	0.179	10.7

Table 3.18: Analysis of samples collected at the sea during the third field study

Test Number	Sample Number	Volume of Dye solution in cc.	Volume of water added in cc.	Reading on spectrophotmeter	Concentration of the dye 1×10^{-6} gram/cc.	Actual concentration of the sample 1×10^{-5} gram/cc.	Average Concentration of the sample 1×10^{-5} gram/cc.
1	2	3	4	5	6	7	8
Morning Test 1	1(a)	2.50	10.00	1.298	7.44	3.72	4.39
	1(b)	5.00	5.00	0.676	5.07	5.07	
	2(a)	2.50	5.00	1.045	6.20	3.10	3.09
	2(b)	5.00	5.00	0.519	3.08	3.08	
	3(a)	2.50	10.00	0.892	5.3	2.65	2.66
	3(b)	5.00	5.00	0.447	2.66	2.66	
Morning Test 2	1(a)	2.50	10.00	1.041	6.18	3.09	3.08
	1(b)	5.00	5.00	0.515	3.06	3.06	
	2(a)	2.50	10.00	1.044	6.19	3.04	3.09
	2(b)	5.00	5.00	0.518	3.08	3.08	
	3(a)	2.50	10.00	1.159	6.88	3.44	3.42
	3(b)	5.00	5.00	0.571	3.39	3.39	
Morning Test 3	1(a)	2.50	10.00	1.040	6.17	3.08	3.08
	1(b)	5.00	5.00	0.518	3.08	3.08	
	2(a)	2.50	10.00	0.854	5.07	2.54	2.54
	2(b)	5.00	5.00	0.427	2.54	2.54	
Afternoon Test 1	1(a)	5.00	15.00	1.669	9.9	3.96	3.98
	1(b)	5.00	5.00	0.853	5.06	4.04	
	2(a)	5.00	15.00	1.716	10.1	4.04	4.06
	2(b)	5.00	5.00	0.861	5.00	4.08	
	3(a)	5.00	15.00	1.604	9.51	3.80	4.10
	3(b)	5.00	5.00	0.812	5.49	4.39	

Table 3.19: Analysis of samples collected at the pump chamber during third field study

Test Number	Sample Number	Volume of Dye solution in cc.	Volume of water added in cc.	Reading on spectro-photmeter	Concen-tration of the dye 1 x 10^{-6} gram/cc.	Actual concen-tration of the sample 1 x 10^{-5} gram/cc.	Average Concen-tration of the sample 1 x 10^{-5} gram/cc.
1	2	3	4	5	6	7	8
Afternoon Test 2	1(a)	5.00	15.00	1.684	9.99	3.99	4.01
	1(b)	5.00	5.00	0.852	5.06	4.04	
	2(a)	5.00	15.00	1.443	8.56	3.42	3.44
	2(b)	5.00	5.00	0.73	4.33	3.46	
	3(a)	5.00	15.00	1.516	8.99	3.59	3.62
	3(b)	5.00	5.00	0.774	4.59	3.65	
Afternoon Test 3	1(a)	5.00	15.00	1.549	9.19	3.68	3.69
	1(b)	5.00	5.00	0.780	4.63	3.70	
	2(a)	5.00	15.00	1.522	9.03	3.61	3.69
	2(b)	5.00	5.00	0.798	4.73	3.78	
	3(a)	5.00	15.00	1.318	7.82	3.13	3.19
	3(b)	5.00	5.00	0.685	4.06	3.25	
Afternoon Test 4	1(a)	5.00	15.00	1.386	8.22	3.28	3.34
	1(b)	5.00	5.00	0.718	4.26	3.40	
	2(a)	5.00	15.00	1.423	8.44	3.37	3.36
	2(b)	5.00	5.00	0.702	4.17	3.34	
Afternoon Test 5	1(a)	5.00	15.00	1.476	8.75	3.5	3.49
	2(b)	5.00	5.00	0.735	4.36	3.48	
	2(a)	5.00	15.00	1.431	8.49	3.39	3.41
	2(b)	5.00	5.00	0.721	4.28	3.42	

Table 3.20: Analysis of samples collected at the pump chamber during third field study

Test Number	Dye concentration in the chamber 1×10^{-5} gram/cc.	Dye concentration in the sea 1×10^{-7} gram/cc.	Dilution achieved	Average dilution/ Standard deviation
Morning Test 1	4.39	6.91	63.53	44.95/ 11.99
		8.27	45.22	
	3.09	5.83	53.00	
		8.51	33.78	
	2.66	9.11	29.19	
Morning Test 2	3.08	7.57	40.68	42.13/ 4.94
		6.01	51.24	
	3.09	7.19	42.97	
		8.57	37.98	
	3.42	9.05	37.79	
Morning Test 3		10.1	30.49	28.91/ 1.01
	3.08	11.1	27.74	
		10.0	28.10	
	2.54	8.57	29.63	
		8.87	28.63	
Afternoon Test 1	3.98	9.83	40.48	51.66/ 7.70
		7.62	52.75	
	4.06	6.32	64.24	
		8.45	48.28	
	4.10	7.80	52.56	

Table 3.21: Measured dilution during third field study

Test Number	Dye concentration in the chamber 1 x 10^{-5} gram/cc.	Dye concentration in the sea 1 x 10^{-7} gram/cc.	Dilution achieved	Average dilution/ Standard deviation
Afternoon Test 2	4.01	11.2	35.80	47.67/ 9.22
		9.59	38.84	
	3.44	7.06	48.72	
		5.89	59.93	
	3.62	6.57	55.09	
Afternoon Test 3	3.69	7.37	50.06	42.46/ 6.15
		8.69	42.46	
	3.69	7.62	48.42	
		9.29	37.02	
	3.19	9.29	34.33	
Afternoon Test 4		7.13	46.85	43.33/ 5.99
	3.34	6.57	50.83	
		7.44	45.03	
	3.36	10.4	33.30	
		8.27	40.63	
Afternoon Test 5		5.27	55.66	47.41/ 9.99
	3.49	8.87	39.35	
		6.14	56.84	
	3.41	6.39	53.36	
		10.7	31.86	

Table 3.22: Measured dilution during third field study

Test Number	Pump chamber reading for inflow		Volume of water in m^3	Rate of inflow in m^3/sec 1×10^{-3}	Pump chamber reading for outflow		Volume of water in m^3	Extra volume due to inflow in m^3	Total volume of outflow in m^3	Rate of outflow in the outfall in m^3/sec. 1×10^{-2}	Rate of outflow in each nozzle in LPS
	time in sec.	depth in m.			time in sec.	depth in m.					
Morning Test 1	173	0.356	1.566	9.05	115	0.356	1.566	1.401	2.607	2.26	11.3
Morning Test 2	183	0.356	1.566	8.55	105	0.356	1.566	0.898	2.464	2.34	11.7
Morning Test 3	101	0.254	1.118	11.06	109	0.356	1.566	1.206	2.772	2.54	12.7
Afternoon Test 1	210	0.356	1.566	7.45	104	0.356	1.566	0.776	2.342	2.25	11.3
Afternoon Test 2	200	0.356	1.566	7.83	122	0.356	1.566	0.955	2.521	2.07	10.35
Afternoon Test 3	183	0.356	1.566	8.56	109	0.356	1.566	0.933	2.499	2.29	11.45
Afternoon Test 4	190	0.356	1.566	8.24	103	0.356	1.566	0.849	2.415	2.34	11.7
Afternoon Test 5	203	0.356	1.566	7.71	112	0.356	1.566	0.864	2.43	2.17	10.85

Cross sectional area of the pumpchamber = $2.59 \times 1.70 = 4.4\ m^2$

Cross sectional area of the nozzle = $7.85 \times 10^{-3} m^2$

Table 3.23: Calculation of Inflow rate and Outflow rate of the outfall during third field study

Depth z	Q	V	F_Δ	$\frac{z}{d \cdot F_\Delta}$	$S_{o(jet)}$	$S_{o(cm)}$	IF $S_{o(cm)}/S_{o(jet)}$
5.31	11.30	1.44	8.81	6.03	28.87	34.04	1.1
5.31	11.70	1.49	9.12	5.82	28.58	33.83	1.1
5.31	12.70	1.62	9.90	5.36	27.95	33.42	1.2
5.42	11.25	1.43	8.77	6.18	29.69	34.90	1.1
5.42	10.35	1.32	8.07	6.72	30.47	35.48	1.1
5.42	11.45	1.46	8.93	6.07	29.53	34.79	1.1
5.42	11.70	1.49	9.12	5.94	29.35	34.65	1.1
5.42	10.85	1.38	8.46	6.41	30.02	35.14	1.1

z = Depth of receiving water in meters
Q = Rate of discharge from the nozzle in litres/sec.
V = Velocity of the jet in meters/sec.
F_Δ = Densimetric Froude number of the jet
d = diameter of the nozzle
$S_{o(jet)}$ = overall theoretical dilution for a horizontal jet
$S_{o(cm)}$ = overall theoretical dilution for the circular mixing tube
IF = Improvement factor $S_{o(cm)}/S_{o(jet)}$

Table 3.24: Calculated theoretical dilution for the Circular mixing tube at the outfall during third field study

Nozzle Type	Theoretical dilution	Measured dilution	Percentage error	Average theoretical dilution	Average measured dilution	Average percentage error
Vertical jet	27.19	29.87	9.6	30.20	29.79	-1
	30.18	33.08	9.6			
	30.18	41.91	38.6			
	33.25	24.93	-25.0			
	33.25	19.17	-42.3			
Horizontal jet	37.54	37.92	1.0	36.89	35.09	-1
	37.25	31.97	-14.2			
	38.95	40.37	3.6			
	38.65	35.34	-8.56			
	38.45	38.85	1.02			
	28.90	32.74	13.3			
	36.39	32.20	-11.5			
Mixing tube	34.04	44.95	32.0	34.53	43.57	26
	33.83	42.13	24.53			
	33.42	28.91	-13.5			
	34.90	51.66	48.00			
	35.48	47.67	34.36			
	34.79	42.46	22.05			
	34.65	43.33	25.10			
	35.14	47.41	34.91			

Table 3.25: Summary of calculated and measured dilutions during the field study

Chapter 4

Development of two dimensional slot mixing tube

4.1 Introduction

In previous chapters it was shown that the dilution of an effluent could be increased by using a pre-dilution device. Previous studies on these devices were done by Nece et al (1966), Silvester (1967), and by Agg and White (1974) who found that the improvement achieved with their pre-dilution devices was limited to a factor of about two.

Based on the studies conducted by Silvester (1967, 1972), Argaman did an experimental study on a model mixing tube. His pre-dilution device, called the mixing tube, consisted of a circular tube of diameter 'D' bigger than the discharging jet diameter 'd', and of length equal to seven times its diameter. He concluded that the initial dilution within the mixing tube was a function of the diameter ratio D/d. The improvement factor, defined as the ratio of, the overall dilution achieved with the mixing tube attached to a discharging jet, to the dilution of the discharging jet alone, was also limited to a factor of about two. He achieved the highest improvement factor at the lowest diameter ratio D/d of 1.2.

The basic reason for this limitation was that the combination of increased flow (Q to nQ), reduced density difference ($\Delta\rho$ to $\frac{\Delta\rho}{n}$) and increased diameter(d to D) reduced the relative depth (Y/d to Y/D) and increased the densimetric Froude number ($F_{\Delta 1}$ to $F_{\Delta 2}$). This resulted in less mixing between the end of the mixing tube and the surface of the receiving fluid than was achieved by the jet. without a mixing tube. From Figure 2.4 it can be clearly seen that the reduction in relative depth and increase in densimetric Froude number reduces the dilution in the buoyant jet. The combination of increased dilution in the mixing tube followed by decreased dilution in the buoyant jet resulted in limiting the improvement factor to a factor of about two.

4.1.1 Multiple jets

One way to improve the effectiveness of the mixing tubes would be to increase the dilution that occurs between the end of the mixing tube and the surface of the receiving fluid.

Consider S_1 to be the overall dilution for a horizontal buoyant jet of diameter 'd' discharging at a depth 'Y' and S_2 to be the overall dilution with a mixing tube of diameter 'D' attached to it. The improvement factor (IF) for the mixing tube would be thus,

$$IF = \frac{S_2}{S_1} \tag{4.1}$$

If 'n' is the dilution taking place within the mixing tube and S_d is the dilution in the buoyant jet between the end of the the mixing tube and the surface of receiving fluid, then

$$S_2 = nS_d \tag{4.2}$$

Thus,

$$IF = \frac{nS_d}{S_1} \tag{4.3}$$

Typically S_d is less than S_1 because of the changes discussed earlier. However, in order to take full advantage of pre- dilution 'n' , S_d must be kept greater than or equal to S_1. It is known that the two variables that influence the overall dilution of a buoyant jet are densimetric Froude number and the relative depth. Thus by maintaining the relative depth and densimetric Froude number of the discharge from the mixing tube approximately equal to those of the discharging jet, S_d could be made equal to S_1. One way to achieve this would be to have multiple jets at the end of the mixing tube.

The minimum number of jets required to maintain S_d greater than, or equal to, S_1 could be calculated approximately on the assumption that there is no mixing

Q_1 = rate of discharge from the jet

Q_2 = rate of discharge from the mixing tube

g'_1 = $g\frac{\Delta\rho_1}{\rho}$

g'_2 = $g\frac{\Delta\rho_2}{\rho}$

n = dilution within the mixing tube.

x = number of nozzles

$\Delta\rho_1$ = difference in density between the fluid discharging from the jet and the surrounding fluid

$\Delta\rho_2$ = difference in density between the fluid discharging from the mixing tube nozzles and the surrounding fluid

= $\frac{\Delta\rho_1}{n}$

g = gravitational acceleration

ρ = density of the receiving fluid

$F_{\Delta 1}, F_{\Delta 2}$ = densimetric Froude numbers of discharging jet and the individual jets at the end of the mixing tube respectively

For the densimetric Froude number $F_{\Delta 2}$ of each individual jet to be less than or equal to the densimetric Froude number $F_{\Delta 1}$ of the original jet

$$\frac{Q_2/x}{\frac{\pi}{4}{d_2}^2\sqrt{g'_2 d_2}} = \frac{Q_1}{\frac{\pi}{4}{d_1}^2\sqrt{g'_1 d_1}}$$

But due to initial dilution of 'n' in the mixing tube;

$$Q_2 = nQ_1 \qquad g'_2 = g'_1/n$$

thus,

$$\frac{nQ_1/x}{\frac{\pi}{4}{d_2}^2\sqrt{(g'_1/n)d_2}} = \frac{Q_1}{\frac{\pi}{4}{d_1}^2\sqrt{g'_1 d_1}}$$

between one jet and another. Any mixing which did occur would reduce dilution and would thus require a greater number of jets.

Assume there are x nozzles of diameter d_2 at the end of the mixing tube and let the diameter of the nozzle discharging into the mixing tube be d_1 The arrangement in shown, together with notation in Figure 4.1

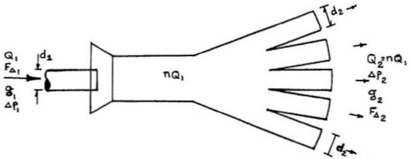


Figure 4.1: Arrangement of multiple jets

and,

$$x = n^{3/2}\left(\frac{d_1}{d_2}\right)^{5/2} \tag{4.4}$$

Assuming that $d_2 = d_1$ in order to maintain a constant relative depth,

$$x = n^{3/2}$$

But on the other hand, if $d_2 < d_1$ then

$$x > n^{3/2}$$

4.2 Slot mixing tube

For a circular mixing tube, the initial dilution n within the mixing tube is given by the equation developed by Argaman (1975) as

$$n = K_1(D/d) + K_2 \tag{4.5}$$

Where K_1 and K_2 are constants having values equal to 0.8 and 0.7 respectively. Equation 4.5 shows that, for a variation in diameter ratio between 1.2 to 6, the initial dilution 'n' varies between 1.7 and 5.5. The number of nozzles needed to have a multiple jet design (section 4.1) for this variation of 'n' would range between 3 and 14 (or more if $d_2 < d_1$). The derivation for the number of jets required to have a multiple jet design (section 2.1.4) is based on the assumption that there is no intermixing of the jets released by the nozzles. Hence it would be necessary

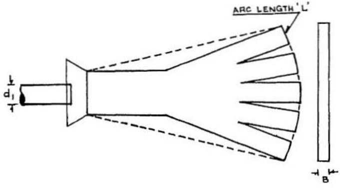


Figure 4.2: Development of the slot mixing tube

to ensure that there is no intermixing between the jets in the multiple jet design. To eliminate the intermixing, it would be necessary to increase the length of each nozzle at the outlet of the mixing tube. This increase in length of individual nozzles would increase friction and would probably decrease the dilution within the mixing tube. Another alternative would be to join all the nozzles as shown in Figure 4.2 so that a slot is formed at the outlet of the mixing tube.

As mentioned earlier, the main objective of having a multiple jet discharge from a mixing tube is to have values of Y/D and F_Δ at the end of the mixing tube the same as those of the discharging jet. In a two dimensional slot jet the dilution (see section 2.1.4) depends on the densimetric Froude number and the relative depth, where these parameters are based on the depth of the slot (instead of the diameter of a circular nozzle) Thus by adjusting the height of the slot it should be possible to arrange for the dilution between the slot and the surface to be of the same order as that which would be achieved by the original jet. To function properly the cross sectional area of the mixing tube should be constant along its length and greater than the cross sectional area of the original jet. Furthermore it would be beneficial for the entry to the mixing tube to be circular or approximately circular. These criteria lead to a design in which the height of the mixing tube decreases with distance along the tube (to obtain a thin slot at the end) while the width of the tube increases with distance along the tube in order to maintain a constant cross sectional area. It was also considered that tubes would be easier to fabricate if they were made from flat plexiglass sheets, having a square cross section at entry and tapering to a thin rectangle slot at the end.

4.3 Experimental models of two dimensional slot mixing tubes

In order to study the performance of the slot mixing tube, it was decided to build a model and test it under laboratory conditions. By joining all the nozzles to form a slot , the ratio of depth to the width of the slot would become high. Thus the flow through this slot might be considered two dimensional and the theory for the two dimensional buoyant discharge could be applied to obtain approximate values for slot to surface dilution. This, of course, ignores the end effects but the use of two dimensional theory would be convenient and was considered to be acceptable for an investigation of the feasibility of using slot mixing tubes.

In order to consider the discharge as two- dimensional it is necessary to have an even flow distribution along the exit slot. Because the width of the mixing tube increases gradually towards the outlet of the mixing tube, the distribution of flow within the mixing tube depends partly on the angle made by the side wall with the axis of the mixing tube. This angle is represented as θ (Figure 4.3). Having a narrow angle would result in a long mixing tube which would increase the friction losses. On the other hand a wider angle may result in water within the mixing tube leaving the side walls and concentrating along the axis of the mixing tube. This would result in more flow at the center and less flow at the edges. The angle of divergence used in a venturimeter was hence used as a guide for selecting appropriate angle θ.

Previous studies done by Silvester(1967) and Argaman(1975) have shown that an appropriate length for a mixing tube would be seven times the diameter. Because the length and θ are interrelated in the design of the mixing tube, it was decided to determine the length for angles between 10 degrees and 20 degrees.

Due to the difficulty in reducing a circular tube into a rectangular slot, it was decided to use a square tube as indicated earlier. Because of convenience, a 7.62 cm. x 7.62 cm (3 in. x 3 in.) square tube was initially considered. The depth of the exit slot was fixed at 1.27 cm (0.5 in.) which required the width of the slot to be equal to 45.72 cm (18.0in.) for equal entry and exit areas. For different divergence angles θ the length of the mixing tube was calculated as shown below.

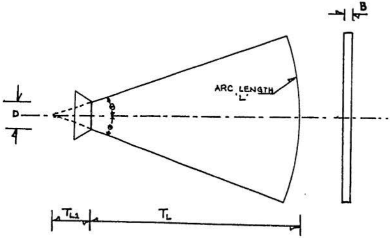


Figure 4.3: Basic lengths of the slot mixing tube

L = 45.72 cm (18 in.)
D = 7.62 cm. (3 in.)
θ = angle of divergence in degrees
$T_{L1} = \frac{D/2}{\tan\theta}$
T_L = length of the mixing tube in cm.
$= \frac{180L}{2\theta\pi} - T_{L1}$

Table 4.1 shows the length for corresponding values of θ. Though it seems large, it was finally decided to have diverging angle θ of 20 degrees which corresponds to the length of 55.01 cm. (21.66 in.) (seven times the sides of the square cross section of the slot mixing tube). These values would satisfy both the limitation for θ and length mentioned earlier.

Three models were constructed. Figure 4.4 shows the dimensions of Model X1. Transparent plexiglass was used to fabricate the model. This facilitated viewing

θ in degree	T_{L1} in cm.	$T_{L1} + T_L$ in cm.	T_L in cm.
5	43.53	261.60	218.41
10	21.61	130.96	109.35
15	14.21	87.29	73.07
20	10.46	65.48	55.01
25	8.17	52.37	44.19

Table 4.1: Typical values of the length T_{L1} and divergence angle θ of Model X1

of the flow inside the mixing tube. Aluminum plates were provided at the mouth of the mixing tube. The mixing tube was supported with a stand so that it could be placed horizontally in position. An actual photograph of Model X1 shown in Figure 4.5

Another smaller model with a 5.08 cm. x 5.08 cm. (2 in x 2 in.) square tube was also designed following the same procedure. All dimensions for this mixing tube were reduced to two thirds of those of Model X1 except the divergence angle θ. Thus Model X2 was geometrically similar to Model X1, but was smaller. Figures 4.6 and 4.7 show the actual measurements and photograph of Model X2.

In Model Y1, the cross sectional area was identical to that of Model X2; namely 5.08 x 5.08 cm. The divergence angle θ was reduced to 10 degrees and the depth of the slot was increased to 1.27 cm. (0.5 in.). This reduced the length of the slot to 20.32 cm (8 in.) providing a longer (length =43.80 cm.) and narrower mixing tube when compared to Model X2. All three models were provided with aluminum strips bent at an angle of 30 degrees with the axis of the mixing tube in order to direct the surrounding water into the tube. The mixing tube was attached to a stand so that the axis of the mixing tube would be horizontal. Figures 4.8 and 4.9 and show the actual dimensions and the photograph of the model Y1 respectively.

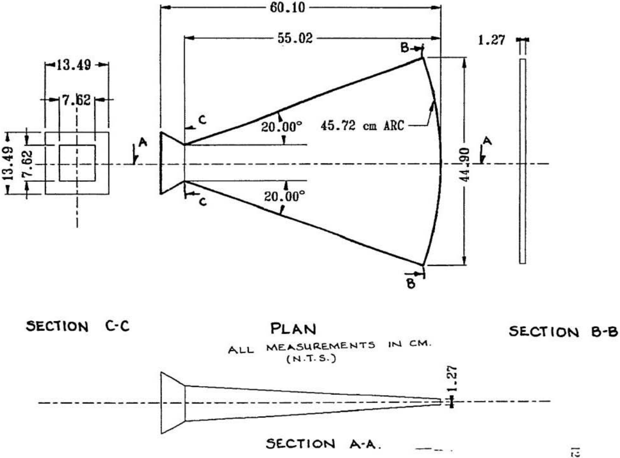


Figure 4.4: Actual dimensions of the Model X1

Figure 4.5: Photograph of the Model X1

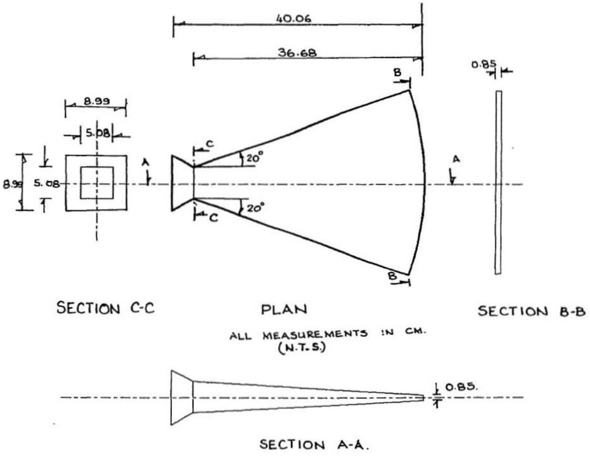


Figure 4.6: Dimensions of the Model X2

Figure 4.7: Photograph of the Model X2

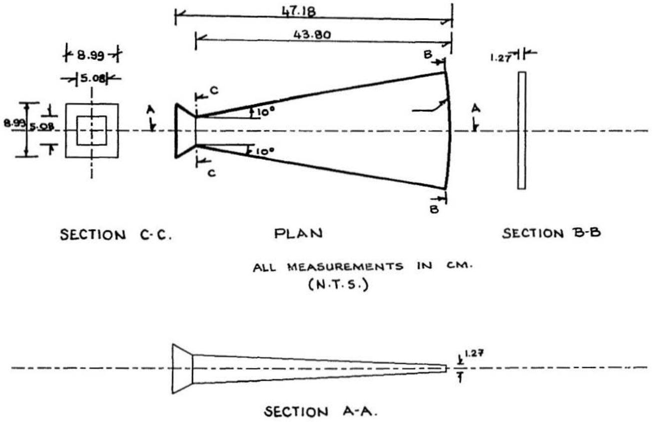


Figure 4.8: Dimensions of the Model Y1

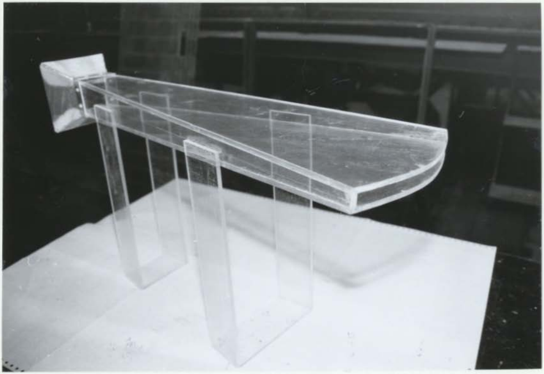


Figure 4.9: Photograph of the Model Y1

Chapter 5

Laboratory study of slot mixing tubes

5.1 Experimental arrangements

5.1.1 Experimental set-up

Experiments to determine the dilution of three slot mixing tubes were carried out in the Fluid Mechanics Laboratory of Memorial University of Newfoundland. The experimental set up (Figure 5.1) consisted of a steel tank 'A', 1.83 meters x 1.83 meters (6 ft. X 6 ft.) in cross section and 1.52 meters (5 ft.) deep, and an aluminum tank 'B' of diameter 0.78 meters (2.564) and 1.22 meters (4 ft.) deep. Two sides of tank A were provided with glass walls to facilitate viewing when the experiment was in progress. A platform 46 cm. wide and 1.83 m. long, was provided 60 cm. from the top of the tank to facilitate taking samples and to step into the tank. A 5.08 cm. (2 inch) diameter inlet was provided in the steel wall 33 cm. from the bottom of the tank. This inlet was made with a threaded socket so that nozzles of different sizes could be fitted in. An outlet with a control valve 'A' was provided at the bottom of the tank for emptying the tank when needed. Tank 'A' was used to store the ambient fluid and tank B was used to store the discharging fluid during the experiment. Tank B was connected to the inlet of tank A through a centrifugal pump and a flow meter. A control valve 'C' was provided between the pump and the flow meter to control the flow rate of the discharging jet during the experiment. An outlet with a control valve 'B' was provided close to the bottom of tank B for collecting samples from the tank during the test. Three nozzles each 30 cm. long having a threaded end which fitted the inlet of tank A were used during the test. Three different sizes were used. These were of diameters 5.08 cm, 3.81 cm and 2.54 cm. (2 inch, 1.5 inch and 1 inch). The flowmeter provided between the pump and the inlet of tank A had a rated maximum discharge of 400 litres/min. and provided an accurate flow measurement from 20 % to 100 % of the maximum discharge. A switch board was provided to control the operation of the centrifugal pump. Figures 5.1 and 5.2 show the sketch and photograph of the set up respectively.

5.1.2 Flow meter

The flow meter located between the pump and the inlet nozzle was of the rotameter type from Fischer Scientific (Precision Bore Flowmeter, Tube Number FP-2-27-G-10/27). A photograph of the flow meter is shown in Figure 5.3. It consisted of a steel float within a glass tube. The calibration in terms of percentage of full scale flow was written on the glass tube. The flow meter used in the experimental set up had a flow rate of 400 litres/minute at 100% opening. Correction factors to be

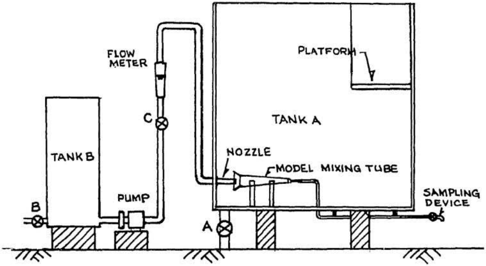


Figure 5.1: Experimental Set-up

Figure 5.2: Photograph of the Experimental Set-up

Figure 5.3: Photograph of the Flow meter

used to reduce the readings of the flow meter for fluids other than fresh water were provided with the instrument. These factors were provided by the manufacturer for varying specific gravities and various floats.

The flow meter was calibrated prior to use. This was done by filling tank A with fresh water to a depth of 30 cm. With the pump switched on water was pumped into tank A at different rates and the time taken for the water level to rise 10 cm was noted. This was done with the rotameter set at different readings (from 40% to 80%of full scale at 10% intervals). Each flow was tested three times to obtain an average time recording. These showed that the manufacturer's calibration was accurate within 1% to 2% of the measured flow.

5.1.3 Preliminary experiments

Preliminary experiments were done to check the flow distribution along the slot of the mixing tube. In order to consider the slot discharge from the mixing tube as a two dimensional buoyant jet it was necessary to get an even distribution of flow along the slot. A red dye was used to check the flow distribution. To start with the 5.08 cm. diameter nozzle was fixed to the inlet of tank A. The model mixing tube of cross section 7.62cm. x 7.62 cm.(3 in. x 3 in.) was placed at a distance of one jet diameter (5.08 cm.) from the face of the nozzle. Care was taken to ensure that the axis of the nozzle coincided with the axis of the mixing tube. Weights were laid on the legs of the mixing tube to prevent it from moving due to the force of the jet. All valves (A,B and C) were closed and tanks A and B were filled with fresh water up to a depth of 76.0 cm. and 116 cm. from the bottom respectively. A plastic flexible bottle fitted with a long fine steel tube, was filled with a red dye solution.

To start the experiments the pump was switched on and the valve C' (Figure 5.1) was opened slowly to give a full flow through the nozzle. Red dye was now injected near the mouth of the mixing tube by the person stationed on the platform of tank A. It was clearly seen that the red dye was sucked into the mixing tube. This showed that surrounding water was being entrained into the mixing tube. To check the distribution of the flow leaving the tube, red dye was injected all along the periphery of the slot and the strength of flow of the red dye was observed. It was felt that there was more flow at the centre of the slot and less towards the sides. The flow pattern during the first test is shown in Figure 5.4. This showed more flow at the centre and less flow at each side of the mixing tube. The test was repeated at different discharge rates and the same results were observed. Although these tests were qualitative, they showed clearly that there was an uneven distribution of flow. Most of the flow remained in the centre of the tube and little dispersed to either side.

In order to improve the distribution within the mixing tube it was decided to insert wedge shaped baffles into the flow path. It was hoped that they would divide the flow and direct it towards the sides of the tube. Initially three baffles were used and were placed at a distance of 7.62 cm. from the face of the mixing tube. Each baffle (Figure 5.5) was 8.9 cm. (3.5 inches) long and 0.6 cm. (0.25 inches) wide. They were shaped as a wedge with the sharp edge facing towards the mouth of the mixing tube. Placing three baffles divided the mixing tube into four equal parts. The experiment was repeated following the same procedure as before. A slight

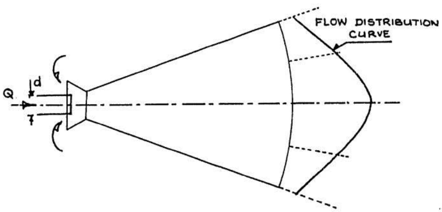


Figure 5.4: Flow pattern with in the slot mixing tube during the first test (Model X1)

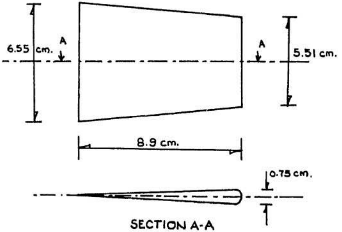


Figure 5.5: Baffles used to divide the flow within the slot mixing tube

improvement in the flow pattern was observed but there was still some bulking towards the centre with less flow at either side (see Figure 5.6). Based on these experiments it was decided to gradually change the angle of the sides by reshaping the walls inside the mixing tube. Curved styrofoam sides along with one central baffle were finally used. The shape of the sides was determined on a trial and error basis by conducting additional experiments until the distribution of the flow exiting from the mixing tube seemed reasonably uniform. The final flow pattern is shown schematically in Figure 5.7. This layout was used in all future experiments.

5.1.4 Sampling methods

The main purpose of the experimental study was to measure the dilution within the mixing tube. Hence, it was necessary to measure the concentration of some tracer between the two ends of the mixing tube. Due to the presence of a density difference between the discharging fluid and the receiving fluid in the practical application of the buoyant jet, it was decided to use either hot and cold water or salt and fresh water as ambient and jet fluid.

The possibility of having hot water for the discharging jet and cold water for the ambient receiving fluid was first considered. This would provide a density difference between the discharging and receiving fluid. The difference of temperature between the two ends of the mixing tube would be a measure of the dilution achieved within the mixing tube. For this purpose consideration was given to the use of a set of thermocouples with a digital reader. However, because of the loss of heat that occurs between tank B and the inlet nozzle, the possibility of considering the

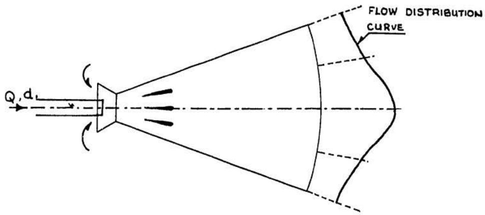


Figure 5.6: Flow pattern within the slot mixing tube with three baffles (Model X1)

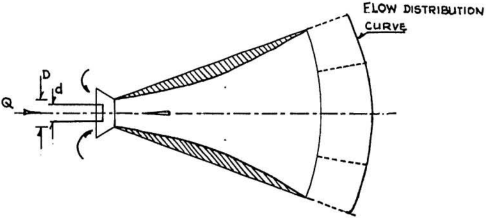


Figure 5.7: Flow pattern with bell shaped sides and central baffle (Model X1)

temperature of the hot water in tank B to be same as that at the mouth of the mixing tube was ruled out. It was also considered difficult to introduce a probe near the outlet of the jet because it would interfere with the jet flow. This introduced a major problem in measuring the initial temperature of the jet which was an important value in the calculation of the dilution.

The option of salt and fresh water was then considered. Under normal circumstances it would be usual for the receiving water to be saline while the jet effluent would be fresh. However to reduce the amount of salt necessary for each experiment it was decided to reverse the process and use salt water for the jet with tank A filled with fresh water. This has no effect on the hydraulics of the mixing process and merely reverses the direction of the resultant gravitational/buoyancy force which effects the rise/fall of the rising plume. In any case it was considered that the density difference would not play a significant part in determining the pre-dilution within the mixing tube. With fairly high jet velocities, inertia and momentum effects will be much more significant than buoyancy effects in the short distance between the jet exit and the entry to the mixing tube. Also, since subsequent dilution from the slot was not measured during the same test, it had no deleterеous effect on the final results. However use of salt water as the jet fluid changed the flow calibration of the flow meter. As mentioned in section 5.1.1, because the flow meter was calibrated using fresh water, a correction factor was used for all the measured flow rates. The correction factor of 1.01 was read from the correction chart provided with the instrument for salt water of density 1.026 used in the experiment. The measured values corresponding to percentage openings were multiplied by the correction factor for future calculations. Because the salinity of the jet at the mouth of the mixing tube would be same as the salinity of salt water in tank B. it was decided to collect the samples in tank B instead of collecting the samples at the mouth of the mixing tube. To determine the salinity of the flow leaving the mixing tube and to check on the flow distribution, it was decided to collect the samples at five points along the exit slot of the mixing tube. These points were evenly spaced from one end of the slot to the other. The average of these five samples was taken to represent the salinity of the jet at the end of the mixing tube. The dilution within the mixing tube was calculated from the salinities of the various samples. (see section 5.4).

5.1.5 Sampling device

Because of the limited storage of the discharging fluid in tank B, it was only possible to run the test for a fixed time at a particular discharge rate. Hence it was necessary to collect all five samples during that time.

A sampling device was built to collect the samples from the five points along the slot. A 0.625 cm (5/8 inch) diameter copper pipe 20 cm. long was bent at right angles and was connected to a long flexible plastic tube. The plastic tube was then connected to a pipe running through the bottom of the tank A. A tap arrangement was provided at the end of the pipe so that the fluid, from the point where the copper tube was placed, would flow through the tap by the action of gravity. A steel rod 1 m long, was fixed to the bent part of the copper tube so that the opening end of the copper tube could be placed at any point along the slot by a person standing on the platform of tank A. The time taken to fill the whole sampling device before a sample could be collected was also measured. With this arrangement samples could be collected from any point by allowing sufficient time to fill the sampling device with the fluid at that particular point. This method was complicated because of the need for two persons to collect the samples and to measure the time between the samples. This device was used successfully for some preliminary experiments. However it was cumbersome to use in the main experiments and another device which permitted simultaneous collection of five samples at fixed locations was designed.

The new sampling device consisted of five copper pipes fixed to a stand. These pipes were bent so that they coincided with the five sampling points along the slot. The other ends of these pipes were connected through flexible plastic tubes to five different pipes running through the bottom of tank A. Separate tap arrangements were constructed for each of the five pipes. When the taps were operated fluid flowed through the pipes under the action of gravity. These could thus be used to sample the fluid exiting from the mixing tube. It should also be noted that since the discharging jet was heavier than the receiving water the subsequent plume bent towards the bottom of the tank. Thus there was no interference of the plume with the discharging jet.

The previous sampling device was used to collect samples around the mouth of the mixing tube thus providing the salinity of the surrounding fluid at the time of sampling. The Photograph of the whole experimental set up with the mixing tube and sampling device in place is as shown in Figure 5.8.

5.1.6 Salinity meter

A portable conductivity/salinity meter (model number YSI Model 33) from Fisher Scientific was used to analyze the samples. The salinity meter had a measuring range of salinity from zero to forty parts/thousand. This model could also be used for temperature and conductivity measurements. Setting the salinity meter to the sample temperature would automatically compensate for temperature in salinity readings. A probe with a long lead was provided with the instrument for measuring the temperature/salinity of the samples. The probe was cylindrical in shape with a diameter of 3 cm. and a height of 5 cm. Manufacturer's recommendations were to immerse the probe completely in the sample before making any measurements. A measuring jar was thus used to make the measurements and it was found that 100 ml. was needed to immerse the probe sufficiently so as to make a reliable measurement of the temperature/salinity. The salinity meter was battery powered by two D size batteries.

To measure the salinity of the sample, the salinity meter was initialized by setting the instrument to give a particular reading (the red line) on the dial gauge by using the adjustment knob. The measuring probe was then immersed in the sample and the instrument was set to read the temperature. The instrument was then adjusted for the appropriate temperature and the salinity of the sample was directly read in parts per thousand from the dial gauge. This procedure automatically compensated for temperature in all salinity readings.

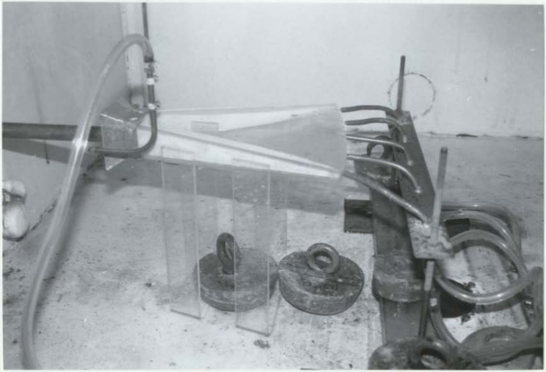


Figure 5.8: Photograph of the mixing tube and sampling device in place

5.2 Experimental procedure

5.2.1 General

As mentioned earlier in section 5.1.1, three models were tested in the experiments. Model X1 and Model X2 were of same shape and had a cross sectional area of 58.08sq.cm and 25.81 sq.cm respectively. Model Y1 was of a different shape but also had cross sectional area of 25.81 sq.cm. Figures 4.5, 4.7 and 4.9 shows the photograph of the models X1, X2 and Y1 respectively. Model X1 was tested with all three different sized nozzles mentioned earlier and this gave three different area ratios. Because models X2 and Y2 were smaller, having a cross section of 25.81 sq.cm in cross section, they were tested with only two nozzles, namely 3.81 cm and 2.54 cm diameter. This provided only two area ratios for these two models. To check the effect of variation in the flow rate on the initial dilution within the mixing tube, tests were undertaken at different flow rates for each set of nozzles and mixing tubes. Flows were measured using the flowmeter described in section 5.1.2. Tests were run at five different flow rates namely; 5.39, 4.72, 4.04, 3.37.2.69 litres/sec. with nozzles of diameters 3.81 cm and 2.54 cm. whereas experiments were run with only four flow rates, excluding the flow rate of 2.69 litres/sec. with the nozzle of 5.08cm diameter. This was because the 5.08cm diameter nozzle did not flow full at a flow rate of 2.69 litres/sec. Tests were repeated three times at each flow rate.

Initial tests were done with models X1 and X2 (The procedure is explained in section 5.3.3). Twenty four different tests (with each test being repeated three times) gave a total of 72 experiments. However, because of an error, which will be explained in the following sections, these tests were all repeated. Ten tests and thirty experiments were then conducted with model Y1. The results of all the experiments are given in the Appendix.

5.2.2 Salt water preparation

The salinity meter used in the study had a measurable range of salinity from 0 parts/thousand to 40 parts/thousand. Because the samples collected from tank B represented the salinity of the jet, care was taken to prepare the salt water in tank B to be within the measurable limits. This would facilitate the salinity measurement by avoiding the back calculation required to calculate the salinity of the samples if they were higher than the measurable limits. The amount of salt to be added to keep the salinity of the salt water in tank B below 40 parts/thousand was calculated as follows:

Diameter of tank B = 78 cm.
Maximum depth of water in tank B = 116 cm.
Cross sectional area of tank B = $\frac{\pi}{4}$x78^2
= 4775.94 sq.cm.
Total volume of water in tank B = 554.3 x 10^3 cc.
Density of water = 1 gram/cc
Total amount of salt to be added to 554.3 x 10^3 cc. of water to have a concentration of 40 parts/thousand = (554.3 x 10^3 x 40)/1000
= 22172 grams
= 22.17 kg.

Typically the salinity of the jet was maintained between 27.0 and 36.0 parts/thousand. The ambient fluid was fresh water at the beginning of the test and, in the initial series of tests, the salinity increased as testing proceeded. As will be discussed, this caused some problems and in a later series of tests tank A was flushed out between tests so that the salinity was always that of the fresh water supply. To prepare the salt water, valve B (Figure 5.1) was closed and tank B was filled with 30 to 40 cm. of water. Between 15 to 20 kg. of dry salt was poured into the tank. Water in the tank B was thoroughly mixed using a rod until all the salt was dissolved. Fresh water was then added to bring the level to the upper mark. The water was constantly stirred to ensure an even salinity throughout the water column prior to the beginning of any test.

5.2.3 Test procedure

As mentioned earlier, tests were conducted in the fluids laboratory of Memorial University of Newfoundland. To start with, the 5.08 cm. diameter nozzle was fixed to the inlet of tank A. The model mixing tube X1 was then placed at a distance of one jet diameter from the face of the nozzle. Weights were laid on the legs of the mixing tube in order to prevent the movement of the mixing tube due to the force of the discharging jet. The sampling device with five sampling pipes was moved in front of the mixing tube so that the sampling pipe inlet coincided with the sampling point of the slot. Care was taken to ensure that the centre point of the sampling tube was aligned with the centre line of the slot. The other sampling device, with a steel rod attached to hold it in place, was fixed near the mouth of the mixing tube to collect the samples of the surrounding water. All valves were closed and tank A was filled with fresh water to a depth of 76 cm. Salt water in tank B was prepared as described in section 2.2.3. All taps connected to the sampling device were opened so as to have a free flow of water from tank A. Sampling bottles were numbered and were placed near the taps for easy access. The time required for the samples collected at the end of the sampling device to represent the fluid at the point of sampling was also measured and was found to vary between 5 and 10 sec. It was decided to collect two samples from tank B, one before and one after collecting the samples from the end of the mixing tube. The time required to collect the sample from tank B by opening and closing valve B was between 15 and 20 sec. This was more than the time required for water from the end of the mixing tube to reach the end of the sampling device, so that the samples collected from the sampling device correctly represented the sample from the sampling point. This facilitated easy collection of samples without the need to measure the time between collecting the sample from tank B and the samples from the end of the mixing tube.

The pump was switched on and valve C was opened slowly to allow salt water to flow through the inlet nozzle. The valve was then adjusted to give the desired reading on the flow meter. Valve B was opened and the sample from tank B was collected. The samples from the end of the mixing tube along with the sample of the receiving water were then collected from the tap arrangement. To end the sampling procedure the second sample from the tank B was collected. When all the samples had been collected the discharge through the jet was increased and after an appropriate lag time samples were again collected. This procedure was continued until tank B became empty. Tests resumed after both tanks A and B had been cleaned out and refilled.

At the conclusion of each experiment a number of samples were available for analysis. These were:

1 Two samples from tank B giving samples of the fluid in the jet.

2 Five samples of the fluid leaving the end of the mixing tube.

3 One sample from tank A containing the receiving fluid from tank A.

The size of sample needed for analysis was around 100 ml. Hence, sampling bottles measuring 150 ml. were used for sampling and care was taken to fill the sampling bottles to their neck during sampling.

The first experiments were undertaken using a 5.08 cm diameter jet and the model mixing tube X1. This was tested at flow rates of 5.39, 4.72, 4.04, 3.37.2.69 Litres/sec. each flow rate being tested three times. When this was completed the 5.08 cm nozzle was replaced by 3.81 cm (1.5 inch) nozzle and then the 2.54cm (1 inch) nozzle, all tests being repeated for each nozzle. Model X2 was tested in a generally similar pattern.

5.3 Analysis of samples

Samples were analyzed using the salinity meter described in 5.1.5. To do this, the sample was transformed to a clean dry measuring jar. The salinity probe was inserted and adjusted for temperature. Following this adjustment the salinity was read and recorded. Detailed results are given in Appendix. Typical results are

TEST NUMBER : 6 MODEL NUMBER: X1

FLOW METER READING IN PERCENTAGE: = 70%

FLOW RATE IN LITRES/SEC. : = 4.67

CORRECTION FACTOR FOR SALT WATER: = 1.01

ACTUAL FLOW RATE IN LITRES/SEC., Q= 4.72

Sample	Trial 1 Salinity in ppt	Trial 2 Salinity in ppt	Trial 3 Salinity in ppt
T1	31.00	31.00	31.50
T2	31.00	31.50	31.50
1	15.00	16.00	16.50
2	17.00	17.00	18.00
3	18.00	19.00	19.50
4	17.00	17.50	18.00
5	15.00	16.00	16.00
Salinity S2	0.00	3.00	5.00
Average of 1-5 Salinity S3	16.40	17.20	17.60
Average of T1 & T2 Salinity S1	31.00	31.25	31.50
Initial dilution n	1.89	2.00	2.10

T1 & T2 : Samples collected from tank B
Samples 1-5 : Samples collected from the end of the mixing tube according to the figure shown in page one of Appendix
S2 : Sample of the surrounding water
n : Initial dilution within the mixing tube

Table 5.1: Salinity of samples at Q = $4.72 \times 10^{-3}\ m^3/s$ measured during the test 6

shown in Table 5.1. This mixing shows the salinity of the two samples of jet fluid (T1 and T2) along with the samples (nos. 1 to 5) taken from the mixing tube. These sampling points were located as shown the first page of the appendix. The measured salinities of three trials show a reasonably uniform salinity distribution across the slot exit of the mixing tube with a variation from about about 16 parts per thousand at the edges to a maximum of 19 at the mid point. The average salinity was determined for each trial and this was used in calculating the dilution within the mixing tube. The salinity of the surrounding water depended on the time of sampling. It was zero during trial 1, when the test was started with fresh water in tank A and increased in the later trials. The following section explains how dilutions were determined.

5.4 Calculation of dilution

The average of all five samples collected at the end of the mixing tube was taken to represent the salinity along the slot and the average of the samples collected from tank B was taken as the salinity of the jet. One sample was also taken near the entry to the mouth of the mixing tube. This gave the salinity of the receiving water. Dilutions were calculated as follows using the data in Table 5.1 for illustrative purposes.

Consider a general case of the slot mixing tube with the following flow parameters:

S_1 = salinity of the jet fluid
S_2 = salinity of the receiving fluid
S_3 = average salinity of the fluid discharged from the mixing tube
Q_1 = volume of the jet fluid
Q_2 = volume of the receiving fluid entrained into the mixing tube
$Q_1 + Q_2$ = volume of the fluid from the mixing tube

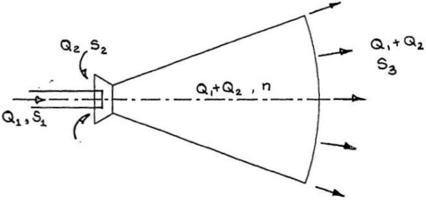


Figure 5.9: Flow parameters of a slot mixing tube

$$\begin{aligned} \text{Dilution within the mixing tube} = n &= (Q_1 + Q_2)/Q_1 \\ &= 1 + Q_2/Q_1 \end{aligned}$$

but

$$\begin{aligned} Q_1S_1 + Q_2S_2 &= (Q_1 + Q_2)S_3 \\ S_1 + (Q_2/Q_1)S_2 &= S_3 + (Q_2/Q1)S_3 \\ Q_2/Q_1(S_2 - S_3) &= (S_3 - S_1) \\ Q_2/Q_1 &= (S_3 - S_1)/(S_2 - S_3) \\ &= (S_1 - S_3)/(S_3 - S_2) \\ n &= 1 + (S_1 - S_3)/(S_3 - S_2) \end{aligned}$$

or

$$n = (S_1 - S_2)/(S_3 - S_2)$$

From Table 5.1,

For trial 1, $S_2 = 0.0$, $S_1 = 31.0$, $S_3 = 16.4$

$$\begin{aligned} n &= (31.0 - 0.0)/(16.4 - 0.0) \\ &= 1.89 \end{aligned}$$

For trial 2, $S_2 = 3.0$, $S_1 = 31.25$, $S_3 = 17.2$

$$\begin{aligned} n &= (31.25 - 3.0)/(17.2 - 3.0) \\ &= 2.00 \end{aligned}$$

For trial 1, $S_2 = 5.0$, $S_1 = 31.5$, $S_3 = 17.6$

$$\begin{aligned} n &= (31.5 - 5.0)/(17.6 - 5.0) \\ &= 2.10 \end{aligned}$$

$$\text{Average dilution for test number 6} = (1.89 + 2.00 + 2.10)/3$$
$$= 2.00$$

Dilutions were calculated in the same manner for all the tests. Average dilution was calculated for each test and Tables 5.2 to 5.6 show the average dilutions along with the rate of discharge, Area ratio (ratio of cross-sectional area of the jet to the cross-sectional area of the mixing tube) and jet Froude number for each test.

As mentioned earlier, Argaman (1975) showed that the initial dilution within the mixing tube was a function only of the diameter ratio of the mixing tube and the discharging jet. In order to compare the results of the model mixing tubes with those of circular mixing tubes, the initial dilution n was plotted as a function of the area ratio Am/Aj. Here the area ratio is defined as the ratio of the cross-sectional area of the mixing tube to the cross-sectional area of the discharging jet. The reason for using the area ratio instead of the diameter ratio was because the cross section of the model mixing tube was not circular. Figures 5.10 and 5.11 show the variation of n as a function of area ratio at different flow rates.

To compare the results of the circular mixing tube with that of the model mixing tube, the linear relationship for a circular mixing tube was superimposed on Figures 5.10 and 5.11. Note that the straight line equation 4.4 for diameter ratio becomes parabolic when used with area ratios. The initial dilution in the model mixing tube was generally slightly less than the initial dilution in the circular mixing tube. More variation in the initial dilution was observed with increase in the

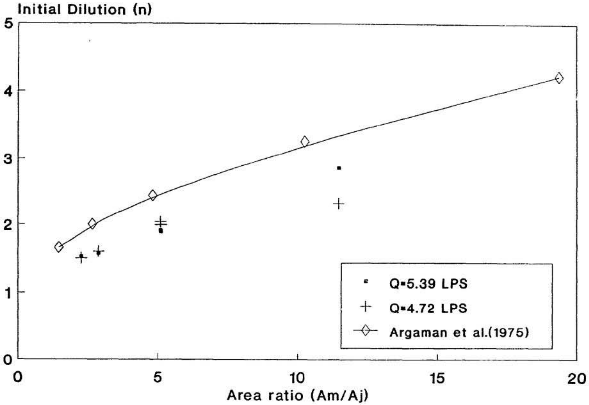


Figure 5.10: Variation of dilution n within the mixing tube with the Area ratio

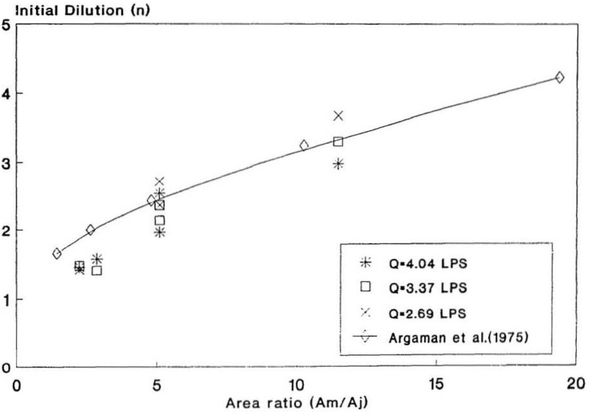


Figure 5.11: Variation of dilution n within the mixing tube with the Area ratio

value of the area ratio. From these figures it is evident that there is variation in initial dilution at different flow rates for the same area ratio which is different from the results of Argaman for a circular mixing tube. The variation in initial dilution with the flow rate also shows that the initial dilution n is not only a function of Area ratio but varies also with the flow rate Q and hence with the Froude number F. In dimensionless terms Argaman found that

$$n = \phi(\frac{D}{d})$$

whereas these results indicate that , for the slot tube,

$$n = \phi(\frac{Am}{Aj}, F)$$

Note particularly that F is the Froude number of the jet and not the densimetric Froude number. It is given by

$$F = \frac{Q}{Aj\sqrt{gd}}$$

In order to study the trend of the variation of initial dilution, n was plotted against different Froude numbers F for the same area ratios. Figure 5.12 shows the variation of n with the jet Froude number F. There was a lot of scatter in the plotted points. The initial dilution slightly increased with increase in Froude number for the area ratios of 2.87 and 2.26, whereas the initial dilution decreased with increasing Froude numbers for the area ratios of 11.46, 5.1 and 5.09. There was no continuity in the initial dilution for the area ratios of 5.09 (for model X2) and 5.1 (for model X1) which are close values. Instead there was a distinct break in the initial dilution values for these area ratios. The scatter and inconsistency shown in Figure 5.12 was thought to be due to experimental errors related to the procedure used.

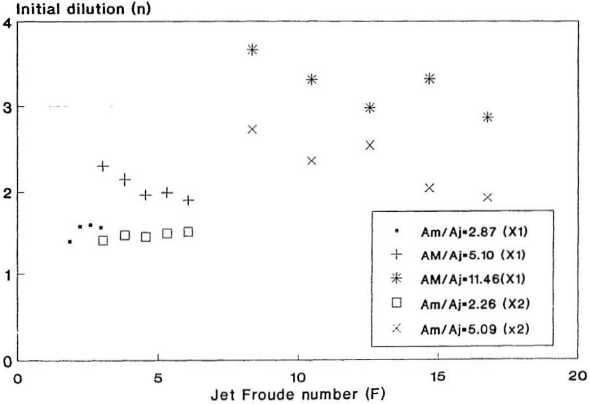


Figure 5.12: Variation of initial dilution *n* with jet Froude number

During the first set of tests, explained in section 2.2.4, tank A was not emptied after each test, but, depending on the amount of salt solution in tank B, sampling was continued. Although the salt concentration of the surrounding water was measured and was used in the calculation of the dilution (section 5.4), it was possible that there was a stratification in tank A with more salinity at the bottom and less towards the water surface. However during the calculation of dilution, the salinity of the surrounding water was considered to be uniform and this may have led to an error in the calculation of dilution. In addition flow from the nozzle was continuous which would lead to a time variation in the salinity of the receiving water. As the testing proceeded there would be a general increase in receiving water salinity in the vicinity of the nozzle and there may have been changes in salinity between the beginning and end of any particular test. Thus the single sample of receiving water taken during the test may not have been representative. This could have caused significant errors in calculating the dilution. It was hence decided to repeat the tests with a slight variation in the test procedure.

5.5 Second set of experiments

As mentioned earlier, because of the experimental scatter found in the first experiments, it was decided to repeat the experiments with the same flow conditions but with a slight variation in experimental procedure.

During the second set of experiments tank A was emptied after each trial instead of continuing the experiment again with an increased flow. To start the next trial, valve A was closed and tank A was again filled with fresh water. This rectified the error in the experimental procedure because the receiving water salinity was always equal to that of the fresh water supply throughout the trial and the samples of the receiving water collected during the test always had zero salinity. This also eliminated the possible interference of the effluent with the incoming jet. The salt water in tank B was mixed with a rod to achieve an even salt concentration throughout the water column.

The same number of tests discussed in section 5.2.1 were conducted with model mixing tube X1 following the new procedure. Because tank A was emptied and refilled with fresh water before each trial the receiving water sample was always zero. Following the determination of sample salinities, (Shown in Appendix 1) the dilutions within the mixing tubes were calculated as described earlier. At this point the initial dilution was plotted against the Froude number for different area ratios. As in the previous case, the initial dilution decreased with the increase in Froude number. The variation of the initial dilution was found consistent at different area ratios and there was much less experimental scatter. Then, to check the validity of the dimensionless plot, the experiments were continued with the Model mixing tube X2. The Model mixing tube X2 was a scale model of Model mixing tube X1 and had a cross sectional area of 25.81 sq. cm. (4 sq.inch). This model was too small for the large nozzle and was thus tested with the 3.81 cm. and 2.54 cm. diameter nozzles following the same experimental procedures. The combined results of Model X1 and Model X2 mixing tubes together with calculated values of Froude number F, Flow rate 'Q' , Area ratios Am/Aj and the average initial dilutions for each test are shown in Table 5.7 to 5.11. Figure 5.13 shows the variation of initial dilution n with the Froude number F for different area ratios. It can be clearly seen that

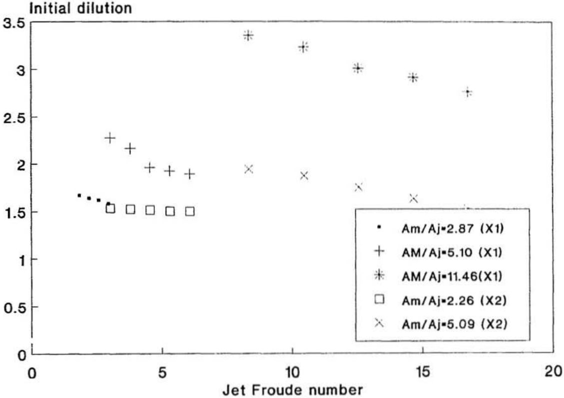


Figure 5.13: Variation of dilution n within the mixing tube with jet Froude number F during the second set of Experiments (Model X1 and X2)

the trend in the variation of initial dilution n is the same for all area ratios. The initial dilution reduces with increase in the jet Froude number. There is a little scatter in the plotted points but overall there is a smooth transition. Because of the fixed area of the models and the limitation in the availability of pipes used to represent the nozzles, it was not possible to exactly duplicate the area ratios of model X1 with model X2. However the curve obtained for an area ratio of 5.10 with model X1 is very close to that obtained with an area ratio of 5.02 with model X2. Similarly the curves for area ratios of 2.87 and 2.26 from models X1 and X2 respectively are very close. This agreement in results from the two geometrically similar tubes of different size supports the fact that the initial dilution is not only a function of the area ratio but also depends on the Froude number. Typically Figure 5.13 shows that the dilution within the mixing tube decreases slightly as the jet Froude number increases, and increases as the area ratio increases. The decrease with Froude number is relatively small. For example, with an area ratio of about 5.1 the dilution decreases from about 2.3 at a Froude number of 3.0 to about 1.6 at a Froude number of 17. However at a constant Froude number of about 8.0 the dilution increases from a value of 1.5 at an area ratio of 2.3 to as much as 3.5 at an area ratio of 11.5.

Tests were also conducted using the Model Y1 with the same experimental procedures. As mentioned earlier Model Y1 was smaller than Model X1 and hence tests were conducted using only two different nozzles. Tables 5.12 and 5.13 shows the average dilution within the mixing tube for all the tests. Figure 5.14 shows the variation of dilution within the mixing tube with the Froude number F. The trend in variation of initial dilution n is same as that of the models X1 and X2.

The initial dilution n within the mixing tube decreases as the jet Froude number increases and increases as the area ratio increases.

5.6 Calculation of overall dilution

The overall dilution is defined as the dilution between the discharge point and the surface of the receiving fluid. Hence if a mixing tube is installed to a discharging jet, the overall dilution would be the product of the dilution within the mixing tube and the dilution between the mixing tube and the surface of the receiving water. For the models described here the mixing tube discharged through a rectangular slot with length/breadth ratio equal to 32. At this geometry the discharge from the mixing tube was treated as a two dimensional jet. End effects were ignored in the following analysis which was undertaken to determine the approximate overall dilution of the mixing tube studied. The effect of ignoring the end effects is probably to overestimate subsequent dilution between the mixing tube and the surface. However experimentation would be necessary to quantify the effect. Having decided to treat the discharge from the mixing tube as a two dimensional jet, the theories developed by Abraham (1965) and Fan and Brooks(1969) were considered for calculating the subsequent dilution of the buoyant jet from the slot mixing tube. Experimental verification of both the theories was done by Cederwall (Cederwall, 1971) who found a close correlation between the theories and experiments (see section 2.1.4). Fan and Brooks theory was considered to be an improvement on Abraham's theory and hence was used to estimate the subsequent dilution from the slot mixing tube. Figure 5.15 shows the graphical presentation of Fan and Brooks

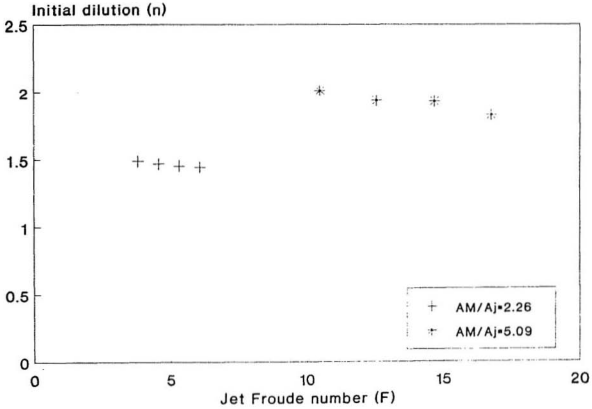


Figure 5.14: Variation of dilution n within the mixing tube with jet Froude number F (Model Y1).

theory along with the experiments of Cederwall. This figure was used to calculate the subsequent dilution from the slot mixing tube. A typical case of ambient surrounding water of depth 100 cm with no stratification was considered for the calculation purpose. Other flow parameters such as rate of discharge and density difference were taken from the experimental measurements. The x co-ordinate in Figure 5.15 namely $\left(\frac{Y}{B}\right)^{1/2} F_{\Delta(sm)}{}^{-2/3}$ was calculated using the assumed depth of ambient water and the depth of the slot of the model mixing tube and the densimetric Froude number of the jet. The corresponding y co-ordinate namely $S_d\left(\frac{Y}{B}\right)^{-1/2}$ was then directly read from the figure. The dilution S_d was then calculated from this relationship. The overall dilution of the slot mixing tube was hence the product of dilution within the mixing tube and the calculated subsequent dilution. A sample calculation of the subsequent dilution and hence the overall dilution is shown below.

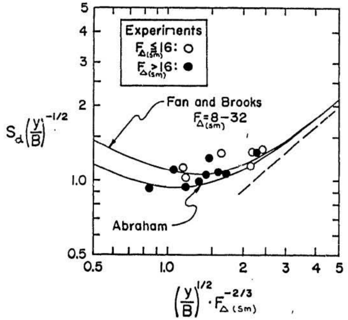


Figure 5.15: Graphical representation of center-line dilution for two dimensional buoyant jet in stagnant environment and comparison with experimental data (Cederwall, 1971)

Q_1 = rate of discharge from the jet
Q_2 = rate of discharge from the mixing tube
Am = cross-sectional area of the mixing tube
Aj = cross-sectional area of the discharging jet
d = diameter of the discharging jet
B = depth of the slot of the mixing tube
Y = depth of the receiving fluid
ρ = density of the receiving fluid
$\Delta\rho_1$ = difference in density between the fluid discharging from the jet and the surrounding fluid
$\Delta\rho_2$ = difference in density between the fluid discharging from the mixing tube and the surrounding fluid
= $\frac{\Delta\rho_1}{n}$
g = gravitational acceleration
g'_1 = $g\frac{\Delta\rho_1}{\rho}$
g'_2 = $g\frac{\Delta\rho_2}{\rho}$
n = dilution within the mixing tube.
$F_{\Delta(j)}, F_{\Delta(sm)}$ = densimetric Froude numbers of discharging jet and the slot mixing tube respectively

Because 'n' is the dilution within the mixing tube we can write

$$Q_2 = nQ_1 \qquad g'_2 = g'_1/n$$

and

$$F_{\Delta(j)} = \frac{Q_1}{Aj\sqrt{g'_1 d}} \tag{5.1}$$

$$F_{\Delta(sm)} = \frac{nQ_1}{Am\sqrt{g'_1 B/n}} \tag{5.2}$$

$$\frac{F_{\Delta(sm)}}{F_{\Delta(j)}} = n^{1.5}\left(\frac{Aj}{Am}\right)\left(\frac{d}{B}\right)^{1/2}$$

$$F_{\Delta(sm)} = F_{\Delta(j)} n^{1.5}\left(\frac{Aj}{Am}\right)\left(\frac{d}{B}\right)^{1/2} \tag{5.3}$$

Calculation of subsequent dilution:

Considering test number 33 as the typical test, the different flow parameters are

d = 5.08×10^{-2} m.
B = 0.0127 m.
Am/Aj = 5.10
Q = 2.69×10^{-3} m^3/sec.
$\Delta\rho$ = 0.026
g' = 0.2485
n = 2.27

Therefore from equations 5.1 and 5.3

$$F_{\Delta(j)} = 24.28$$

$$F_{\Delta(sm)} = 28.20$$

Assuming the depth of the receiving fluid as 1.0 meter, the X- coordinate of the Figure 5.15, developed by Cederwall would be

X-coordinate:

$$\left(\frac{Y}{B}\right)^{1/2} F_{\Delta(sm)}{}^{-2/3} = 0.96$$

For this value of the X-coordinate, the corresponding Y-coordinate is read as

$$S_d \left(\frac{Y}{B} \right)^{-1/2} = 1.11$$

Subsequent dilution S_d for the slot mixing tube is then calculated as

$$S_d = 9.85$$

The overall dilution for the slot mixing tube would be the product of the dilution 'n' within the mixing tube and the subsequent dilution S_d . Thus the overall dilution $S_{o(sm)}$ would be,

$$S_{o(sm)} = S_d * n = 22.36$$

Table 5.14 shows the overall dilution calculated for the second series of tests with Model X1 and X2.

A comparison was made between the predicted overall dilution from the slot mixing tubes and a circular mixing tube. The equations developed by Argaman and Cederwall (equations 2.40 and 2.41) were applied to a circular mixing tube having the same cross-sectional area as that of the experimental Model slot mixing tube. Density differences, flows and depths etc., were taken to be same as the values used in the computation of the overall dilution (section 5.6) for the slot mixing tube. The improvement in overall dilution for a slot mixing tube relative to a circular mixing tube was calculated by taking the ratio of the predicted overall dilutions of the slot mixing tube to the circular mixing tube. The improvements in overall dilution for Models X1 and X2 are tabulated in Table 5.15.

Calculations for overall dilution and the improvement over circular mixing tube were also done for Model Y1 following the same procedure. Tables 5.16 and 5.17 shows the overall dilution and the improvement of overall dilution of Model Y1 when compared to a circular mixing tube. These results are plotted in Figure 5.16 and 5.17. Figure 5.16 shows the variation of the ratio of overall dilution with the densimetric Froude number of the jet at different area ratios for models X1 and X2. This show that the ratio of overall dilution decreases with increase in the densimetric Froude number. The ratio was above 1.0 for densimetric Froude numbers from 10 to 35 and for area ratios from 2.26 to 5.10. Results obtained from Model X1 (Am/Aj = 2.87 and 5.10) agreed well with those from Model X2 (Am/Aj = 2.26 and 5.09). Results of the ratio of overall dilution were also plotted for model Y1 (Figure 5.17). The same general trends were observed but, for model Y1, the ratio was always less than 1.0.

5.7 Discussion

Model mixing tubes X1 and X2 were geometrically similar with the length of the mixing tube being approximately seven times the side of their square cross-section at the entry. The divergence angle was 20 degrees and the ratio of depth of the slot to the slot length was 36. Model Y1 had a length more than seven times the side of its square cross-section. The divergence angle was 10 degrees and the ratio of slot depth to the length of the slot was only 16. Model Y1 was thus longer and narrower than Model X1 and to some extant, was more three dimensional and more like a standard cylindrical mixing tube. From Figure 5.16 and 5.17 it is apparent

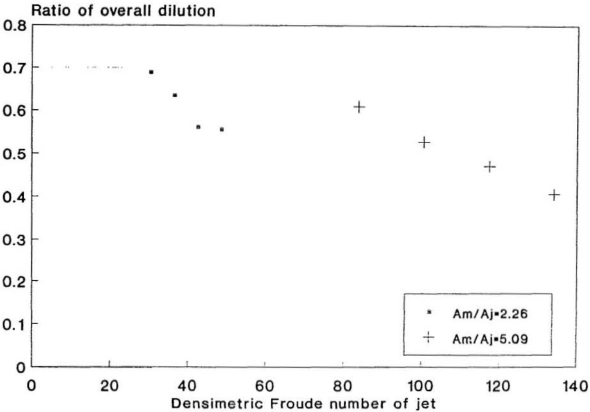


Figure 5.17: Improvement of overall dilution of slot mixing tube model Y1 when compared to circular mixing tube

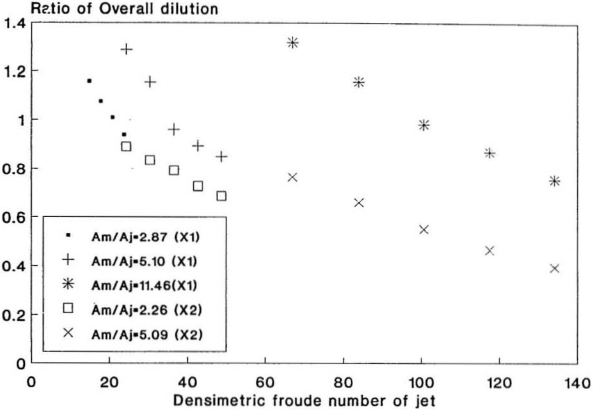


Figure 5.16: Improvement of overall dilution of slot mixing tube models X1 and X2 when compared to circular mixing tube

that models X1 and X2 performed substantially better than Model Y1. In fact over the whole of the range tested Model Y1 compared unfavourably with a standard circular mixing tube giving overall dilutions of only 0.4 to 0.7 of that which would be achieved by a standard tube.

For both the shapes tested the ratio of dilution with a slot tube to dilution with a cylindrical tube increased as the densimetric Froude number decreased and also increased as the area ratio increased. The best results, however, showed that the slot tube was only 1.2 to 1.3 times as effective as a cylindrical tube and, bearing in mind the potential limitations of the theory used to estimate subsequent dilution following discharge from the slot, this improvement was only an approxiamtion. Nevertheless the trend is such that there is some optimism.

Most outfalls operate at low densimetric Froude numbers and figures 5.16 and 5.17 show that the ratio increases as the densimetric Froude number decreases. Unfortunately it was not possible to obtain results at densimetric Froude numbers substantially less than 20 with the present experimental set-up. This was partly because of the difficulty in measuring lower flows with the rotameter available, but a more important reason lies in the nature of the flow pattern at low flows. The best flow distribution at exit from the slot tube tended to occur at the highest flows. As the flow from the nozzle decreased there was a tendency for the flow to separate from the sides of the mixing tube. This gives a very unevenly distributed flow from the exit slot with most of the flow occuring at the center and with little at the edges. A flow of this nature could not be considered to be two dimensional. It is necessary also to make some comments on the two dimensional nature of the flow from the exit slot. With a width to depth ratio of 36 to 1 (Models X1 and X2) and an even distribution across the slot, it is reasonable to consider the flow, at that point, to be two dimensional. However, as soon as the flow exits and begins to rise towards the surface, end effects begin to modify the two dimensional nature of the flow. These effects become more and more important with distance from the slot. If a substantial depth of water exists above the slot the flow will have become three dimensional before reaching the surface. Under these circumstances the use of a two dimensional theory provides only a guide to the magnitude of the dilution which might be experienced. However, in the absence of time to conduct experimental measurements of subsequent dilution, it was considered that the two dimensional theory would be adequate particularly as the experiments were designed primarily to test the feasibility of the idea of using a slot mixing tube rather than to design a particular tube which could be used in practice.

Test no.	Model no.	Dia. of the jet d in cm.	Am/Aj	Flow meter reading in %	Discharge Q in Litres/sec.	Froude number $F = \frac{Q/A_j}{\sqrt{gd}}$	Initial Dilution n	Average initial diluition
1	X1	5.08	2.87	80	5.39	2.96	1.53	1.56
	X1	5.08	2.87	80	5.39	2.96	1.55	
	X1	5.08	2.87	80	5.39	2.96	1.60	
2	X1	5.08	2.87	70	4.72	2.59	1.53	1.59
	X1	5.08	2.87	70	4.72	2.59	1.56	
	X1	5.08	2.87	70	4.72	2.59	1.67	
3	X1	5.08	2.87	60	4.04	2.22	1.55	1.57
	X1	5.08	2.87	60	4.04	2.22	1.57	
	X1	5.08	2.87	60	4.04	2.22	1.59	
4	X1	5.08	2.87	50	3.37	1.85	1.39	1.40
	X1	5.08	2.87	50	3.37	1.85	1.40	
	X1	5.08	2.87	50	3.37	1.85	1.41	

Table 5.2: Average dilution within the slot mixing tube during tests 1 to 4

Test no.	Model no.	Dia. of the jet d in cm.	Am/Aj	Flow meter reading in %	Discharge Q in Litres/sec.	Froude number $F = \frac{Q/Aj}{\sqrt{gd}}$	Initial Dilution n	Average initial diluition
5	X1	3.81	5.10	80	5.39	6.07	1.81	1.87
	X1	3.81	5.10	80	5.39	6.07	1.87	
	X1	3.81	5.10	80	5.39	6.07	1.94	
6	X1	3.81	5.10	70	4.72	5.31	1.89	2.00
	X1	3.81	5.10	70	4.72	5.31	2.00	
	X1	3.81	5.10	70	4.72	5.31	2.10	
7	X1	3.81	5.10	60	4.04	4.55	1.91	1.97
	X1	3.81	5.10	60	4.04	4.55	1.94	
	X1	3.81	5.10	60	4.04	4.55	2.05	
8	X1	3.81	5.10	50	3.37	3.80	2.00	2.14
	X1	3.81	5.10	50	3.37	3.80	2.17	
	X1	3.81	5.10	50	3.37	3.80	2.25	
9	X1	3.81	5.10	40	2.69	3.03	2.26	2.30
	X1	3.81	5.10	40	2.69	3.03	2.31	
	X1	3.81	5.10	40	2.69	3.03	2.32	

Table 5.3: Average dilution within the slot mixing tube during tests 5 to 9

Test no.	Model no.	Dia. of the jet d in cm.	Am/Aj	Flow meter reading in %	Discharge Q in Litres/sec.	Froude number $F = \frac{Q/Aj}{\sqrt{gd}}$	Initial Dilution n	Average initial diluition
10	X1	2.54	3.03	80	5.39	16.74	2.52	2.85
	X1	2.54	3.03	80	5.39	16.74	3.01	
	X1	2.54	3.03	80	5.39	16.74	3.03	
11	X1	2.54	3.03	70	4.72	14.66	3.11	3.31
	X1	2.54	3.03	70	4.72	14.66	3.30	
	X1	2.54	3.03	70	4.72	14.66	3.52	
12	X1	2.54	3.03	60	4.04	12.54	2.89	2.98
	X1	2.54	3.03	60	4.04	12.54	2.98	
	X1	2.54	3.03	60	4.04	12.54	3.08	
13	X1	2.54	3.03	50	3.37	10.46	3.00	3.31
	X1	2.54	3.03	50	3.37	10.46	3.41	
	X1	2.54	3.03	50	3.37	10.46	3.51	
14	X1	2.54	3.03	40	2.69	8.35	3.44	3.67
	X1	2.54	3.03	40	2.69	8.35	3.66	
	X1	2.54	3.03	40	2.69	8.35	3.90	

Table 5.4: Average dilution within the slot mixing tube during tests 10 to 14

Test no.	Model no.	Dia. of the jet d in cm.	Am/Aj	Flow meter reading in %	Discharge Q in Litres/sec.	Froude number $F = \frac{Q/Aj}{\sqrt{gd}}$	Initial Dilution n	Average initial diluition
15	X2	3.81	5.09	80	5.39	6.07	1.49	1.51
	X2	3.81	5.09	80	5.39	6.07	1.51	
	X2	3.81	5.09	80	5.39	6.07	1.53	
16	X2	3.81	5.09	70	4.72	5.31	1.47	1.49.
	X2	3.81	5.09	70	4.72	5.31	1.50	
	X2	3.81	5.09	70	4.72	5.31	1.51	
17	X2	3.81	5.09	60	4.04	4.55	1.42	1.45
	X2	3.81	5.09	60	4.04	4.55	1.46	
	X2	3.81	5.09	60	4.04	4.55	1.48	
18	X2	3.81	5.09	50	3.37	3.80	1.45	1.47
	X2	3.81	5.09	50	3.37	3.80	1.47	
	X2	3.81	5.09	50	3.37	3.80	1.49	
19	X2	3.81	5.09	40	2.69	3.03	1.36	1.41
	X2	3.81	5.09	40	2.69	3.03	1.41	
	X2	3.81	5.09	40	2.69	3.03	1.47	

Table 5.5: Average dilution within the slot mixing tube during tests 15 to 19

Test no.	Model no.	Dia. of the jet d in cm.	Am/Aj	Flow meter reading in %	Discharge Q in Litres/sec.	Froude number $F = \frac{Q/A_j}{\sqrt{gd}}$	Initial Dilution n	Average initial diluition
20	X2	2.54	2.26	80	5.39	16.74	1.89	1.90
	X2	2.54	2.26	80	5.39	16.74	1.90	
	X2	2.54	2.26	80	5.39	16.74	1.92	
21	X2	2.54	2.26	70	4.72	14.66	2.00	2.04
	X2	2.54	2.26	70	4.72	14.66	2.03	
	X2	2.54	2.26	70	4.72	14.66	2.10	
22	X2	2.54	2.26	60	4.04	12.54	2.30	2.54
	X2	2.54	2.26	60	4.04	12.54	2.46	
	X2	2.54	2.26	60	4.04	12.54	2.87	
23	X2	2.54	2.26	50	3.37	10.46	2.32	2.36
	X2	2.54	2.26	50	3.37	10.46	2.38	
	X2	2.54	2.26	50	3.37	10.46	2.38	
24	X2	2.54	2.26	40	2.69	8.35	2.60	2.71
	X2	2.54	2.26	40	2.69	8.35	2.75	
	X2	2.54	2.26	40	2.69	8.35	2.79	

Table 5.6: Average dilution within the slot mixing tube during tests 20 to 24

Test no.	Model no.	Dia. of the jet d in cm.	Am/Aj	Flow meter reading in %	Discharge Q in Litres/sec.	Froude number $F = \frac{Q/Aj}{\sqrt{gd}}$	Initial Dilution n	Average initial diluition
25	X1	5.08	2.87	80	5.39	2.96	1.60	1.58
	X1	5.08	2.87	80	5.39	2.96	1.57	
	X1	5.08	2.87	80	5.39	2.96	1.58	
26	X1	5.08	2.87	70	4.72	2.59	1.64	1.62
	X1	5.08	2.87	70	4.72	2.59	1.60	
	X1	5.08	2.87	70	4.72	2.59	1.62	
27	X1	5.08	2.87	60	4.04	2.22	1.64	1.64
	X1	5.08	2.87	60	4.04	2.22	1.67	
	X1	5.08	2.87	60	4.04	2.22	1.61	
28	X1	5.08	2.87	50	3.37	1.85	1.65	1.67
	X1	5.08	2.87	50	3.37	1.85	1.67	
	X1	5.08	2.87	50	3.37	1.85	1.70	

Table 5.7: Average dilution within the slot mixing tube during second series of tests 25 to 28

Test no.	Model no.	Dia. of the jet d in cm.	Am/Aj	Flow meter reading in %	Discharge Q in Litres/sec.	Froude number $F = \frac{Q/A_j}{\sqrt{gd}}$	Initial Dilution n	Average initial diluition
29	X1	3.81	5.1	80	5.39	6.07	1.84	1.89
	X1	3.81	5.1	80	5.39	6.07	1.90	
	X1	3.81	5.1	80	5.39	6.07	1.93	
30	X1	3.81	5.1	70	4.72	5.31	1.92	1.92
	X1	3.81	5.1	70	4.72	5.31	1.88	
	X1	3.81	5.1	70	4.72	5.31	1.97	
31	X1	3.81	5.1	60	4.04	4.55	1.97	1.96
	X1	3.81	5.1	60	4.04	4.55	1.94	
	X1	3.81	5.1	60	4.04	4.55	1.97	
32	X1	3.81	5.1	50	3.37	3.80	2.12	2.16
	X1	3.81	5.1	50	3.37	3.80	2.18	
	X1	3.81	5.1	50	3.37	3.80	2.18	
33	X1	3.81	5.1	40	2.69	3.03	2.29	2.27
	X1	3.81	5.1	40	2.69	3.03	2.26	
	X1	3.81	5.1	40	2.69	3.03	2.26	

Table 5.8: Average dilution within the slot mixing tube during second series of tests 29 to 33

Test no.	Model no.	Dia. of the jet d in cm.	Am/Aj	Flow meter reading in %	Discharge Q in Litres/sec.	Froude number $F = \frac{Q/Aj}{\sqrt{gd}}$	Initial Dilution n	Average initial diluition
34	X1	2.54	11.46	80	5.39	16.74	2.52	2.76
	X1	2.54	11.46	80	5.39	16.74	2.72	
	X1	2.54	11.46	80	5.39	16.74	3.04	
35	X1	2.54	11.46	70	4.72	14.66	2.93	2.90
	X1	2.54	11.46	70	4.72	14.66	2.91	
	X1	2.54	11.46	70	4.72	14.66	2.86	
36	X1	2.54	11.46	60	4.04	12.54	2.90	3.01
	X1	2.54	11.46	60	4.04	12.54	3.06	
	X1	2.54	11.46	60	4.04	12.54	3.08	
37	X1	2.54	11.46	50	3.37	10.46	3.17	3.23
	X1	2.54	11.46	50	3.37	10.46	3.25	
	X1	2.54	11.46	50	3.37	10.46	3.28	
38	X1	2.54	11.46	40	2.69	8.35	3.37	3.35
	X1	2.54	11.46	40	2.69	8.35	3.40	
	X1	2.54	11.46	40	2.69	8.35	3.27	

Table 5.9: Average dilution within the slot mixing tube during second series of tests 34 to 38

Test no.	Model no.	Dia. of the jet d in cm.	Am/Aj	Flow meter reading in %	Discharge Q in Litres/sec.	Froude number $F = \frac{Q/A_j}{\sqrt{gd}}$	Initial Dilution n	Average initial dilution
39	X2	3.81	2.26	80	5.39	6.07	1.49	1.50
	X2	3.81	2.26	80	5.39	6.07	1.48	
	X2	3.81	2.26	80	5.39	6.07	1.52	
40	X2	3.81	2.26	70	4.72	5.31	1.51	1.51
	X2	3.81	2.26	70	4.72	5.31	1.47	
	X2	3.81	2.26	70	4.72	5.31	1.54	
41	X2	3.81	2.26	60	4.04	4.55	1.54	1.52
	X2	3.81	2.26	60	4.04	4.55	1.51	
	X2	3.81	2.26	60	4.04	4.55	1.51	
42	X2	3.81	2.26	50	3.37	3.80	1.51	1.52
	X2	3.81	2.26	50	3.37	3.80	1.52	
	X2	3.81	2.26	50	3.37	3.80	1.53	
43	X2	3.81	2.26	40	2.69	3.03	1.45	1.46
	X2	3.81	2.26	40	2.69	3.03	1.45	
	X2	3.81	2.26	40	2.69	3.03	1.48	

Table 5.10: Average dilution within the slot mixing tube during second series of tests 39 to 43

Test no.	Model no.	Dia. of the jet d in cm.	Am/Aj	Flow meter reading in %	Discharge Q in Litres/sec.	Froude number $F = \frac{Q/Aj}{\sqrt{gd}}$	Initial Dilution n	Average initial diluition
44	X2	2.54	5.09	80	5.39	16.74	1.48	1.52
	X2	2.54	5.09	80	5.39	16.74	1.50	
	X2	2.54	5.09	80	5.39	16.74	1.58	
45	X2	2.54	5.09	70	4.72	14.66	1.67	1.63
	X2	2.54	5.09	70	4.72	14.66	1.61	
	X2	2.54	5.09	70	4.72	14.66	1.62	
46	X2	2.54	5.09	60	4.04	12.54	1.70	1.75
	X2	2.54	5.09	60	4.04	12.54	1.82	
	X2	2.54	5.09	60	4.04	12.54	1.74	
47	X2	2.54	5.09	50	3.37	10.46	1.83	1.89
	X2	2.54	5.09	50	3.37	10.46	1.90	
	X2	2.54	5.09	50	3.37	10.46	1.93	
48	X2	2.54	5.09	40	2.69	8.35	1.93	1.94
	X2	2.54	5.09	40	2.69	8.35	1.94	
	X2	2.54	5.09	40	2.69	8.35	1.95	

Table 5.11: Average dilution within the slot mixing tube during second series of tests 44 to 48

Test no.	Model no.	Dia. of the jet d in cm.	Am/Aj	Flow meter reading in %	Discharge Q in Litres/sec.	Froude number $F = \frac{Q/Aj}{\sqrt{gd}}$	Initial Dilution n	Average initial diluition
49	Y1	3.81	5.09	80	5.39	6.07	1.43	1.44
	Y1	3.81	5.09	80	5.39	6.07	1.44	
	Y1	3.81	5.09	80	5.39	6.07	1.45	
50	Y1	3.81	5.09	70	4.72	5.31	1.46	1.46
	Y1	3.81	5.09	70	4.72	5.31	1.46	
	Y1	3.81	5.09	70	4.72	5.31	1.46	
51	Y1	3.81	5.09	60	4.04	4.55	1.46	1.46
	Y1	3.81	5.09	60	4.04	4.55	1.46	
	Y1	3.81	5.09	60	4.04	4.55	1.46	
52	Y1	3.81	5.09	50	3.37	3.80	1.49	1.49
	Y1	3.81	5.09	50	3.37	3.80	1.50	
	Y1	3.81	5.09	50	3.37	3.80	1.48	

Table 5.12: Average dilution within the slot mixing tube Y1 during tests 49 to 52

Test no.	Model no.	Dia. of the jet d in cm.	Am/Aj	Flow meter reading in %	Discharge Q in Litres/sec.	Froude number $F = \frac{Q/Aj}{\sqrt{gd}}$	Initial Dilution n	Average initial diluition
53	Y1	2.54	5.09	80	5.39	16.74	1.82	1.83
	Y1	2.54	5.09	80	5.39	16.74	1.84	
	Y1	2.54	5.09	80	5.39	16.74	1.84	
54	Y1	2.54	5.09	70	4.72	14.66	1.92	1.94
	Y1	2.54	5.09	70	4.72	14.66	1.93	
	Y1	2.54	5.09	70	4.72	14.66	1.94	
55	Y1	2.54	5.09	60	4.04	12.54	1.88	1.94
	Y1	2.54	5.09	60	4.04	12.54	1.94	
	Y1	2.54	5.09	60	4.04	12.54	2.00	
56	Y1	2.54	5.09	50	3.37	10.46	1.98	2.01
	Y1	2.54	5.09	50	3.37	10.46	2.00	
	Y1	2.54	5.09	50	3.37	10.46	2.04	

Table 5.13: Average dilution within the slot mixing tube during second series of tests 53 to 56

Test No.	Am/Aj	$F_{\Delta(jet)}$	$F_{\Delta(sm)}$	n	X co-ordinate	Y co-ordinate	S_d	$S_{o(sm)}$
25	2.87	23.70	32.79	1.58	0.87	1.16	10.28	16.28
26	2.87	20.75	29.82	1.62	0.92	1.13	10.02	16.23
27	2.87	17.76	25.99	1.64	1.01	1.10	9.76	16.01
28	2.87	14.82	22.28	1.67	1.12	1.08	9.57	15.98
29	5.10	48.64	42.92	1.89	0.72	1.28	11.35	21.45
30	5.10	42.60	38.49	1.92	0.78	1.22	10.82	20.77
31	5.10	36.46	33.98	1.96	0.85	1.17	10.38	20.34
32	5.10	30.41	32.79	2.16	0.87	1.16	10.29	22.23
33	5.10	24.28	28.20	2.27	0.96	1.11	9.85	22.36
34	11.46	134.04	75.85	2.76	0.5	1.47	13.04	35.99
35	11.46	117.38	71.54	2.90	0.51	1.46	12.95	37.56
36	11.46	100.47	64.75	3.01	0.55	1.42	12.59	37.90
37	11.46	83.81	60.04	3.23	0.58	1.38	12.24	39.54
38	11.46	66.90	50.62	3.35	0.65	1.32	11.71	39.23
39	2.26	48.64	83.53	1.50	0.57	1.39	15.10	22.65
40	2.26	42.60	73.44	1.50	0.62	1.34	14.57	21.86
41	2.26	36.46	63.68	1.51	0.68	1.31	14.24	21.50
42	2.26	30.41	53.48	1.52	0.77	1.23	13.37	20.32
43	2.26	24.28	43.54	1.54	0.88	1.15	12.50	19.25
44	5.09	134.04	85.46	1.52	0.56	1.40	15.21	23.12
45	5.09	117.38	83.11	1.63	0.57	1.39	15.10	24.61
46	5.09	100.47	79.13	1.75	0.59	1.37	14.89	26.06
47	5.09	83.81	74.09	1.89	0.62	1.34	14.57	27.54
48	5.09	66.90	61.50	1.94	0.7	1.30	14.13	27.41

Tests 25 to 38 are conducted with Model X1 and Tests 39 to 48 are conducted with Model X2

Table 5.14: Predicted overall dilution of the slot mixing tube Models X1 and X2

Test No.	Am/Aj	$F_{\Delta(jet)}$	$S_{o(cm)}$	slot mixing tube n	 S_d	 $S_{o(sm)}$	IF $S_{o(sm)}/S_{o(cm)}$
25	2.87	23.70	17.28	1.58	10.28	16.24	0.94
26	2.87	20.75	16.03	1.62	10.02	16.23	1.01
27	2.87	17.76	14.91	1.64	9.76	16.01	1.07
28	2.87	14.82	13.80	1.67	9.57	15.98	1.16
29	5.10	48.64	25.25	1.89	11.35	21.45	0.85
30	5.10	42.60	23.22	1.92	10.82	20.77	0.89
31	5.10	36.46	21.19	1.96	10.38	20.34	0.96
32	5.10	30.41	19.24	2.16	10.29	22.23	1.16
33	5.10	24.28	17.34	2.27	9.85	22.36	1.29
34	11.46	134.04	47.62	2.76	13.04	35.99	0.76
35	11.46	117.38	43.13	2.90	12.95	37.56	0.87
36	11.46	100.47	38.59	3.01	12.59	37.90	0.98
37	11.46	83.81	34.17	3.23	12.24	39.54	1.16
38	11.46	66.90	29.75	3.35	11.71	39.23	1.32
39	2.26	48.64	32.86	1.50	15.10	22.65	0.69
40	2.26	42.60	30.01	1.50	14.57	21.86	0.73
41	2.26	36.46	27.14	1.51	14.24	21.50	0.79
42	2.26	30.41	24.36	1.52	13.37	20.32	0.83
43	2.26	24.28	21.62	1.54	12.50	19.25	0.89
44	5.09	134.04	58.84	1.52	15.21	23.12	0.39
45	5.09	117.38	53.08	1.63	15.10	24.61	0.46
46	5.09	100.47	47.25	1.75	14.89	26.06	0.55
47	5.09	83.81	41.56	1.89	14.57	27.54	0.66
48	5.09	66.90	35.84	1.94	14.13	27.41	0.76

Tests 25 to 38 are conducted with Model X1 and Tests 39 to 48 are conducted with Model X2

Table 5.15: Improvement of overall dilution of Model X1 and X2 when compared to circular mixing tube

Test No.	Am/Aj	$F_{\Delta(jet)}$	$S_{o(cm)}$	slot mixing tube			IF
				n	S_d	$S_{o(sm)}$	$S_{o(sm)}/S_{o(cm)}$
49	2.26	48.64	32.86	1.44	12.59	18.13	0.55
50	2.26	42.60	30.01	1.46	11.62	16.97	0.57
51	2.26	36.46	27.14	1.46	11.70	17.08	0.63
52	2.26	30.41	24.36	1.49	11.26	16.78	0.69
53	5.09	134.04	58.84	1.83	13.03	23.84	0.41
54	5.09	117.38	53.08	1.93	12.95	24.99	0.47
55	5.09	100.47	47.25	1.94	12.86	24.95	0.53
56	5.09	83.81	41.56	2.01	12.59	25.31	0.61

Table 5.16: Predicted overall dilution of the slot mixing tube (Model Y1)

Test No.	Am/Aj	$F_{\Delta(jet)}$	$F_{\Delta(sm)}$	n	X co-ordinate	Y co-ordinate	S_d	$S_{o(sm)}$
49	2.26	48.64	64.82	1.45	0.55	1.42	12.59	18.13
50	2.26	42.60	56.70	1.45	0.60	1.31	11.62	16.97
51	2.26	36.46	49.95	1.47	0.65	1.32	11.70	17.08
52	2.26	30.41	42.48	1.49	0.73	1.27	11.26	16.78
53	5.09	134.04	92.27	1.83	0.43	1.46	12.95	23.70
54	5.09	117.38	87.31	1.93	0.45	1.47	13.03	25.15
55	5.09	100.47	75.19	1.94	0.50	1.45	12.86	24.95
56	5.09	83.81	66.45	2.01	0.54	1.42	12.59	25.31

Table 5.17: Improvement of overall dilution of Model Y1 when compared to circular mixing tube

Chapter 6

Conclusion and Recommendations

6.1 Field Study

During the field study the average dilution achieved at the outfall when vertical nozzles were installed was in reasonable agreement with the theoretical dilution calculated for a vertical buoyant jet. Due to the error in installation, the field tests were repeated for horizontal buoyant jets. As expected, an increase in measured dilution was achieved with the horizontal jet when compared to the vertical buoyant jet. Measured dilutions for both horizontal and vertical buoyant jets were in good agreement with the calculated theoretical dilutions. Although the percentage errors between the measured and calculated dilutions were high for individual tests, the errors between the average values of measured and calculated dilutions were found to be only 1% for both horizontal and vertical buoyant jets. Results showed that there was no over or under-prediction of the dilution measured in the field. Hence there was a close correlation between the measured and calculated dilutions for both horizontal and vertical jets.

There was a higher variation between the calculated and measured values for the test done after installing the cylindrical mixing tube. The percentage error then was always in excess of 25% with measured dilutions always being greater than the calculate theoretical dilutions. This implies that the mixing tube performed better in the field than predicted by the theory. However the final results might be influenced by the receiving water temperature and salinity which were assumed to be same for all three field tests. It should also be noted that the stratification and velocity of the receiving water also were not taken into account during the calculation. Mixing tubes were left in place for the whole winter months of 1990. After removal, they were found to be in good shape except for the rust on the stands which were made of mild steel. However it should be noted that no major storms and no severe ice conditions were experienced during the winter of 1990. The good condition of the tube on removal cannot therefore be taken as an assurance that the design was structurally adequate under all winter conditions.

6.2 Experimental Study

Experimental studies done on slot mixing tubes showed that the dilution within the mixing tubes decreased with an increase in Froude number at all area ratios. It was thus clear that the dilution within the mixing tube was not only a function of area ratio, as given by the theory for circular mixing tubes, but was also a function of jet Froude number. The subsequent dilution from the slot mixing tube was calculated using the existing theory for a two dimensional buoyant jet developed by Fan and Brooks (1968). Experimental flow conditions and 1.0 meter depth of receiving fluid were assumed for calculation purposes. Overall dilution was calculated by taking the product of the measured initial dilution within the mixing tube and the calculated subsequent dilution. Comparison was made between the performance of the slot mixing tube with a circular mixing tube having the same cross sectional area and operating under the same flow conditions as that of the slot mixing tube. Results showed that improvement in overall dilution of a slot mixing tube compared to a circular mixing tube decreased with increase in the densimetric Froude number of the jet for all the different area ratios. The slot mixing tube performed better at lower Froude numbers. Models X1 and X2 performed better than Model Y1 but the maximum improvement relative to a cylindrical mixing tube was no more than 1.2 to 1.3 within the range tested. Model Y1 showed no improvement over a circular mixing tube. Due to the limitations of the two dimensional buoyant jet theory used for calculating the subsequent dilution, the overall dilution of the slot mixing tube was only an approximation. Nevertheless the trends shown were optimistic.

6.3 Recommendations for further laboratory research

As mentioned earlier, slot mixing tubes performed better at lower Froude numbers. Further experiments at lower Froude numbers could provide better improvement over the circular mixing tubes and should be undertaken to ascertain the magnitude of any such improvement. From the trends shown in Figure 5.16 it is apparent that further experimental work is required for slots operating at low Froude numbers but with a large area ratio. However at low Froude numbers the flow from the slot mixing tube is concentrated at the center of the slot with low flow at the edges. Hence it would be difficult to obtain even flow distribution all along the slot and the slot might need to be redesigned to ensure an even distribution of flow.

Further experiments are also required to remove the problems associated with using a two dimensional theory for the dilution between the slot exit and the surface. These dilutions should be measured in a separate series of experiments.

In conclusion it can be said that the results obtained from the slot mixing tubes show some positive trends to indicate that slot tubes might be an improvement over circular mixing tubes. Unfortunately the improvement does not seem particularly substantial. However results certainly indicate that further work should be done along the same general lines.

Chapter 7

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Chapter 8

Appendix

Figures 8.1 and 8.2 show the position of the sampling points at which samples were collected during the tests.

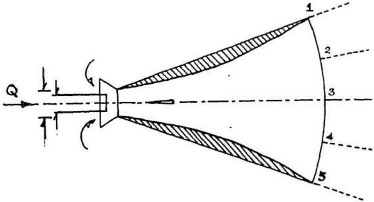

Figure 8.1: Sampling points for Models X1 and X2

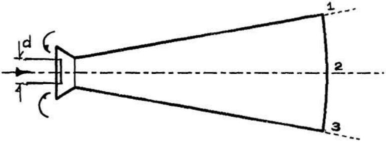

Figure 8.2: Sampling points for Model Y1

TEST NUMBER : 1 MODEL NUMBER: X1

FLOW METER READING IN PERCENTAGE: = 80%

FLOW RATE IN LITRES/SEC. : = 5.33

CORRECTION FACTOR FOR SALT WATER: = 1.01

ACTUAL FLOW RATE IN LITRES/SEC., Q= 5.39

Sample	Trial 1 Salinity in ppt	Trial 2 Salinity in ppt	Trial 3 Salinity in ppt
T1	31.00	30.50	30.50
T2	30.50	30.50	30.50
1	18.50	19.00	19.00
2	21.00	21.50	21.00
3	22.50	23.00	23.00
4	20.00	21.00	21.00
5	18.50	19.00	19.00
Salinity S2	0.00	3.00	4.00
Average of 1-5 Salinity S3	20.10	20.70	20.60
Average of T1 & T2 Salinity S1	30.75	30.50	30.50
Initial dilution n	1.53	1.55	1.60

T1 & T2 : Samples collected from tank B
Samples 1-5 : Samples collected from the end of the mixing tube according to the figure shown in page one of Appendix
S2 : Sample of the surrounding water
n : Initial dilution within the mixing tube

TEST NUMBER : 2 MODEL NUMBER: X1

FLOW METER READING IN PERCENTAGE: = 70%

FLOW RATE IN LITRES/SEC. : = 4.67

CORRECTION FACTOR FOR SALT WATER: = 1.01

ACTUAL FLOW RATE IN LITRES/SEC., Q= 4.72

Sample	Trial 1 Salinity in ppt	Trial 2 Salinity in ppt	Trial 3 Salinity in ppt
T1	30.50	31.00	31.00
T2	31.00	31.00	31.00
1	19.00	19.50	19.00
2	20.50	21.50	21.00
3	22.50	23.00	22.50
4	20.00	21.50	20.50
5	18.50	19.50	19.00
Salinity S2	0.00	3.00	4.50
Average of 1-5 Salinity S3	20.10	20.10	20.40
Average of T1 & T2 Salinity S1	30.75	31.00	31.00
Initial dilution n	1.53	1.56	1.67

T1 & T2 : Samples collected from tank B
Samples 1-5 : Samples collected from the end of the mixing tube according to the figure shown in page one of Appendix
S2 : Sample of the surrounding water
n : Initial dilution within the mixing tube

TEST NUMBER : 3

MODEL NUMBER: X1

FLOW METER READING IN PERCENTAGE: = 60%

FLOW RATE IN LITRES/SEC. : = 4.00

CORRECTION FACTOR FOR SALT WATER: = 1.01

ACTUAL FLOW RATE IN LITRES/SEC., Q= 4.04

Sample	Trial 1 Salinity in ppt	Trial 2 Salinity in ppt	Trial 3 Salinity in ppt
T1	30.50	30.50	30.50
T2	30.50	30.50	30.50
1	18.00	19.00	19.50
2	20.50	21.00	21.50
3	22.00	22.50	23.00
4	20.00	21.00	21.00
5	18.00	19.00	19.50
Salinity S2	0.00	3.00	4.50
Average of 1-5 Salinity S3	19.70	20.50	20.90
Average of T1 & T2 Salinity S1	30.50	30.50	30.50
Initial dilution n	1.55	1.57	1.59

T1 & T2 : Samples collected from tank B
Samples 1-5 : Samples collected from the end of the mixing tube according to the figure shown in page one of Appendix
S2 : Sample of the surrounding water
n : Initial dilution within the mixing tube

TEST NUMBER : 4 MODEL NUMBER: X1

FLOW METER READING IN PERCENTAGE: = 50%

FLOW RATE IN LITRES/SEC. : = 3.33

CORRECTION FACTOR FOR SALT WATER: = 1.01

ACTUAL FLOW RATE IN LITRES/SEC., Q= 3.37

Sample	Trial 1 Salinity in ppt	Trial 2 Salinity in ppt	Trial 3 Salinity in ppt
T1	29.00	29.00	29.00
T2	29.00	29.00	29.00
1	19.50	20.00	20.00
2	21.50	22.50	22.50
3	23.00	23.50	24.00
4	21.00	22.00	20.00
5	19.50	20.00	20.00
Salinity S2	0.00	3.00	4.00
Average of 1-5 Salinity S3	20.90	21.60	21.80
Average of T1 & T2 Salinity S1	29.00	29.00	29.00
Initial dilution n	1.39	1.40	1.41

T1 & T2	: Samples collected from tank B
Samples 1-5	: Samples collected from the end of the mixing tube according to the figure shown in page one of Appendix
S2	: Sample of the surrounding water
n	: Initial dilution within the mixing tube

TEST NUMBER : 5 MODEL NUMBER: X1

FLOW METER READING IN PERCENTAGE: = 80%

FLOW RATE IN LITRES/SEC. : = 5.33

CORRECTION FACTOR FOR SALT WATER: = 1.01

ACTUAL FLOW RATE IN LITRES/SEC., Q= 5.39

Sample	Trial 1 Salinity in ppt	Trial 2 Salinity in ppt	Trial 3 Salinity in ppt
T1	31.50	31.00	32.00
T2	32.00	32.00	32.00
1	16.00	17.00	17.50
2	17.50	19.00	20.00
3	19.00	21.00	21.50
4	17.50	19.50	20.00
5	16.00	17.00	18.00
Salinity S2	0.00	4.00	6.00
Average of 1-5 Salinity S3	17.20	18.70	19.40
Average of T1 & T2 Salinity S1	31.75	31.50	32.00
Initial dilution n	1.84	1.87	1.94

T1 & T2 : Samples collected from tank B

Samples 1-5 : Samples collected from the end of the mixing tube according to the figure shown in page one of Appendix

S2 : Sample of the surrounding water

n : Initial dilution within the mixing tube

TEST NUMBER : 6 MODEL NUMBER: X1

FLOW METER READING IN PERCENTAGE: = 70%

FLOW RATE IN LITRES/SEC. : = 4.67

CORRECTION FACTOR FOR SALT WATER: = 1.01

ACTUAL FLOW RATE IN LITRES/SEC., Q= 4.72

Sample	Trial 1 Salinity in ppt	Trial 2 Salinity in ppt	Trial 3 Salinity in ppt
T1	31.00	31.00	31.50
T2	31.00	31.50	31.50
1	15.00	16.00	16.50
2	17.00	17.00	18.00
3	18.00	19.00	19.50
4	17.00	17.50	18.00
5	15.00	16.00	16.00
Salinity S2	0.00	3.00	5.00
Average of 1-5 Salinity S3	16.40	17.20	17.60
Average of T1 & T2 Salinity S1	31.00	31.25	31.50
Initial dilution n	1.89	2.00	2.10

T1 & T2 : Samples collected from tank B
Samples 1-5 : Samples collected from the end of the mixing tube according to the figure shown in page one of Appendix
S2 : Sample of the surrounding water
n : Initial dilution within the mixing tube

TEST NUMBER : 7 MODEL NUMBER: X1

FLOW METER READING IN PERCENTAGE: = 60%

FLOW RATE IN LITRES/SEC. : = 4.00

CORRECTION FACTOR FOR SALT WATER: = 1.01

ACTUAL FLOW RATE IN LITRES/SEC., Q= 4.04

Sample	Trial 1 Salinity in ppt	Trial 2 Salinity in ppt	Trial 3 Salinity in ppt
T1	31.00	31.00	31.00
T2	31.00	31.00	31.00
1	15.00	16.50	16.50
2	16.50	18.00	18.00
3	18.00	19.50	19.00
4	16.50	18.00	17.50
5	15.00	16.50	16.00
Salinity S2	0.00	3.50	4.50
Average of 1-5 Salinity S3	16.20	17.70	17.40
Average of T1 & T2 Salinity S1	31.00	31.00	31.00
Initial dilution n	1.91	1.94	2.05

T1 & T2	: Samples collected from tank B
Samples 1-5	: Samples collected from the end of the mixing tube according to the figure shown in page one of Appendix
S2	: Sample of the surrounding water
n	: Initial dilution within the mixing tube

TEST NUMBER : 8 MODEL NUMBER: X1

FLOW METER READING IN PERCENTAGE: = 50%

FLOW RATE IN LITRES/SEC. : = 3.33

CORRECTION FACTOR FOR SALT WATER: = 1.01

ACTUAL FLOW RATE IN LITRES/SEC., Q= 3.37

Sample	Trial 1 Salinity in ppt	Trial 2 Salinity in ppt	Trial 3 Salinity in ppt
T1	30.50	31.00	31.00
T2	31.00	31.00	31.50
1	14.50	15.00	15.00
2	15.50	16.00	17.00
3	17.00	17.50	18.00
4	15.50	16.00	17.00
5	14.50	15.00	15.00
Salinity S2	0.00	3.00	4.50
Average of 1-5 Salinity S3	15.40	15.90	16.40
Average of T1 & T2 Salinity S1	30.75	31.00	31.25
Initial dilution n	2.00	2.17	2.25

T1 & T2 : Samples collected from tank B
Samples 1-5 : Samples collected from the end of the mixing tube according to the figure shown in page one of Appendix
S2 : Sample of the surrounding water
n : Initial dilution within the mixing tube

TEST NUMBER : 9 MODEL NUMBER: X1

FLOW METER READING IN PERCENTAGE: = 40%

FLOW RATE IN LITRES/SEC. : = 2.67

CORRECTION FACTOR FOR SALT WATER: = 1.01

ACTUAL FLOW RATE IN LITRES/SEC., Q= 2.69

Sample	Trial 1 Salinity in ppt	Trial 2 Salinity in ppt	Trial 3 Salinity in ppt
T1	30.00	30.00	30.00
T2	30.00	30.00	30.00
1	12.00	13.50	14.00
2	13.50	15.00	15.50
3	15.00	16.00	17.00
4	13.50	15.00	15.50
5	12.50	14.00	14.00
Salinity S2	0.00	3.00	4.00
Average of 1-5 Salinity S3	13.3	14.70	15.20
Average of T1 & T2 Salinity S1	30.00	30.00	30.00
Initial dilution n	2.26	2.31	2.32

T1 & T2 : Samples collected from tank B

Samples 1-5 : Samples collected from the end of the mixing tube according to the figure shown in page one of Appendix

S2 : Sample of the surrounding water

n : Initial dilution within the mixing tube

TEST NUMBER : 10 **MODEL NUMBER: X1**

FLOW METER READING IN PERCENTAGE: = 80%

FLOW RATE IN LITRES/SEC. : = 5.33

CORRECTION FACTOR FOR SALT WATER: = 1.01

ACTUAL FLOW RATE IN LITRES/SEC., Q= 5.39

Sample	Trial 1 Salinity in ppt	Trial 2 Salinity in ppt	Trial 3 Salinity in ppt
T1	31.00	31.00	31.00
T2	31.00	31.00	31.00
1	11.00	11.00	12.00
2	12.50	12.50	13.00
3	14.00	14.00	14.50
4	12.50	12.50	13.00
5	11.50	11.50	12.00
Salinity S2	0.00	3.00	4.00
Average of 1-5 Salinity S3	12.30	12.30	12.90
Average of T1 & T2 Salinity S1	31.00	31.00	31.00
Initial dilution n	2.52	3.01	3.03

T1 & T2 : Samples collected from tank B

Samples 1-5 : Samples collected from the end of the mixing tube according to the figure shown in page one of Appendix

S2 : Sample of the surrounding water

n : Initial dilution within the mixing tube

TEST NUMBER : 12 MODEL NUMBER: X1

FLOW METER READING IN PERCENTAGE: = 60%

FLOW RATE IN LITRES/SEC. : = 4.00

CORRECTION FACTOR FOR SALT WATER: = 1.01

ACTUAL FLOW RATE IN LITRES/SEC., Q= 4.04

Sample	Trial 1 Salinity in ppt	Trial 2 Salinity in ppt	Trial 3 Salinity in ppt
T1	33.00	33.00	33.00
T2	33.00	33.00	33.00
1	10.00	12.50	13.50
2	11.50	13.50	14.00
3	14.00	15.00	15.50
4	11.50	13.50	14.00
5	10.00	12.50	13.50
Salinity S2	0.00	3.50	5.00
Average of 1-5 Salinity S3	11.40	13.40	14.10
Average of T1 & T2 Salinity S1	33.00	33.00	33.00
Initial dilution n	2.89	2.98	3.08

T1 & T2	: Samples collected from tank B
Samples 1-5	: Samples collected from the end of the mixing tube according to the figure shown in page one of Appendix
S2	: Sample of the surrounding water
n	: Initial dilution within the mixing tube

TEST NUMBER : 11 MODEL NUMBER: X1

FLOW METER READING IN PERCENTAGE: = 70%

FLOW RATE IN LITRES/SEC. : = 4.67

CORRECTION FACTOR FOR SALT WATER: = 1.01

ACTUAL FLOW RATE IN LITRES/SEC., Q= 4.72

Sample	Trial 1 Salinity in ppt	Trial 2 Salinity in ppt	Trial 3 Salinity in ppt
T1	33.00	33.00	33.00
T2	33.00	33.00	33.00
1	9.50	11.00	11.00
2	10.50	12.00	13.00
3	13.00	14.00	14.50
4	10.50	12.00	13.00
5	9.50	11.00	11.50
Salinity S2	0.00	3.00	4.50
Average of 1-5 Salinity S3	10.60	12.00	12.60
Average of T1 & T2 Salinity S1	33.00	33.00	33.00
Initial dilution n	3.11	3.33	3.52

T1 & T2 : Samples collected from tank B
Samples 1-5 : Samples collected from the end of the mixing tube according to the figure shown in page one of Appendix
S2 : Sample of the surrounding water
n : Initial dilution within the mixing tube

TEST NUMBER : 13 MODEL NUMBER: X1

FLOW METER READING IN PERCENTAGE: = 50%

FLOW RATE IN LITRES/SEC. : = 3.33

CORRECTION FACTOR FOR SALT WATER: = 1.01

ACTUAL FLOW RATE IN LITRES/SEC., Q= 3.37

Sample	Trial 1 Salinity in ppt	Trial 2 Salinity in ppt	Trial 3 Salinity in ppt
T1	33.00	33.00	33.00
T2	33.00	33.00	33.00
1	10.00	10.50	10.50
2	11.00	12.00	12.50
3	13.00	14.00	14.00
4	11.00	12.00	12.00
5	10.00	10.50	10.50
Salinity S2	0.00	3.00	3.50
Average of 1-5 Salinity S3	11.00	11.80	11.90
Average of T1 & T2 Salinity S1	33.00	33.00	33.00
Initial dilution n	3.00	3.41	3.51

T1 & T2 : Samples collected from tank B

Samples 1-5 : Samples collected from the end of the mixing tube according to the figure shown in page one of Appendix

S2 : Sample of the surrounding water

n : Initial dilution within the mixing tube

TEST NUMBER : 14 MODEL NUMBER: X1

FLOW METER READING IN PERCENTAGE: = 40%

FLOW RATE IN LITRES/SEC. : = 2.67

CORRECTION FACTOR FOR SALT WATER: = 1.01

ACTUAL FLOW RATE IN LITRES/SEC., Q= 2.69

Sample	Trial 1 Salinity in ppt	Trial 2 Salinity in ppt	Trial 3 Salinity in ppt
T1	33.00	33.00	33.00
T2	33.00	33.00	33.00
1	8.50	10.00	11.00
2	10.00	11.50	12.00
3	11.50	13.00	13.00
4	9.50	11.50	12.00
5	8.50	10.00	11.00
Salinity S2	0.00	3.00	4.50
Average of 1-5 Salinity S3	9.60	11.20	11.80
Average of T1 & T2 Salinity S1	33.00	33.00	33.00
Initial dilution n	3.44	3.66	3.90

T1 & T2 : Samples collected from tank B

Samples 1-5 : Samples collected from the end of the mixing tube according to the figure shown in page one of Appendix

S2 : Sample of the surrounding water

n : Initial dilution within the mixing tube

TEST NUMBER : 15 MODEL NUMBER: X2

FLOW METER READING IN PERCENTAGE: = 80%

FLOW RATE IN LITRES/SEC. : = 5.33

CORRECTION FACTOR FOR SALT WATER: = 1.01

ACTUAL FLOW RATE IN LITRES/SEC., Q= 5.39

Sample	Trial 1 Salinity in ppt	Trial 2 Salinity in ppt	Trial 3 Salinity in ppt
T1	30.00	30.00	30.00
T2	30.00	30.00	30.00
1	18.50	19.50	19.50
2	21.00	22.00	22.00
3	22.50	23.00	23.00
4	20.00	21.00	21.50
5	18.50	19.00	19.00
Salinity S2	0.00	3.00	4.00
Average of 1-5 Salinity S3	20.10	20.90	21.00
Average of T1 & T2 Salinity S1	30.00	30.00	30.00
Initial dilution n	1.49	1.51	1.53

T1 & T2 : Samples collected from tank B

Samples 1-5 : Samples collected from the end of the mixing tube according to the figure shown in page one of Appendix

S2 : Sample of the surrounding water

n : Initial dilution within the mixing tube

TEST NUMBER : 16 MODEL NUMBER: X2

FLOW METER READING IN PERCENTAGE: = 70%

FLOW RATE IN LITRES/SEC. : = 4.67

CORRECTION FACTOR FOR SALT WATER: = 1.01

ACTUAL FLOW RATE IN LITRES/SEC., Q= 4.72

Sample	Trial 1 Salinity in ppt	Trial 2 Salinity in ppt	Trial 3 Salinity in ppt
T1	30.00	30.00	30.00
T2	30.00	30.00	30.00
1	19.00	19.50	19.50
2	21.00	22.00	22.00
3	22.50	23.00	23.50
4	21.00	21.50	22.00
5	18.50	19.00	19.00
Salinity S2	0.00	3.00	4.00
Average of 1-5 Salinity S3	20.40	21.00	21.20
Average of T1 & T2 Salinity S1	30.00	30.00	30.00
Initial dilution n	1.47	1.50	1.51

T1 & T2 : Samples collected from tank B
Samples 1-5 : Samples collected from the end of the mixing tube according to the figure shown in page one of Appendix
S2 : Sample of the surrounding water
n : Initial dilution within the mixing tube

TEST NUMBER : 17 MODEL NUMBER: X2

FLOW METER READING IN PERCENTAGE: = 60%

FLOW RATE IN LITRES/SEC. : = 4.00

CORRECTION FACTOR FOR SALT WATER: = 1.01

ACTUAL FLOW RATE IN LITRES/SEC., Q= 4.04

Sample	Trial 1 Salinity in ppt	Trial 2 Salinity in ppt	Trial 3 Salinity in ppt
T1	31.00	31.00	31.00
T2	31.00	31.00	31.00
1	20.50	21.00	21.00
2	22.00	22.50	22.50
3	24.00	24.00	24.50
4	22.50	22.50	22.50
5	20.00	21.00	21.00
Salinity S2	0.00	3.00	4.00
Average of 1-5 Salinity S3	21.80	22.20	22.30
Average of T1 & T2 Salinity S1	31.00	31.00	31.00
Initial dilution n	1.42	1.46	1.48

T1 & T2	: Samples collected from tank B
Samples 1-5	: Samples collected from the end of the mixing tube according to the figure shown in page one of Appendix
S2	: Sample of the surrounding water
n	: Initial dilution within the mixing tube

TEST NUMBER : 18 MODEL NUMBER: X2

FLOW METER READING IN PERCENTAGE: = 50%

FLOW RATE IN LITRES/SEC. : = 3.33

CORRECTION FACTOR FOR SALT WATER: = 1.01

ACTUAL FLOW RATE IN LITRES/SEC., Q= 3.37

Sample	Trial 1 Salinity in ppt	Trial 2 Salinity in ppt	Trial 3 Salinity in ppt
T1	31.00	31.00	31.00
T2	31.00	31.00	31.00
1	20.00	20.50	21.00
2	22.00	22.50	22.50
3	23.50	24.00	24.50
4	22.00	22.50	22.50
5	19.50	20.50	21.00
Salinity S2	0.00	3.00	4.50
Average of 1-5 Salinity S3	21.40	22.00	22.30
Average of T1 & T2 Salinity S1	31.00	31.00	31.00
Initial dilution n	1.45	1.47	1.49

T1 & T2	: Samples collected from tank B
Samples 1-5	: Samples collected from the end of the mixing tube according to the figure shown in page one of Appendix
S2	: Sample of the surrounding water
n	: Initial dilution within the mixing tube

TEST NUMBER : 19 MODEL NUMBER: X2

FLOW METER READING IN PERCENTAGE: = 40%

FLOW RATE IN LITRES/SEC. : = 2.67

CORRECTION FACTOR FOR SALT WATER: = 1.01

ACTUAL FLOW RATE IN LITRES/SEC., Q= 2.69

Sample	Trial 1 Salinity in ppt	Trial 2 Salinity in ppt	Trial 3 Salinity in ppt
T1	31.00	31.50	31.50
T2	31.00	31.50	31.50
1	21.50	22.00	21.50
2	23.00	23.50	23.50
3	25.00	25.00	25.00
4	23.00	23.00	23.00
5	21.50	22.00	21.50
Salinity S2	0.00	3.00	4.50
Average of 1-5 Salinity S3	22.80	23.20	22.90
Average of T1 & T2 Salinity S1	31.00	31.50	31.50
Initial dilution n	1.36	1.41	1.47

T1 & T2 : Samples collected from tank B

Samples 1-5 : Samples collected from the end of the mixing tube according to the figure shown in page one of Appendix

S2 : Sample of the surrounding water

n : Initial dilution within the mixing tube

TEST NUMBER : 20 MODEL NUMBER: X2

FLOW METER READING IN PERCENTAGE: = 80%

FLOW RATE IN LITRES/SEC. : = 5.33

CORRECTION FACTOR FOR SALT WATER: = 1.01

ACTUAL FLOW RATE IN LITRES/SEC., Q= 5.39

Sample	Trial 1 Salinity in ppt	Trial 2 Salinity in ppt	Trial 3 Salinity in ppt
T1	32.00	32.00	32.00
T2	32.00	32.00	32.00
1	16.00	16.50	17.00
2	17.00	18.50	19.00
3	18.50	20.50	21.00
4	17.50	19.00	19.50
5	16.00	17.00	17.50
Salinity S2	0.00	3.00	4.50
Average of 1-5 Salinity S3	17.00	18.30	18.80
Average of T1 & T2 Salinity S1	32.00	32.00	32.00
Initial dilution n	1.89	1.90	1.92

T1 & T2	: Samples collected from tank B
Samples 1-5	: Samples collected from the end of the mixing tube according to the figure shown in page one of Appendix
S2	: Sample of the surrounding water
n	: Initial dilution within the mixing tube

TEST NUMBER : 21 MODEL NUMBER: X2

FLOW METER READING IN PERCENTAGE: = 70%

FLOW RATE IN LITRES/SEC. : = 4.67

CORRECTION FACTOR FOR SALT WATER: = 1.01

ACTUAL FLOW RATE IN LITRES/SEC., Q= 4.72

Sample	Trial 1 Salinity in ppt	Trial 2 Salinity in ppt	Trial 3 Salinity in ppt
T1	32.00	32.50	32.50
T2	32.00	32.50	32.50
1	15.00	16.50	16.50
2	16.50	18.00	18.00
3	17.50	19.00	19.50
4	16.00	17.50	18.00
5	15.00	16.50	17.00
Salinity S2	0.00	3.00	4.50
Average of 1-5 Salinity S3	16.00	17.50	17.80
Average of T1 & T2 Salinity S1	32.00	32.50	32.50
Initial dilution n	2.00	2.03	2.10

T1 & T2	: Samples collected from tank B
Samples 1-5	: Samples collected from the end of the mixing tube according to the figure shown in page one of Appendix
S2	: Sample of the surrounding water
n	: Initial dilution within the mixing tube

TEST NUMBER : 22 MODEL NUMBER: X2

FLOW METER READING IN PERCENTAGE: = 60%

FLOW RATE IN LITRES/SEC. : = 4.00

CORRECTION FACTOR FOR SALT WATER: = 1.01

ACTUAL FLOW RATE IN LITRES/SEC., Q= 4.04

Sample	Trial 1 Salinity in ppt	Trial 2 Salinity in ppt	Trial 3 Salinity in ppt
T1	32.00	32.00	32.00
T2	32.00	32.00	32.00
1	13.00	14.00	13.50
2	14.00	15.00	14.00
3	15.50	16.00	15.50
4	14.00	15.00	14.00
5	13.00	14.00	13.50
Salinity S2	0.00	3.00	4.50
Average of 1-5 Salinity S3	13.90	14.80	14.10
Average of T1 & T2 Salinity S1	32.00	32.00	32.00
Initial dilution n	2.30	2.46	2.86

T1 & T2	: Samples collected from tank B
Samples 1-5	: Samples collected from the end of the mixing tube according to the figure shown in page one of Appendix
S2	: Sample of the surrounding water
n	: Initial dilution within the mixing tube

TEST NUMBER : 23 MODEL NUMBER: X2

FLOW METER READING IN PERCENTAGE: = 50%

FLOW RATE IN LITRES/SEC. : = 3.33

CORRECTION FACTOR FOR SALT WATER: = 1.01

ACTUAL FLOW RATE IN LITRES/SEC., Q= 3.37

Sample	Trial 1 Salinity in ppt	Trial 2 Salinity in ppt	Trial 3 Salinity in ppt
T1	33.00	33.00	33.00
T2	33.00	33.00	33.00
1	13.50	14.50	15.00
2	14.50	16.00	16.50
3	15.50	17.50	18.00
4	14.00	15.50	16.50
5	13.50	14.50	15.00
Salinity S2	0.00	3.00	4.00
Average of 1-5 Salinity S3	14.20	15.60	16.20
Average of T1 & T2 Salinity S1	33.00	33.00	33.00
Initial dilution n	2.32	2.38	2.38

T1 & T2 : Samples collected from tank B

Samples 1-5 : Samples collected from the end of the mixing tube according to the figure shown in page one of Appendix

S2 : Sample of the surrounding water

n : Initial dilution within the mixing tube

TEST NUMBER : 24 MODEL NUMBER: X2

FLOW METER READING IN PERCENTAGE: = 40%

FLOW RATE IN LITRES/SEC. : = 2.67

CORRECTION FACTOR FOR SALT WATER: = 1.01

ACTUAL FLOW RATE IN LITRES/SEC., Q= 2.69

Sample	Trial 1 Salinity in ppt	Trial 2 Salinity in ppt	Trial 3 Salinity in ppt
T1	33.00	33.00	33.00
T2	33.00	33.00	33.00
1	11.50	13.00	13.50
2	13.00	14.00	14.50
3	14.50	15.50	16.00
4	13.00	14.00	14.50
5	11.50	13.00	13.50
Salinity S2	0.00	3.00	4.00
Average of 1-5 Salinity S3	12.70	13.90	14.40
Average of T1 & T2 Salinity S1	33.00	33.00	33.00
Initial dilution n	2.60	2.75	2.79

T1 & T2 : Samples collected from tank B

Samples 1-5 : Samples collected from the end of the mixing tube according to the figure shown in page one of Appendix

n : Initial dilution within the mixing tube

TEST NUMBER : 25 MODEL NUMBER: X1

FLOW METER READING IN PERCENTAGE: = 80%

FLOW RATE IN LITRES/SEC. : = 5.33

CORRECTION FACTOR FOR SALT WATER: = 1.01

ACTUAL FLOW RATE IN LITRES/SEC., Q= 5.39

Sample	Trial 1 Salinity in ppt	Trial 2 Salinity in ppt	Trial 3 Salinity in ppt
T1	32.00	32.00	32.00
T2	32.00	32.00	32.00
1	19.00	19.50	19.00
2	20.00	20.50	20.50
3	22.50	22.50	22.00
4	20.50	20.50	20.50
5	18.50	19.00	19.50
Average of 1-5 Salinity S3	20.00	20.40	20.30
Average of T1 & T2 Salinity S1	32.00	32.00	32.00
Initial dilution **n**	1.60	1.57	1.58

T1 & T2 : Samples collected from tank B
Samples 1-5 : Samples collected from the end of the mixing tube according to the figure shown in page one of Appendix
S2 : Sample of the surrounding water
n : Initial dilution within the mixing tube

TEST NUMBER : 26 MODEL NUMBER: X1

FLOW METER READING IN PERCENTAGE: = 70%

FLOW RATE IN LITRES/SEC. : = 4.67

CORRECTION FACTOR FOR SALT WATER: = 1.01

ACTUAL FLOW RATE IN LITRES/SEC., Q= 4.72

Sample	Trial 1 Salinity in ppt	Trial 2 Salinity in ppt	Trial 3 Salinity in ppt
T1	30.00	30.00	30.00
T2	30.00	30.00	29.50
1	17.50	17.50	17.50
2	18.00	18.50	18.00
3	20.50	21.50	21.00
4	18.00	19.00	18.50
5	17.50	17.50	17.00
Average of 1-5 Salinity S3	18.30	18.80	18.40
Average of T1 & T2 Salinity S1	30.00	30.00	29.75
Initial dilution n	1.64	1.60	1.62

T1 & T2 : Samples collected from tank B

Samples 1-5 : Samples collected from the end of the mixing tube according to the figure shown in page one of Appendix

n : Initial dilution within the mixing tube

TEST NUMBER : 27 MODEL NUMBER: X1

FLOW METER READING IN PERCENTAGE: = 60%

FLOW RATE IN LITRES/SEC. : = 4.00

CORRECTION FACTOR FOR SALT WATER: = 1.01

ACTUAL FLOW RATE IN LITRES/SEC., Q= 4.04

Sample	Trial 1 Salinity in ppt	Trial 2 Salinity in ppt	Trial 3 Salinity in ppt
T1	30.00	30.00	30.00
T2	30.00	30.00	30.00
1	17.00	17.00	17.50
2	18.50	18.00	18.50
3	20.50	20.00	21.00
4	18.50	18.00	19.00
5	17.00	20.00	17.50
Average of 1-5 Salinity S3	18.30	18.60	18.70
Average of T1 & T2 Salinity S1	30.00	30.00	30.00
Initial dilution n	1.64	1.67	1.61

T1 & T2 : Samples collected from tank B
Samples 1-5 : Samples collected from the end of the mixing tube according to the figure shown in page one of Appendix
n : Initial dilution within the mixing tube

TEST NUMBER : 28 MODEL NUMBER: X1

FLOW METER READING IN PERCENTAGE: = 50%

FLOW RATE IN LITRES/SEC. : = 3.33

CORRECTION FACTOR FOR SALT WATER: = 1.01

ACTUAL FLOW RATE IN LITRES/SEC., Q= 3.37

Sample	Trial 1 Salinity in ppt	Trial 2 Salinity in ppt	Trial 3 Salinity in ppt
T1	32.00	32.00	32.00
T2	32.00	32.00	32.00
1	18.50	18.00	17.50
2	19.50	19.50	19.00
3	21.00	21.00	20.50
4	19.50	19.50	19.00
5	18.50	18.00	18.00
Average of 1-5 Salinity S3	19.40	19.20	18.80
Average of T1 & T2 Salinity S1	32.00	32.00	32.00
Initial dilution n	1.65	1.67	1.70

T1 & T2 : Samples collected from tank B

Samples 1-5 : Samples collected from the end of the mixing tube according to the figure shown in page one of Appendix

n : Initial dilution within the mixing tube

TEST NUMBER : 29 MODEL NUMBER: X1

FLOW METER READING IN PERCENTAGE: = 80%

FLOW RATE IN LITRES/SEC. : = 5.33

CORRECTION FACTOR FOR SALT WATER: = 1.01

ACTUAL FLOW RATE IN LITRES/SEC., Q= 5.39

Sample	Trial 1 Salinity in ppt	Trial 2 Salinity in ppt	Trial 3 Salinity in ppt
T1	33.00	33.50	33.50
T2	33.50	33.50	33.50
1	17.00	16.00	16.00
2	18.00	18.00	18.00
3	20.00	19.50	19.00
4	18.00	18.00	18.00
5	17.00	16.50	16.00
Average of 1-5 Salinity S3	18.00	17.60	17.40
Average of T1 & T2 Salinity S1	33.25	33.50	33.50
Initial dilution n	1.84	1.90	1.93

T1 & T2 : Samples collected from tank B
Samples 1-5 : Samples collected from the end of the mixing tube according to the figure shown in page one of Appendix
n : Initial dilution within the mixing tube

TEST NUMBER : 30 MODEL NUMBER: X1

FLOW METER READING IN PERCENTAGE: = 70%

FLOW RATE IN LITRES/SEC. : = 4.67

CORRECTION FACTOR FOR SALT WATER: = 1.01

ACTUAL FLOW RATE IN LITRES/SEC., Q= 4.72

Sample	Trial 1 Salinity in ppt	Trial 2 Salinity in ppt	Trial 3 Salinity in ppt
T1	32.00	32.00	32.50
T2	32.00	32.00	32.50
1	15.50	16.00	15.50
2	16.50	17.00	16.50
3	18.50	19.00	18.00
4	17.00	17.00	16.50
5	16.00	16.00	16.00
Average of 1-5 Salinity S3	16.70	17.40	16.50
Average of T1 & T2 Salinity S1	32.00	32.00	32.50
Initial dilution n	1.92	1.88	1.97

T1 & T2 : Samples collected from tank B
Samples 1-5 : Samples collected from the end of the mixing tube according to the figure shown in page one of Appendix
n : Initial dilution within the mixing tube

TEST NUMBER : 31 MODEL NUMBER: X1

FLOW METER READING IN PERCENTAGE: = 60%

FLOW RATE IN LITRES/SEC. : = 4.00

CORRECTION FACTOR FOR SALT WATER: = 1.01

ACTUAL FLOW RATE IN LITRES/SEC., Q= 4.04

Sample	Trial 1 Salinity in ppt	Trial 2 Salinity in ppt	Trial 3 Salinity in ppt
T1	32.50	32.50	32.50
T2	32.50	32.00	32.50
1	15.50	16.00	15.50
2	16.50	17.00	16.50
3	18.00	18.00	18.00
4	16.50	16.50	16.50
5	16.00	15.50	16.00
Average of 1-5 Salinity S3	16.50	16.60	16.50
Average of T1 & T2 Salinity S1	32.50	32.25	32.50
Initial dilution n	1.97	1.94	1.97

T1 & T2 : Samples collected from tank B
Samples 1-5 : Samples collected from the end of the mixing tube according to the figure shown in page one of Appendix
n : Initial dilution within the mixing tube

TEST NUMBER : 32 MODEL NUMBER: X1

FLOW METER READING IN PERCENTAGE: = 50%

FLOW RATE IN LITRES/SEC. : = 3.33

CORRECTION FACTOR FOR SALT WATER: = 1.01

ACTUAL FLOW RATE IN LITRES/SEC., Q= 3.37

Sample	Trial 1 Salinity in ppt	Trial 2 Salinity in ppt	Trial 3 Salinity in ppt
T1	32.00	32.00	32.00
T2	32.00	32.00	32.00
1	14.00	13.50	13.50
2	15.50	15.00	14.50
3	17.00	16.00	16.50
4	15.00	15.00	15.00
5	14.00	14.00	14.00
Average of 1-5 Salinity S3	15.10	14.70	14.70
Average of T1 & T2 Salinity S1	32.00	32.00	32.00
Initial dilution n	2.12	2.18	2.18

T1 & T2	: Samples collected from tank
Samples 1-5	: Samples collected from the end of the mixing tube according to the figure shown in page one of Appendix
n	: Initial dilution within the mixing tube

TEST NUMBER : 33 MODEL NUMBER: X1

FLOW METER READING IN PERCENTAGE: = 40%

FLOW RATE IN LITRES/SEC. : = 2.67

CORRECTION FACTOR FOR SALT WATER: = 1.01

ACTUAL FLOW RATE IN LITRES/SEC., Q= 2.69

Sample	Trial 1 Salinity in ppt	Trial 2 Salinity in ppt	Trial 3 Salinity in ppt
T1	32.50	32.50	32.50
T2	32.50	32.50	32.50
1	13.00	13.00	13.00
2	14.50	15.00	15.00
3	16.00	16.50	16.50
4	14.50	14.50	14.50
5	13.00	13.00	13.00
Average of 1-5 Salinity S3	14.20	14.40	14.40
Average of T1 & T2 Salinity S1	32.50	32.50	32.50
Initial dilution n	2.29	2.26	2.26

T1 & T2 : Samples collected from tank B

Samples 1-5 : Samples collected from the end of the mixing tube according to the figure shown in page one of Appendix

n : Initial dilution within the mixing tube

TEST NUMBER : 34 MODEL NUMBER: X1

FLOW METER READING IN PERCENTAGE: = 80%

FLOW RATE IN LITRES/SEC. : = 5.33

CORRECTION FACTOR FOR SALT WATER: = 1.01

ACTUAL FLOW RATE IN LITRES/SEC., Q= 5.39

Sample	Trial 1 Salinity in ppt	Trial 2 Salinity in ppt	Trial 3 Salinity in ppt
T1	31.00	31.00	31.00
T2	31.00	31.00	31.00
1	11.00	10.00	9.50
2	12.50	11.50	10.00
3	14.00	13.00	12.00
4	12.50	11.50	10.00
5	11.50	10.00	9.50
Average of 1-5 Salinity S3	12.30	11.20	10.20
Average of T1 & T2 Salinity S1	31.00	31.00	31.00
Initial dilution n	2.52	2.72	3.04

T1 & T2 : Samples collected from tank B
Samples 1-5 : Samples collected from the end of the mixing tube according to the figure shown in page one of Appendix
n : Initial dilution within the mixing tube

TEST NUMBER : 35 MODEL NUMBER: X1

FLOW METER READING IN PERCENTAGE: = 70%

FLOW RATE IN LITRES/SEC. : = 4.67

CORRECTION FACTOR FOR SALT WATER: = 1.01

ACTUAL FLOW RATE IN LITRES/SEC., Q= 4.72

Sample	Trial 1 Salinity in ppt	Trial 2 Salinity in ppt	Trial 3 Salinity in ppt
T1	36.00	36.00	35.50
T2	36.00	35.50	35.50
1	11.00	11.00	11.00
2	12.00	12.00	12.50
3	14.00	13.50	14.00
4	12.50	12.50	12.50
5	11.00	11.00	11.00
Average of 1-5 Salinity S3	12.10	12.00	12.20
Average of T1 & T2 Salinity S1	36.00	35.75	35.50
Initial dilution n	2.93	2.91	2.86

T1 & T2 : Samples collected from tank B
Samples 1-5 : Samples collected from the end of the mixing tube according to the figure shown in page one of Appendix
n : Initial dilution within the mixing tube

TEST NUMBER : 36 MODEL NUMBER: X1

FLOW METER READING IN PERCENTAGE: = 60%

FLOW RATE IN LITRES/SEC. : = 4.00

CORRECTION FACTOR FOR SALT WATER: = 1.01

ACTUAL FLOW RATE IN LITRES/SEC., Q= 4.04

Sample	Trial 1 Salinity in ppt	Trial 2 Salinity in ppt	Trial 3 Salinity in ppt
T1	32.50	32.50	33.00
T2	32.50	32.50	33.00
1	10.00	10.00	9.50
2	11.00	11.00	11.00
3	13.50	12.50	12.50
4	11.50	11.00	11.00
5	10.00	9.50	9.50
Average of 1-5 Salinity S3	11.20	10.60	10.70
Average of T1 & T2 Salinity S1	32.50	32.50	33.00
Initial dilution n	2.90	3.06	3.08

T1 & T2 : Samples collected from tank B

Samples 1-5 : Samples collected from the end of the mixing tube according to the figure shown in page one of Appendix

n : Initial dilution within the mixing tube

TEST NUMBER : 37 MODEL NUMBER: X1

FLOW METER READING IN PERCENTAGE: = 50%

FLOW RATE IN LITRES/SEC. : = 3.33

CORRECTION FACTOR FOR SALT WATER: = 1.01

ACTUAL FLOW RATE IN LITRES/SEC., Q= 3.37

Sample	Trial 1 Salinity in ppt	Trial 2 Salinity in ppt	Trial 3 Salinity in ppt
T1	33.00	33.00	33.50
T2	33.00	34.00	33.50
1	9.50	9.50	9.00
2	10.50	10.50	10.50
3	12.50	12.00	12.00
4	10.50	10.50	10.50
5	9.50	9.00	9.00
Average of 1-5 Salinity S3	10.50	10.30	10.20
Average of T1 & T2 Salinity S1	33.00	33.50	33.50
Initial dilution n	3.17	3.25	3.28

T1 & T2 : Samples collected from tank B

Samples 1-5 : Samples collected from the end of the mixing tube according to the figure shown in page one of Appendix

n : Initial dilution within the mixing tube

TEST NUMBER : 38 MODEL NUMBER: X1

FLOW METER READING IN PERCENTAGE: = 40%

FLOW RATE IN LITRES/SEC. : = 2.67

CORRECTION FACTOR FOR SALT WATER: = 1.01

ACTUAL FLOW RATE IN LITRES/SEC., Q= 2.69

Sample	Trial 1 Salinity in ppt	Trial 2 Salinity in ppt	Trial 3 Salinity in ppt
T1	34.00	34.00	34.00
T2	34.00	34.00	34.00
1	9.00	9.00	9.00
2	10.50	10.00	10.50
3	12.00	12.00	12.50
4	10.00	10.00	10.50
5	9.00	9.00	9.50
Average of 1-5 Salinity S3	10.10	10.00	10.40
Average of T1 & T2 Salinity S1	34.00	34.00	34.00
Initial dilution n	3.37	3.40	3.27

T1 & T2 : Samples collected from tank B

Samples 1-5 : Samples collected from the end of the mixing tube according to the figure shown in page one of Appendix

n : Initial dilution within the mixing tube

TEST NUMBER : 40 MODEL NUMBER: X2

FLOW METER READING IN PERCENTAGE: = 70%

FLOW RATE IN LITRES/SEC. : = 4.67

CORRECTION FACTOR FOR SALT WATER: = 1.01

ACTUAL FLOW RATE IN LITRES/SEC., Q= 4.72

Sample	Trial 1 Salinity in ppt	Trial 2 Salinity in ppt	Trial 3 Salinity in ppt
T1	32.00	31.50	32.00
T2	32.00	31.50	32.00
1	20.50	20.00	20.00
2	21.50	22.00	21.00
3	22.00	23.00	22.00
4	21.50	21.50	21.00
5	20.50	20.50	20.00
Average of 1-5 Salinity S3	21.20	21.30	20.80
Average of T1 & T2 Salinity S1	32.00	31.50	32.00
Initial dilution n	1.51	1.47	1.54

T1 & T2	: Samples collected from tank B
Samples 1-5	: Samples collected from the end of the mixing tube according to the figure shown in page one of Appendix
n	: Initial dilution within the mixing tube

TEST NUMBER : 39 MODEL NUMBER: X2

FLOW METER READING IN PERCENTAGE: = 80%

FLOW RATE IN LITRES/SEC. : = 5.33

CORRECTION FACTOR FOR SALT WATER: = 1.01

ACTUAL FLOW RATE IN LITRES/SEC., Q= 5.39

Sample	Trial 1 Salinity in ppt	Trial 2 Salinity in ppt	Trial 3 Salinity in ppt
T1	32.00	32.00	31.50
T2	32.00	31.50	31.50
1	20.50	20.50	20.00
2	22.00	21.50	21.00
3	23.00	23.00	22.00
4	21.50	21.50	21.00
5	20.50	20.50	19.50
Average of 1-5 Salinity S3	21.50	21.40	20.70
Average of T1 & T2 Salinity S1	32.00	31.75	31.50
Initial dilution n	1.49	1.48	1.52

T1 & T2 : Samples collected from tank B

Samples 1-5 : Samples collected from the end of the mixing tube according to the figure shown in page one of Appendix

n : Initial dilution within the mixing tube

TEST NUMBER : 41 MODEL NUMBER: X2

FLOW METER READING IN PERCENTAGE: = 60%

FLOW RATE IN LITRES/SEC. : = 4.00

CORRECTION FACTOR FOR SALT WATER: = 1.01

ACTUAL FLOW RATE IN LITRES/SEC., Q= 4.04

Sample	Trial 1 Salinity in ppt	Trial 2 Salinity in ppt	Trial 3 Salinity in ppt
T1	32.00	32.00	32.00
T2	32.00	32.00	32.00
1	20.00	20.50	20.50
2	21.00	21.50	21.50
3	22.00	22.50	22.50
4	21.00	21.50	21.50
5	20.00	20.50	20.00
Average of 1-5 Salinity S3	20.80	21.20	21.20
Average of T1 & T2 Salinity S1	32.00	32.00	32.00
Initial dilution n	1.54	1.51	1.51

T1 & T2	: Samples collected from tank B
Samples 1-5	: Samples collected from the end of the mixing tube according to the figure shown in page one of Appendix
n	: Initial dilution within the mixing tube

TEST NUMBER : 42 MODEL NUMBER: X2

FLOW METER READING IN PERCENTAGE: = 50%

FLOW RATE IN LITRES/SEC. : = 3.33

CORRECTION FACTOR FOR SALT WATER: = 1.01

ACTUAL FLOW RATE IN LITRES/SEC., Q= 3.37

Sample	Trial 1 Salinity in ppt	Trial 2 Salinity in ppt	Trial 3 Salinity in ppt
T1	32.00	31.50	31.50
T2	32.00	31.50	31.50
1	20.00	20.00	19.50
2	21.50	21.00	21.00
3	22.50	22.00	22.00
4	21.50	21.00	21.00
5	20.00	19.50	19.50
Average of 1-5 Salinity S3	21.20	20.70	20.60
Average of T1 & T2 Salinity S1	32.00	31.50	31.50
Initial dilution n	1.51	1.52	1.53

T1 & T2 : Samples collected from tank B

Samples 1-5 : Samples collected from the end of the mixing tube according to the figure shown in page one of Appendix

n : Initial dilution within the mixing tube

TEST NUMBER : 43 MODEL NUMBER: X2

FLOW METER READING IN PERCENTAGE: = 40%

FLOW RATE IN LITRES/SEC. : = 2.67

CORRECTION FACTOR FOR SALT WATER: = 1.01

ACTUAL FLOW RATE IN LITRES/SEC., Q= 2.69

Sample	Trial 1 Salinity in ppt	Trial 2 Salinity in ppt	Trial 3 Salinity in ppt
T1	31.00	31.00	31.00
T2	31.00	31.00	31.00
1	20.50	20.50	20.00
2	21.50	21.50	21.00
3	23.00	23.00	22.50
4	21.50	21.50	21.00
5	20.50	20.50	20.00
Average of 1-5 Salinity S3	21.40	21.40	20.90
Average of T1 & T2 Salinity S1	31.00	31.00	31.00
Initial dilution n	1.45	1.45	1.48

T1 & T2 : Samples collected from tank B
Samples 1-5 : Samples collected from the end of the mixing tube according to the figure shown in page one of Appendix
n : Initial dilution within the mixing tube

TEST NUMBER : 44 MODEL NUMBER: X2

FLOW METER READING IN PERCENTAGE: = 80%

FLOW RATE IN LITRES/SEC. : = 5.33

CORRECTION FACTOR FOR SALT WATER: = 1.01

ACTUAL FLOW RATE IN LITRES/SEC., Q= 5.39

Sample	Trial 1 Salinity in ppt	Trial 2 Salinity in ppt	Trial 3 Salinity in ppt
T1	31.00	31.00	31.50
T2	31.00	31.00	31.50
1	20.00	19.00	19.00
2	21.00	20.50	20.00
3	22.50	22.00	22.00
4	21.00	21.00	20.00
5	20.00	20.00	19.00
Average of 1-5 Salinity S3	20.90	20.50	20.00
Average of T1 & T2 Salinity S1	31.00	31.00	31.50
Initial dilution n	1.48	1.50	1.58

T1 & T2	: Samples collected from tank B
Samples 1-5	: Samples collected from the end of the mixing tube according to the figure shown in page one of Appendix
n	: Initial dilution within the mixing tube

TEST NUMBER : 45 MODEL NUMBER: X2

FLOW METER READING IN PERCENTAGE: = 70%

FLOW RATE IN LITRES/SEC. : = 4.67

CORRECTION FACTOR FOR SALT WATER: = 1.01

ACTUAL FLOW RATE IN LITRES/SEC., Q= 4.72

Sample	Trial 1 Salinity in ppt	Trial 2 Salinity in ppt	Trial 3 Salinity in ppt
T1	30.00	30.00	30.00
T2	30.00	30.00	29.50
1	17.00	17.50	17.00
2	18.00	18.50	18.50
3	20.00	21.00	20.50
4	18.00	18.50	18.50
5	17.00	17.50	17.50
Average of 1-5 Salinity S3	18.00	18.60	18.040
Average of T1 & T2 Salinity S1	30.00	30.00	29.75
Initial dilution n	1.67	1.61	1.62

T1 & T2	: Samples collected from tank B
Samples 1-5	: Samples collected from the end of the mixing tube according to the figure shown in page one of Appendix
n	: Initial dilution within the mixing tube

TEST NUMBER : 46 MODEL NUMBER: X2

FLOW METER READING IN PERCENTAGE: = 60%

FLOW RATE IN LITRES/SEC. : = 4.00

CORRECTION FACTOR FOR SALT WATER: = 1.01

ACTUAL FLOW RATE IN LITRES/SEC., Q= 4.04

Sample	Trial 1 Salinity in ppt	Trial 2 Salinity in ppt	Trial 3 Salinity in ppt
T1	32.00	32.50	32.50
T2	32.00	32.50	32.50
1	17.50	17.00	17.50
2	19.00	18.00	18.50
3	21.00	20.00	21.00
4	19.00	18.00	18.50
5	17.50	16.50	17.50
Average of 1-5 Salinity S3	18.80	17.90	18.60
Average of T1 & T2 Salinity S1	32.00	32.50	32.50
Initialdilution n	1.70	1.82	1.74

T1 & T2	: Samples collected from tank B
Samples 1-5	: Samples collected from the end of the mixing tube according to the figure shown in page one of Appendix
n	: Initial dilution within the mixing tube

TEST NUMBER : 47 MODEL NUMBER: X2

FLOW METER READING IN PERCENTAGE: = 50%

FLOW RATE IN LITRES/SEC. : = 3.33

CORRECTION FACTOR FOR SALT WATER: = 1.01

ACTUAL FLOW RATE IN LITRES/SEC., Q= 3.37

Sample	Trial 1 Salinity in ppt	Trial 2 Salinity in ppt	Trial 3 Salinity in ppt
T1	33.00	33.50	33.50
T2	33.00	33.50	33.50
1	17.00	16.00	16.00
2	18.00	18.00	17.50
3	20.00	20.00	20.00
4	18.00	17.50	17.50
5	17.00	16.50	16.00
Average of 1-5 Salinity S3	18.00	17.60	17.40
Average of T1 & T2 Salinity S1	33.00	33.50	33.50
Initial dilution n	1.83	1.90	1.93

T1 & T2 : Samples collected from tank B

Samples 1-5 : Samples collected from the end of the mixing tube according to the figure shown in page one of Appendix

n : Initial dilution within the mixing tube

TEST NUMBER : 48 MODEL NUMBER: X2

FLOW METER READING IN PERCENTAGE: = 40%

FLOW RATE IN LITRES/SEC. : = 2.67

CORRECTION FACTOR FOR SALT WATER: = 1.01

ACTUAL FLOW RATE IN LITRES/SEC., Q= 2.69

Sample	Trial 1 Salinity in ppt	Trial 2 Salinity in ppt	Trial 3 Salinity in ppt
T1	33.50	33.00	33.00
T2	33.50	33.00	33.00
1	16.00	16.00	16.00
2	17.50	17.50	17.00
3	20.00	19.00	19.00
4	17.00	17.00	17.00
5	16.50	16.00	15.50
Average of 1-5 Salinity S3	17.40	17.00	16.90
Average of T1 & T2 Salinity S1	33.50	33.00	33.00
initial dilution n	1.93	1.94	1.95

T1 & T2	: Samples collected from tank B
Samples 1-5	: Samples collected from the end of the mixing tube according to the figure shown in page one of Appendix
n	: Initial dilution within the mixing tube

TEST NUMBER : 49 MODEL NUMBER: Y1

FLOW METER READING IN PERCENTAGE: = 80%

FLOW RATE IN LITRES/SEC. : = 5.33

CORRECTION FACTOR FOR SALT WATER: = 1.01

ACTUAL FLOW RATE IN LITRES/SEC., Q= 5.39

Sample	Trial 1 Salinity in ppt	Trial 2 Salinity in ppt	Trial 3 Salinity in ppt
T1	32.00	32.00	32.00
T2	32.00	32.00	32.00
1	22.00	22.50	22.50
2	22.50	22.50	22.50
3	22.00	22.00	22.00
Average of 1-3 Salinity S3	22.17	22.00	21.17
Average of T1 & T2 Salinity S1	32.00	32.00	32.00
Initial dilution n	1.43	1.44	1.45

T1 & T2 : Samples collected from tank B

Samples 1-3 : Samples collected from the end of the mixing tube according to the figure shown in page one of Appendix

n : Initial dilution within the mixing tube

TEST NUMBER : 50 MODEL NUMBER: Y1

FLOW METER READING IN PERCENTAGE: = 70%

FLOW RATE IN LITRES/SEC. : = 4.67

CORRECTION FACTOR FOR SALT WATER: = 1.01

ACTUAL FLOW RATE IN LITRES/SEC., Q= 4.72

Sample	Trial 1 Salinity in ppt	Trial 2 Salinity in ppt	Trial 3 Salinity in ppt
T1	33.00	32.50	32.50
T2	32.50	32.50	32.50
1	22.50	22.00	22.00
2	23.00	23.00	23.00
3	22.00	22.00	22.00
Average of 1-3 Salinity S3	22.50	22.33	22.33
Average of T1 & T2 Salinity S1	32.75	32.50	32.50
Initial dilution n	1.46	1.46	1.46

T1 & T2	: Samples collected from tank B
Samples 1-3	: Samples collected from the end of the mixing tube according to the figure shown in page one of Appendix
n	: Initial dilution within the mixing tube

TEST NUMBER : 51 MODEL NUMBER: Y1

FLOW METER READING IN PERCENTAGE: = 60%

FLOW RATE IN LITRES/SEC. : = 4.00

CORRECTION FACTOR FOR SALT WATER: = 1.01

ACTUAL FLOW RATE IN LITRES/SEC., Q= 4.04

Sample	Trial 1 Salinity in ppt	Trial 2 Salinity in ppt	Trial 3 Salinity in ppt
T1	32.00	32.00	32.00
T2	32.00	32.00	32.00
1	21.50	21.50	21.50
2	22.50	22.50	22.50
3	22.00	22.00	22.00
Average of 1-3 Salinity S3	22.00	22.00	22.00
Average of T1 & T2 Salinity S1	32.00	32.00	32.00
Initial dilution n	1.46	1.46	1.46

T1 & T2 : Samples collected from tank B

Samples 1-3 : Samples collected from the end of the mixing tube according to the figure shown in page one of Appendix

n : Initial dilution within the mixing tube

TEST NUMBER : 52 MODEL NUMBER: Y1

FLOW METER READING IN PERCENTAGE: = 50%

FLOW RATE IN LITRES/SEC. : = 3.33

CORRECTION FACTOR FOR SALT WATER: = 1.01

ACTUAL FLOW RATE IN LITRES/SEC., Q= 3.37

Sample	Trial 1 Salinity in ppt	Trial 2 Salinity in ppt	Trial 3 Salinity in ppt
T1	32.00	32.50	32.00
T2	32.00	32.00	32.00
1	21.00	20.50	21.00
2	22.00	22.50	22.00
3	21.50	21.50	21.50
Average of 1-3 Salinity S3	21.50	21.50	21.50
Average of T1 & T2 Salinity S1	32.00	32.25	32.00
Initial dilution n	1.49	1.50	1.48

T1 & T2 : Samples collected from tank B

Samples 1-3 : Samples collected from the end of the mixing tube according to the figure shown in page one of Appendix

n : Initial dilution within the mixing tube

TEST NUMBER : 53 MODEL NUMBER: Y1

FLOW METER READING IN PERCENTAGE: = 80%

FLOW RATE IN LITRES/SEC. : = 5.33

CORRECTION FACTOR FOR SALT WATER: = 1.01

ACTUAL FLOW RATE IN LITRES/SEC., Q= 5.39

Sample	Trial 1 Salinity in ppt	Trial 2 Salinity in ppt	Trial 3 Salinity in ppt
T1	33.00	32.50	32.50
T2	33.00	32.50	32.50
1	17.50	17.00	17.50
2	19.00	18.50	18.50
3	18.00	17.50	17.00
Average of 1-3 Salinity S3	18.16	17.67	17.67
Average of T1 & T2 Salinity S1	33.00	32.50	32.50
Initial dilution n	1.82	1.84	1.84

T1 & T2 : Samples collected from tank B

Samples 1-3 : Samples collected from the end of the mixing tube according to the figure shown in page one of Appendix

n : Initial dilution within the mixing tube

TEST NUMBER : 54 MODEL NUMBER: Y1

FLOW METER READING IN PERCENTAGE: = 70%

FLOW RATE IN LITRES/SEC. : = 4.67

CORRECTION FACTOR FOR SALT WATER: = 1.01

ACTUAL FLOW RATE IN LITRES/SEC., Q= 4.72

Sample	Trial 1 Salinity in ppt	Trial 2 Salinity in ppt	Trial 3 Salinity in ppt
T1	32.00	32.00	32.00
T2	32.00	32.00	32.00
1	16.50	16.00	16.00
2	17.50	17.50	17.50
3	16.00	16.00	16.00
Average of 1-3 Salinity S3	16.67	16.50	16.50
Average of T1 & T2 Salinity S1	32.00	32.00	32.00
Initial dilution n	1.92	1.94	1.94

T1 & T2	: Samples collected from tank B
Samples 1-3	: Samples collected from the end of the mixing tube according to the figure shown in page one of Appendix
n	: Initial dilution within the mixing tube

TEST NUMBER : 55 MODEL NUMBER: Y1

FLOW METER READING IN PERCENTAGE: = 60%

FLOW RATE IN LITRES/SEC. : = 4.00

CORRECTION FACTOR FOR SALT WATER: = 1.01

ACTUAL FLOW RATE IN LITRES/SEC., Q= 4.04

Sample	Trial 1 Salinity in ppt	Trial 2 Salinity in ppt	Trial 3 Salinity in ppt
T1	32.00	32.00	32.00
T2	32.00	32.00	32.00
1	16.50	16.00	15.50
2	18.00	17.50	17.00
3	16.50	16.00	15.50
Average of 1-3 Salinity S3	17.00	16.50	16.00
Average of T1 & T2 Salinity S1	32.00	32.00	32.00
Initial dilution n	1.88	1.94	2.00

T1 & T2	: Samples collected from tank B
Samples 1-3	: Samples collected from the end of the mixing tube according to the figure shown in page one of Appendix
n	: Initial dilution within the mixing tube

TEST NUMBER : 56 MODEL NUMBER: Y1

FLOW METER READING IN PERCENTAGE: = 50%

FLOW RATE IN LITRES/SEC. : = 3.33

CORRECTION FACTOR FOR SALT WATER: = 1.01

ACTUAL FLOW RATE IN LITRES/SEC., Q= 3.37

Sample	Trial 1 Salinity in ppt	Trial 2 Salinity in ppt	Trial 3 Salinity in ppt
T1	32.00	32.00	32.00
T2	32.00	32.00	32.00
1	16.00	16.00	15.50
2	16.50	16.50	16.00
3	16.00	15.50	15.50
Average of 1-3 Salinity S3	16.17	16.00	15.67
Average of T1 & T2 Salinity S1	32.00	32.00	32.00
Initial dilution n	1.98	2.00	2.04

T1 & T2 : Samples collected from tank B

Samples 1-3 : Samples collected from the end of the mixing tube according to the figure shown in page one of Appendix

n : Initial dilution within the mixing tube