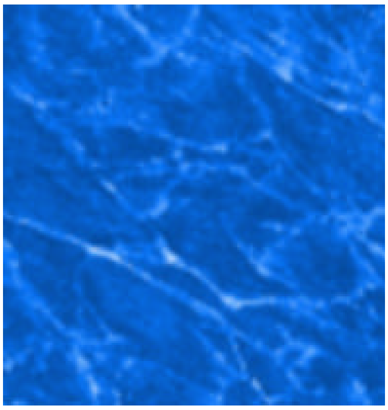

Reducing Mixing Effects In Water Storage Tanks

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SUMMARY

Clean drinking water is becoming more and more of a world wide problem, particularly in developing countries. Rain water harvesting is a technique which is creating growing interests as it is decentralised, locally manageable and relatively cheap to implement. However one barrier to its widespread use, is the issue of health, particularly with regard to bacteria washed in from the roof. There is substantial evidence that this bacteria die off after a period of storage in dark conditions so it is advisable to add water to one part of a tank and take it from another, while not allowing the water to mix.

This report looks at the methods of mixing in water tanks and describes experiments performed on a cylindrical model tank with a negatively buoyant water source discharging through various input arrangements.

Mixing was found to be confined to the bottom of the tank with the height of the mixing front proportional to the product of the Froude number and the inlet diameter, the constant of proportionality changing with different input arrangements. Recommendations are made regarding input and output arrangements based on these results and on observations made during the experiments.

CONTENTS

1. INTRODUCTION

THE NEED

Water is one of the primary needs of human beings. The body is over 60% water and needs over two litres a day to maintain good health. Water is also the universal solvent and is used for washing. According the World Health Organisation, each person needs at least 10 litres a day of potable water for drinking, cooking and dish washing purposes. New sources of water supply, however, are rare and old sources are drying up or are becoming contaminated.

Rainwater harvesting (RWH) is an age old technique that is experiencing a resurgence of interest. This is not only due to the apparent shortcomings of various other techniques being used but due to its convenience. Water is collected where it is used so long trips to the well are avoided. and expensive piping unnecessary.

One of the primary concerns, however, is that of contamination. The water fall onto a surface such as a roof and is then diverted to a storage tank. The surface itself also provides a place for falling vegetable matter, dust and faeces from birds and animals to settle. When the rain falls, this matter is washed into the system along with the water. Filtering can remove the larger debris and various “first flush” systems have been promoted to remove the worst of the contamination but smaller debris such as silt and micro-organisms such as faecal coliforms are not so easily disposed of.

There is strong colloquial evidence to suggest that simply storing water in a dark environment can reduce pathogens significantly as without light, photosynthesis cannot take place and the organisms soon die off. This means that, ideally, new water should enter at one end of a tank while old water should be drawn from the other without allowing the water in the tank to mix. Water in the tank should also be kept still to allow suspended matter to settle to the bottom of the tank.

AIMS AND OBJECTIVES

This project aims to investigate the phenomenon of reductions in pathogens through storage. The work can roughly be divided into answering four main questions:

1. What effects does storage have on pathogen numbers?
2. What are the storage times for pathogen die off and suspended solid settlement?
3. What ere the causes of fluid mixing in water storage tanks?
4. Can mixing effects be reduced significantly, and what methods can be adopted in the design of tanks, inlets, outlets etc. to achieve this?

The work itself can be divided roughly into three stages:

1. Desk Research
   - Health benefits of storage
   - Causes of mixing
   - Quantification
2. Experimentation
3. Recommendations

2. BENEFITS OF RESIDENCE TIME

Storage is one of the most effective methods of wastewater treatment. Commercial waste reduction ponds boast a removal rate of up to 99.8%[1], although the residence time tends to be measured in weeks rather than days. Die-off, sedimentation and predation are the main factors.

2.1 BACTERIA DIE-OFF

Typical die off behaviour for micro-organisms in water follows the pattern of a short period where numbers remain constant followed by a exponential decline in numbers. Adverse environmental factors outstrip supportive factors due to removal of organisms from their natural environment. Sometimes there may be a short term increase in numbers as the micro-organisms take up residence. The main factors for the decline are:

- Algae die off from lack of sunlight
- Competition for food increases
- Predation increases reducing the prey micro-organisms and ultimately starving out the predators
- flocculation and sedimentation remove some bacteria

These factors tend to be lumped together into a die off rate (*k*) which is used in the equation[2]

[1] Gray p276

[2] Droste p172

$$\frac{dc}{dt} = -kc \tag{2.1}$$

Where:

c is the concentration

t is time

Bacterial decay tends to follow an exponential curve, so an appropriate rewriting of equation 2.1 is:

$$c = c_0 e^{-kt} \tag{2.2}$$

Where:

c_0 is the initial concentration

This in turn can be rewritten in terms of t:

$$t = \frac{\ln\left(\frac{c_0}{c}\right)}{k} \tag{2.3}$$

The t_{90} value is a typically published figure. It is the time required for 90% of the bacteria to die off. equation (2.3) can be thus rewritten:

$$t_{90} = \frac{\ln 10}{k} \tag{2.4}$$

Some typical values of k and t_{90} are shown in table 2.1

TABLE 2.1 – VALUES OF k AND t_{90} FOR VARIOUS WATER BODIES[1]

Type	k **(hr^{-1})**	t_{90} **(hr)**
Oxidation pond	0.1	21
Wastewater lagoon	0.008 – 0.029	79 – 276
River water	0.17 – 0.23	10 – 90
Storm water	0.03	72

There is considerable variation and the rates are very dependent on temperature (high temperatures = more die off), UV radiation (more UV = more die off but more algae) etc. Actual rates of die off will have to be determined by experiment on site. Further work could uncover a range of k that corresponds with certain roof types, climate, time of year etc. These results together with the initial concentration and health data can be used in equation (2.3) to determine the residence time necessary for die off to bring the concentration down to a safe level or an appropriate level for secondary treatment.

2.2 SEDIMENTATION

water will also arrive with a load of sediment. While not usually unhealthy, this sediment can discolour and flavour the water which can in itself affect the water's acceptability. Sediment will ultimately settle out of water if it is left still. Particles fall by gravity but are held up by buoyancy and drag. Each particle will find some velocity where these factors balance and will fall at this rate (the terminal velocity). The time it takes for this to happen

[1] Based on data from Droste p 172

depends upon the surface area and density of the particles and their height above the bottom.

For spherical particles at low Reynolds numbers (>0.1) the terminal velocity is given by Stokes Law[1]:

$$u_t = \frac{g d_p^2 (\rho_p - \rho)}{18\mu}$$

where:

u_t is the terminal velocity

g is gravity (9.8 ms^{-1})

d_p is the diameter of the particles

ρ_p is the density of the particle

ρ is the density of water (1000 kg m^{-3})

μ is the viscosity of water (9.4 x 10^{-4} kg m^{-1} s^{-1})

As particles fall at different rates, they run up against each other and form clumps of particles. This process is called flocculation and results in larger particles that fall more quickly. Flocculation results in a reduction in pathogen levels as they can be trapped in the clumps of falling settlement and the method is often used in waste stabilisation ponds where coagulants are added to the water.

1 Perry p 6-50

3. CAUSES OF MIXING

There are five factors affecting the mixing of water in a closed tank:

- Velocity of the incoming stream and its subsequent kinetic energy
- Buoyancy of the incoming stream
- Diffusion
- Convection caused by changes in outside temperature and radiation of sunlight on the tank walls.

3.1 VELOCITY OF THE INCOMING STREAM

When the water enters the tank it will have kinetic energy gained from the fall from the roof. A jet of water results which stirs the water in the tank causing mixing. This turbulent mixing by using a jet of water is often used by the water industry to maintain even chlorine distribution in storage tanks. Rossman and Grayman[1] have shown that the mixing time can be found by

$$\tau_m = \frac{kV^{\frac{2}{3}}}{M^{\frac{1}{2}}} \qquad (3.1)$$

Where:

τ_m is the mixing time defined as the time necessary to achieve 95% uniformity

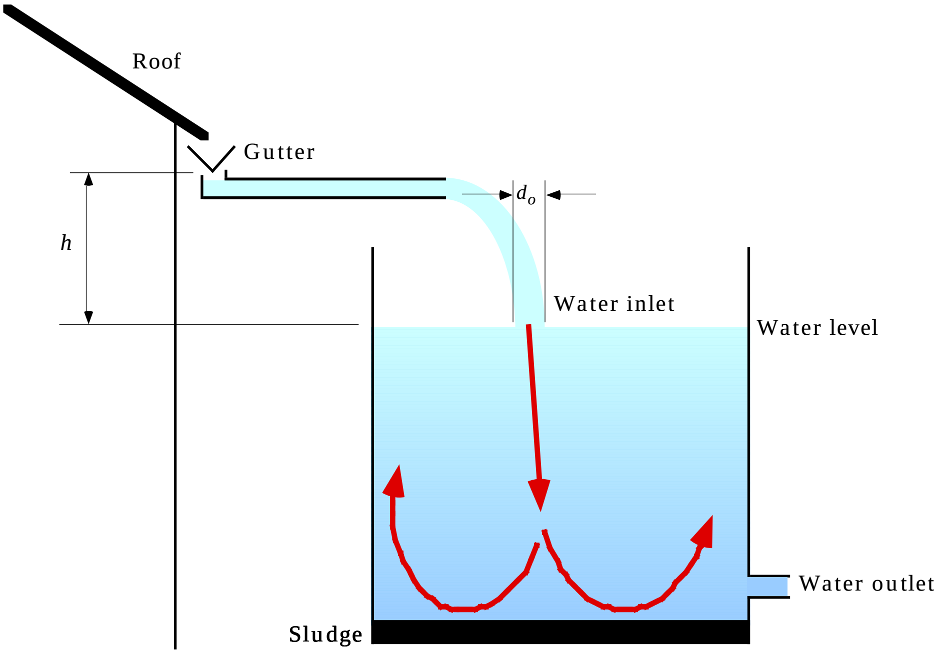
[1] Rossman and Grayman *JoEE* p 758

k is a constant

V is the volume of the tank

M is the momentum flux; the product of discharge and velocity

FIGURE 3.1 – TYPICAL TANK CONFIGURATION



In a typical tank configuration (figure 3.1), the water simply falls freely under gravity from a gutter or delivery pipe and therefore has a vertical component of velocity that is a function of the fall from the inlet of the downpipe to its outlet (h) given by the uniform acceleration equation;

$$u_0 = \sqrt{2gh} \qquad (3.2)$$

Where:

u_0 is the velocity on impact with the water surface

The horizontal component will be much the same as the output velocity from the gutter or pipe.

The area (A_0) of the jet will depend on the discharge (Q) and u_0. Conservation of volume leads to:

$$A_0 = \frac{Q}{u_0} \tag{3.3}$$

Therefore, if the jet is round, the diameter (d_0) will be given by:

$$d_0 = \sqrt{\frac{4Q}{\pi u_0}} \tag{3.4}$$

The velocity decay of the jet is a key factor. Any means possible to lower this will limit the overall circulation. When a jet enters a stationary fluid, it entrains the fluid around it and gains in volume. Conservation of momentum means that the velocity must therefore fall. There has been some work on decay of falling jets, mainly from the point of view of erosion from dam outfall. Ervine and Falvey[1] derived an expression for the velocity decay of a falling circular, non aerated jet:

$$u_{\max} \approx \frac{4u_0 d_0}{L} \tag{3.5}$$

Where:

u_{max} is the velocity at the axis of the jet

L is the depth beneath the surface

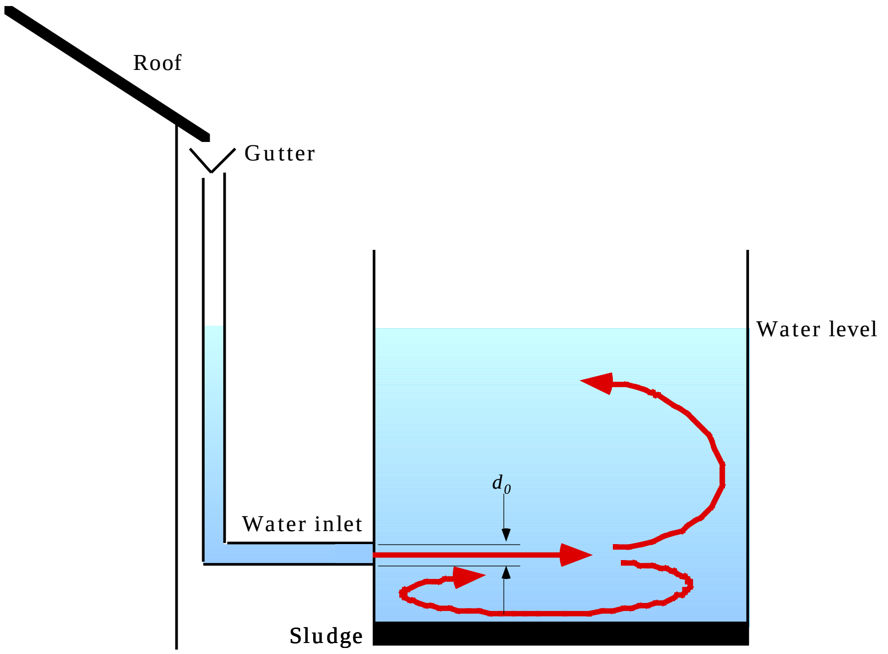
If the jet penetrates to the bottom of the tank, it will disturb the sludge and, if the velocity is sufficient, circulate up into the higher water bringing the sludge with it. Thus not only will the dirt and bacteria from the rainfall

1 **Ervine, D, A. and Falvey, H. T.** "Behaviour of turbulent water jets in the atmosphere and in plunge pools" (*Proceeding of the Institution of Civil Engineers*, 1987, Vol. 83 (2)) quoted in Bohrer et al

and roof mix throughout the tank, but any settled matter will be stirred up and must settle back out again. Falling jets also entrain air as they develop which will cause further mixing as the air bubbles out of the jet as it falls below the surface.

If the jet is submerged (figure 3.2) , the water will fill the downpipe to the level of the water in the tank. When rain falls, the water will rise in the downpipe until the difference in pressure head is enough to overcome the pipe friction.

FIGURE 3.2 – SUBMERGED JET ENTRY



The path of the jet impinges on the opposite wall and causes eddies and circulation upward, sideways and downwards. The downward circulation causes eddies and stirs the sludge but will remain mainly below the outlet due to the barrier of the jet. The sideways and upward circulations cause mixing of the new and old water and steps should be taken to avoid them, particularly the upward circulation as it mixes the oldest water from the top of the tank.

In this case d_0 is the inlet diameter and u_0 will be derived from this, so equation (3.4) will read:

$$u_0 = \frac{4Q}{\pi d_0^2} \qquad (3.6)$$

An empirical relation for the fall in velocity of a jet along its principle axis was found by Rushton[1]

$$\frac{u_x}{u_o} = 1.41\mathrm{Re}^{0.135}\left(\frac{d_o}{x}\right) \qquad (3.7)$$

Where

u_x is the velocity at a point along the centre line of the jet

x is the distance to that point

3.2 Convection of the incoming stream

When water enters the tank it will almost certainly have a different temperature to the water already in the tank. Kincaid and Longly[2] have done modelling that suggests that evaporation causes the temperature of raindrops to approximate the wet bulb temperature of the surrounding air. This temperature is dependent on humidity but is below the dry air temperature.

There is little exchange of air between the top of a water tank and the surrounding atmosphere so the air above the water surface in a tank will

1 Rushton “The axial velocity of a submerged axially symmetrical fluid jet “ (AIChE J 26, pp 1038–1041) Quoted in Perry

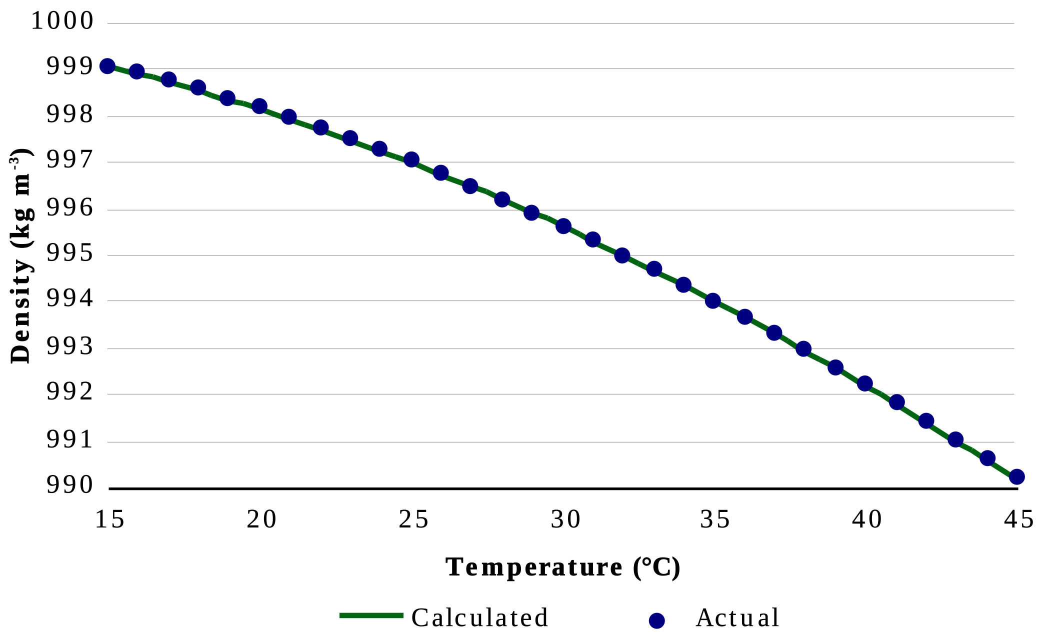
2 Kincaid and Longly

quickly reach saturation and no further heat transfer will then take place by this means, Thus the water temperature will be related to a more general heat balance and will usually be higher than the wet bulb temperature of the surrounding air mainly due to absorption of solar radiation, Rainfall is also often associated with a drop in air temperature and a corresponding drop in wet bulb temperature. This means that the temperature of the stored water will be higher than the temperature of the rain.

A shorter term effect is the temperature of the roof. If the roof has been in sunlight it will be warmer than the surrounding air. When the rain falls on the roof it will be heated and could be warmer than the water in the tank until the roof cools. This effect corresponds with the wash down of the majority of debris and so this water is often disposed of via various “first flush” mechanisms.

The temperature of the rainwater will affect the flow in the tank by changing the buoyancy of the incoming jet.

FIGURE 3.3 – DENSITY OF WATER VS. TEMPERATURE



Water changes density with temperature as shown in figure 3.3. Fitting a curve to the data yields the equation;

$$\rho = -0.005T^2 - 0.0049T + 1000.3 \quad (3.8)$$

which holds ±0.005% between 15°C and 45°C. A temperature difference of ±5° will result in a change in density of ±1 – 2 kg m^{-3}

If a fluid of one density is introduced into a fluid of another, the change in density will give rise to a reduced gravity given by:

$$g' = g\frac{(\rho_f - \rho_a)}{\rho_a} \quad (3.9)$$

Where:

g' is the reduced gravity

g is the acceleration due to gravity

$_f$ is the density of the feed water

ρ_a is the density of the ambient water

A temperature difference of ±5° will result in a reduced gravity of ±0.008 – 0.02 m s^{-3} and he jet will either rise or fall according to this reduced gravity. Factors that will affect this motion are:

- Friction caused by free viscosity on the surface of the jet. This will fall as the jet gains in size
- Reduction in temperature due to convection of the surrounding fluid and entrainment with the surrounding fluid

The principle measure of the buoyant effects on a jet an unconfined or semiconfined body is the densimentric Froude number. This is a non-dimensional ratio of a jets inertia to its buoyancy and is given by:

$$F_d = \frac{u}{\sqrt{g'd}} \qquad (3.10)$$

Where:

F_d is the densimentric Froude number

u is the velocity of the incoming stream

d is the diameter of the incoming stream

When a buoyant jet water is discharged into ambient water, the upwards momentum of the jet will, at some point be defeated by the buoyancy of the tank water. Fischer et al.[1] found that this height is given by:

$$h = k\, F_d\, d \qquad (3.11)$$

Where:

k is a constant usually between 0.5 and 0.7

If a jet is introduced into a closed body such as a tank, it will ultimately impinge on some surface, It will then change direction and in some cases, rise against the reduced gravity and so will attain a similar maximum height. Rossman and Grayman have used equation (3.11) to plot either

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1 **Fischer, H, B., List, E. J., Kohl, R. C. y., Imberger, J. and Brookes, N. H.** *Mixing in Inland and Coastal Waters* (New York: Academic, 1979) Quoted in Rossman and Grayman *JoEE*

stratified or fully mixed behaviour in enclosed tanks with horizontal and vertical inlets. k was found to have a range (between 0.8 and 1.5).

3.3 DIFFUSION

The diffusion of pathogens through water is driven by two effects

- Movement of bacteria by flagellum
- Brownian movement of the fluid

A ready value for this sort of diffusion is unavailable and diffusivities of liquids and gasses are usually found by experiment.

DIFFUSION BY BROWNIAN MOVEMENT

The volumetric diffusivity of the pathogens can be found by considering the problem statistically. If a particle moves randomly, a so called "random walk" it will be likely to move a distance equivalent to[1]:

$$s = \sqrt{2Dt} \tag{3.12}$$

Where

s is the distance travelled

t is the time taken

D is a diffusion constant

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1 http://www.genevue.com/A_Diffus/DiffusMain_1.html

If the particle is moving in a fluid, *D* can be found by the Stokes/Einstein equation[1]:

$$D = \frac{RT}{N}\frac{1}{6\pi r\mu} \tag{3.13}$$

Where

R is the gas constant (8314.41 J kg^{-1} $°K^{-1}$)

T is the temperature (°K)

N is Avogadro's number (6.02 X 10^{26} molecules kg^{-1} mol^{-1})

m is the viscosity (kg m^{-1} s^{-1})

r is the radius of the particle (m)

A pathogen can be considered as a particle with some average radius. Sizes of some common pathogens are in table 3.1:

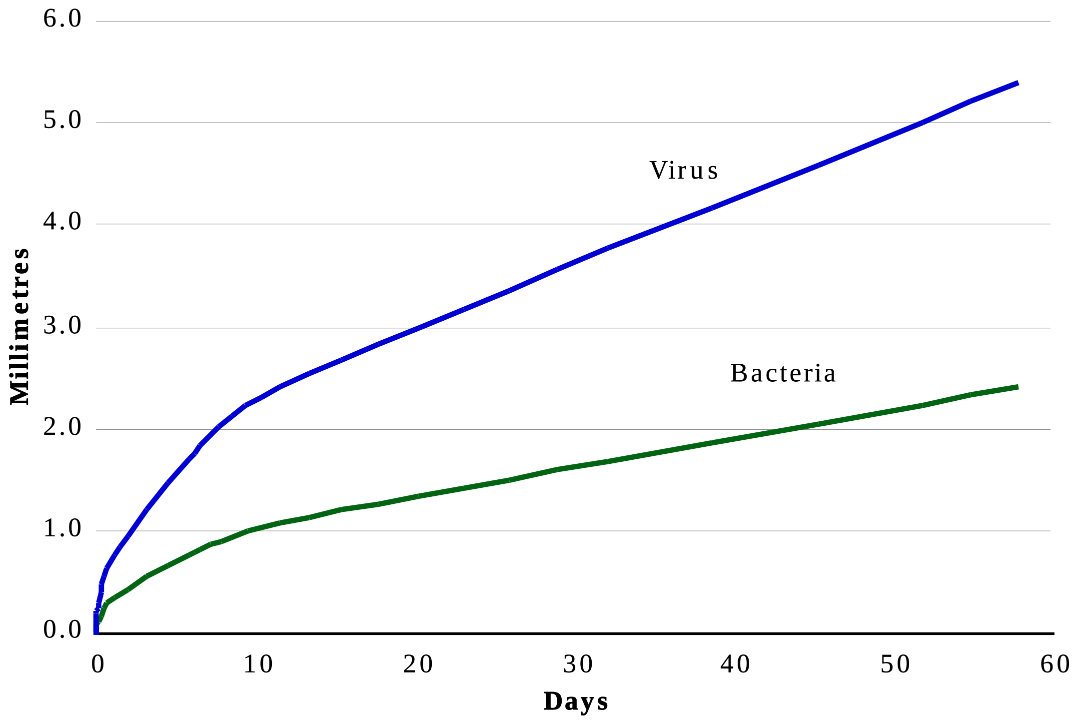
TABLE 3.1 – SIZES OF PATHOGENS[2]

Type	**Example**	**Size (approx.)**
Bacteria	Cholera	1 – 40 μm
Virus	Smallpox	200 nm

1 Einstein p75

2 Data from Droste

FIGURE 3.3 – MOVEMENT OF PATHOGENS BY BROWNIAN MOTION



The average movement is plotted against time in figure 3.3. It proves to be very small but is based only on the effects of Brownian motion, therefore it will not be accurate when flagellum movement is taken into account.

BACTERIAL MODATION

Most bacteria are capable of movement. This is usually accomplished by movement of flagellum (see figure 3.4) but sometimes by other means such as slithering or corkscrew rotation.

FIGURE 3.4 – MODATION BY FLAGELLUM MOVEMENT[1]

POLAR FLAGELLUM PERITRICHOUS FLAGELLUM

Speeds attained are far in excess of those from simple Brownian movement. For example Escherichia coli which is peritrichously flagellated moves at 16.45 $\mu m\ s^{-1}$. Polarly flagellated micro-organisms move about five times faster. Some examples of the flagellation of pathogens is in table 3.2.

TABLE 3.2 – FLAGELLATION OF PATHOGENS

Disease	**Genus[2]**	**Flagellation[3]**
Typhoid	Salmonella typhi	peritrichous
Cholera	Vibro Cholerae	Polar
Gastroentritis	Escherichia coli	Peritrichous
	Salmonella	Peritrichous
	Campylobacter jejuni	Polar
	Yersinia entercolitica	Peritrichous

Bacteria, however don't move in a straight line. Each run ends in a turning motion called a "twiddle". Twiddles are random movements and could result in the next run being in any direction resulting in little net

[1] from Brock et al. p 41

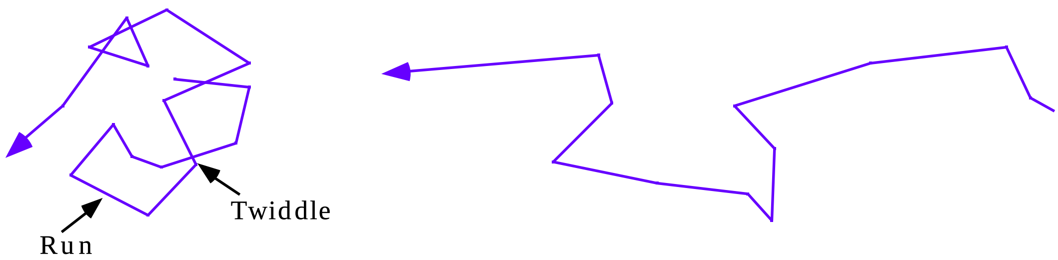
[2] Data from Cairncross & Feachem p260

[3] Data from Brock et al.

movement. A typical pattern of modation is pictured in figure 3.5A. If an attractant such as a food source is present, then the runs become longer in the direction of the attractant and shorter in other directions resulting in a movement towards the attractant. Similarly, if a repellent chemical is present the runs will become longer away from the repellent as in figure 3.5B. This process is called chemotaxis.

FIGURE 3.5; MOVEMENT OF BACTERIA

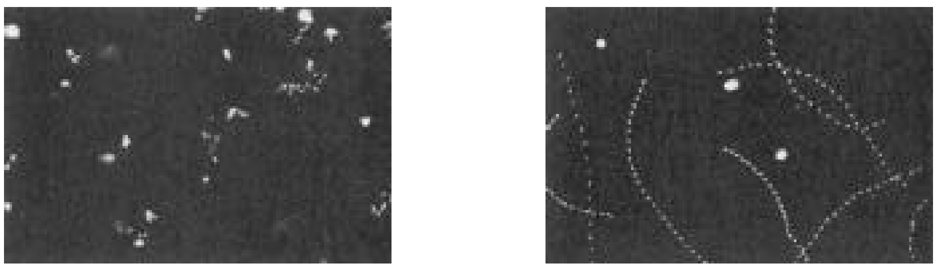
A, NORMAL B, WITH CHEMOTAXIS



Chemotaxis results in swarming, where bacteria toward or away from stimuli e*n mass* this movement is clearly seen in figure 3.6.

FIGURE 3,6 – STROBOSCOPIC PHOTOGRAPHS OF BACTERIAL MODATION

A. WITHOUT CHEMOTAXIS B. WITH CHEMOTAXIS



In a water tank, new water will be attractive and old water repellent as the older water will be depleted of nutrients. The net result should be that any bacterial movement will favour the newer water and may even play a role in depleting the older water.

3.4 CONVECTION BY CHANGES IN OUTSIDE CONDITIONS

Changes in outside temperature can cause flows in the water. If the water in the bottom of the tank is made warmer than the water in the top, then the structure becomes unstable and convection occurs causing mixing. If the water at the top is warmer than the water in the bottom then the water is stable and there is no movement. Heat gain will be mainly in the form of solar radiation; mostly on the top of the tank and heat loss will be mainly from convection with the outside air from the tank sides. In itself this should help create a stable temperature gradient from the bottom to the top of the tank which will increase the stability.

There are also a number design strategies that can be followed to encourage stable temperature gradients

- Paint the tank black on top to encourage solar heat gain at the top of the tank
- Grow trees around the tank perimeter to shade the bottom of the tank

This temperature gradient can also positively enhance the buoyant effects of the incoming stream by increasing the reduced gravity as the jet rises in the tank.

Heat exchange can also have a negative effects if one side of the tank is heated by the sun. Bénard convection will result which will churn the water in the tank causing mixing. This should be a fairly small effect as the temperature difference should not be too great and the cellular nature of the convection will localise mixing effects. Reducing solar radiation on the side of the tank with appropriate paint or tree shading should reduce this problem.

4. THE EXPERIMENTS

The principle area where design can influence residence time is in the area of turbulent mixing by jet momentum. The principle way this can be reduced is nozzle placement and design. Larger diameters will reduce the velocity and reduce mixing, however this can only be pursued to a limited extent. Other strategies could involve different nozzle configurations such as manifold designs and designs that encourage certain fluid behaviours such as horizontal rotation. The experiments were designed to exploit buoyant stratification to investigate these ideas.

4.1 NON-DIMENSIONAL PARAMETERS AND SCALING

Recall, The maximum height of a buoyant jet is proportional to the product of the jet's Froude number and its diameter (equation (3.11)). This can be written non-dimensionally as:

$$\mathrm{F}_d = k\,\frac{h}{d} \qquad (4.1)$$

In a closed tank, a mixing front is formed where the jet reaches its maximum height, This height can be measured for jets of differing Froude numbers and a value for *k* can be found. At the same Froude number, the results are scaled as:

$$\frac{h_m}{d_m} = \frac{h_p}{d_p} \qquad (4.2)$$

Where the subscripts *m* and *p* refer to the model and prototype respectively.

The tests use salt as a medium to raise the density of the jet. This allows good control over the buoyancy and also allows bouyancies to be made much greater than those in the real world which in turn allows higher velocities for closer dynamic similarity as $F_d = \frac{u}{\sqrt{g'd}}$. Velocity can be increased so long as the reduced gravity is also increased. This technique was developed by Linden at al. for studies of natural convection in buildings. Larger bouyancies also reduce the test times and are more tolerant of measuring errors and changes in temperature. Full dynamic similarity was not obtained as the large amounts of salt needed were difficult to mix thoroughly resulting in some errors. The tests times also became so short that measurements were difficult to take. A balance was struck at 60 ml salt to 10 l of water which provided a reduced gravity of -0.052.

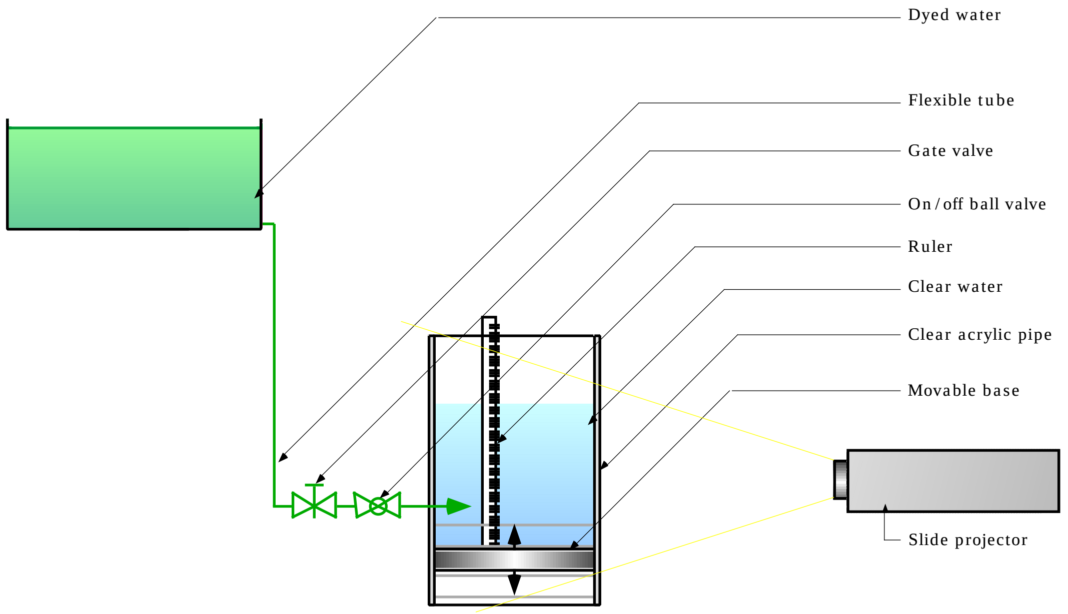
Buoyancy was a product of both temperature and salt content. The calculated densities of the fresh tank water and feed water as well as the salt content were used to calculate *g*' using equation (3.9)

- The density of salt was found by weighing a known quantity. Each ml of salt into 10l of water added 0.1325 kg m^{-3} (it was assumed that the salt completely dissolved)
- The temperature of the tank water and feed water were measured at regular intervals and equation (3.8) was used to find the density
- The dye has a very similar density to water, so it was assumed to play no extra part in the density calculation

4.2 APPARATUS

All experiments used a scale model of a water tank made from a clear pipe with a movable base made from Styrofoam. The overall apparatus is pictured in figure 4.1. Dyed water was stored in a reservoir which was placed at a height of 1.6m above the tank model. The dyed water was fed down a flexible tube and through a nozzle into the tank. A screw down gate valve regulated the flow and a ball valve was used to stop and start each trial. A light sheet was made using a slide projector with a slotted slide.

FIGURE 4.1 – TEST APPARATUS



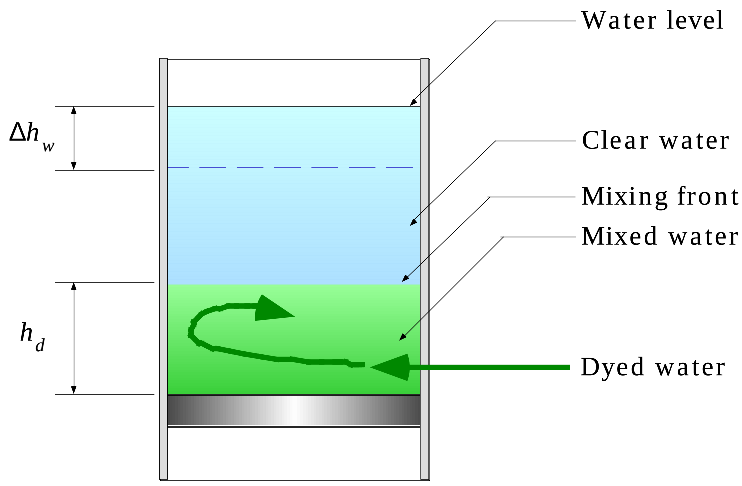
The nozzle arrangement was a standard plumbing fitting into which either different sized inserts or a number of different nozzle configurations made from copper pipe could be fitted. Measurements were taken by siting across two rulers and each trial was timed with a stopwatch.

4.3 METHOD

Food dye was added to the feed water as an indicator as well as a predetermined amount of salt to give it negatively buoyancy. At the start of each set of trials the temperature of the feed water and the tank water were noted.

Most trials started with the tank filled with fresh water to a level of 10 cm . The dyed feed water was discharged into the model and the height of the dyed water mixing front (h_d; see figure 4.2) was measured for each cm of change in water level (Δh_w). The trial ended when the water level reached 15 cm. Several tests were also done with an initial level of 7 cm and final level of 12 cm to test the sensitivity to water level.

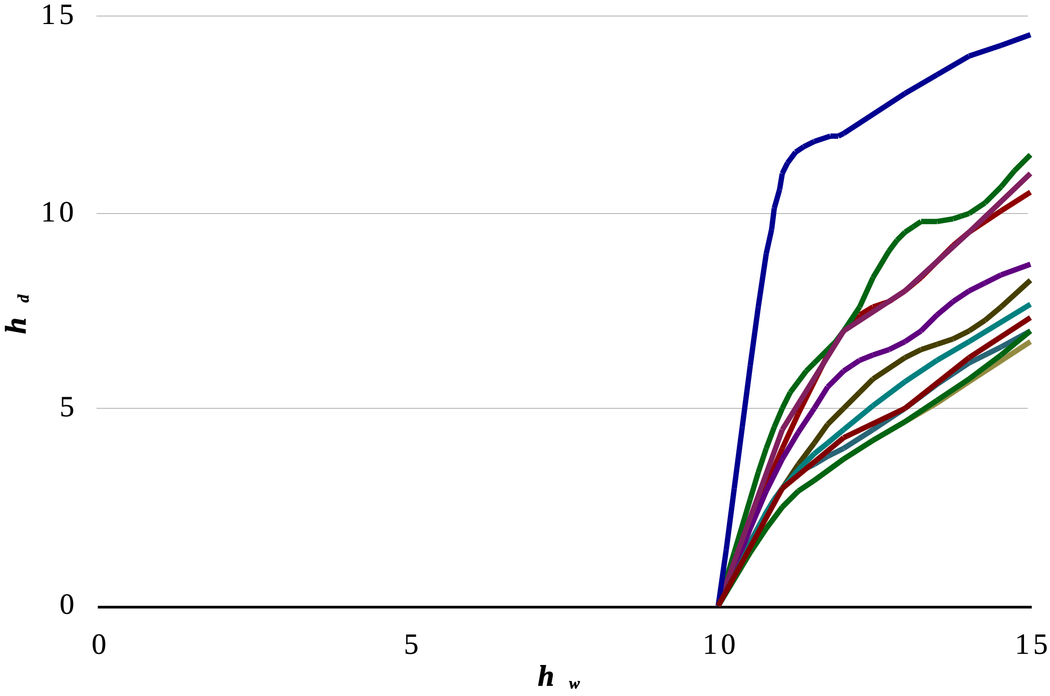
FIGURE 4.2 – MEASURED QUANTITIES



Each test was timed and the total volume discharge ($A\ \Delta h_w$) was divided by the test time to obtain the velocity of the jet. The temperatures and salt quantities were used to calculate the buoyancy. The densimetric Froude number was then calculated from these values and the jet diameter.

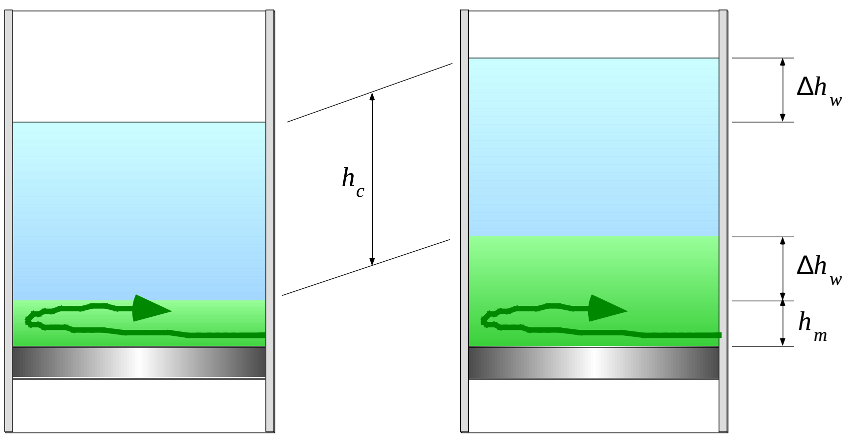
Early in the tests, it became apparent that as the water level rose, it was possible for the mixing front to rise at the same rate ($\Delta h_w = \Delta h_d$).This effect is shown in the unity slope at the end of each line of the graph in figure 4.3.

FIGURE 4.3 – RISE IN WATER LEVEL VS. RISE IN DYED WATER LEVEL



If this was the case, all mixing would be occurring well below the mixing front and there would be no further mixing of clear water as the height of the clear water (h_c) would remain constant (see figure 4.4)., For this reason the height of the water level was subtracted from the height of the dyed water mixing front, leaving only the height where actual mixing was taking place (h_m).

FIGURE 4.4 – DETERMINATION OF ACTUAL MIXING HEIGHT



Measurements were then only taken at the end of each trial when h_c had stabilised. The calculated h_m was then divided by the nozzle diameter and plotted against the calculated densimetric Froude number for the test.

The gate valve was then set to a different discharge and the experiment repeated.

4.4 HORIZONTAL INLET

INTRODUCTION

The first set of experiments were to determine the relative effects of buoyancy and momentum in the mixing behaviour of the tank with a straight horizontal inlet. While Rossman and Grayman had plotted “mixed” or “not mixed” results based on a known height tank and fitted a line between these results[1], these experiments attempted to derive the line directly by plotting the ratio of mixing height to inlet diameter against Froude number. Three nozzle diameters were tried and three quantities of salt. These are detailed in table 4.1

TABLE 4.1 – EXPERIMENTAL VARIABLES

Nozzle Diameters	**Salt Quantities**
6.7 mm	20 ml
8.0 mm	40 ml
10.5 mm	60 ml

1 Rossman and Grayman *JoEE* p759

The jet had two means of impingement on the far wall. If the Froude number was low enough, the jet fell to the floor, moved along it and then climbed the wall. This can be seen in the series of photographs in figure 4.5. If the Froude number was high, the jet impinged the far wall directly and followed the pattern in figure 4.6. In both cases, the jet would climb the wall for a short distance before falling back and filling the bottom. As the jet filled the bottom of the tank, it would again attempt to climb the walls. It was this second climb that formed the bulk of the mixing activity.

FIGURE 4.5 – PROPAGATION JET FALLING TO BOTTOM

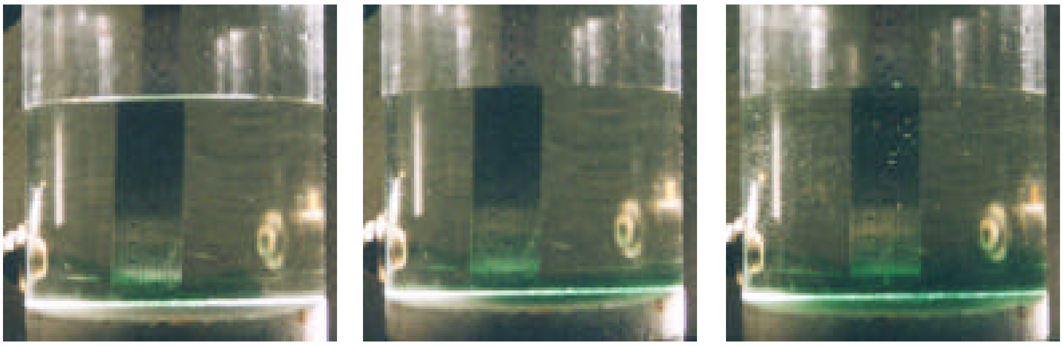
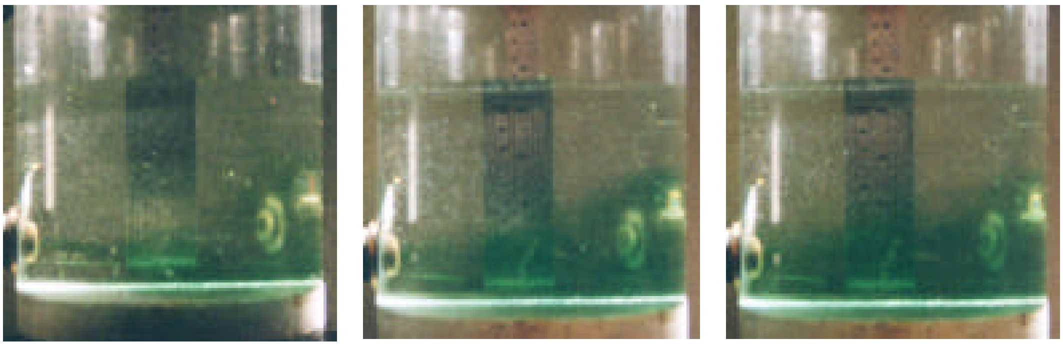
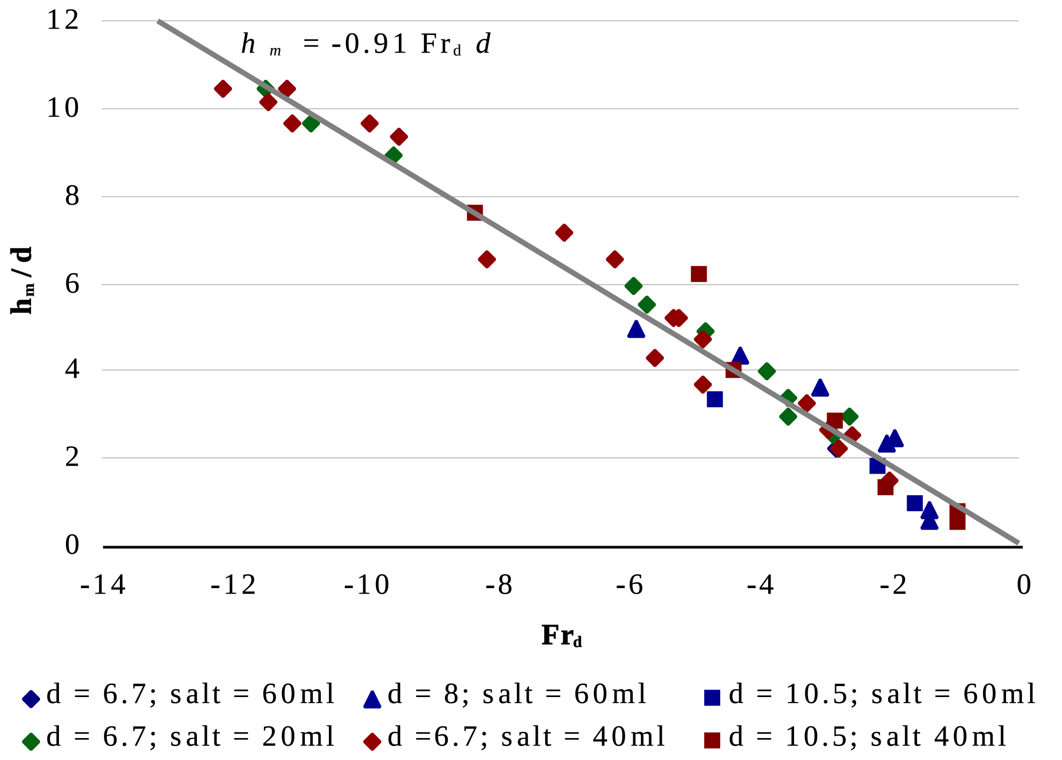


FIGURE 4.6 PROPAGATION OF JET IMPINGING THE FAR WALL



When plotted , all results fall on a straight line through the origin with a gradient of -0.91. This is in reasonable agreement with Rossman and Grayman who found the coefficient to be -0.8. The results are plotted in figure 4.6.

FIGURE 4.6 – FROUDE NUMBER VS. MIXING HEIGHT/INPUT DIAMETER STRAIGHT HORIZONTAL INLET



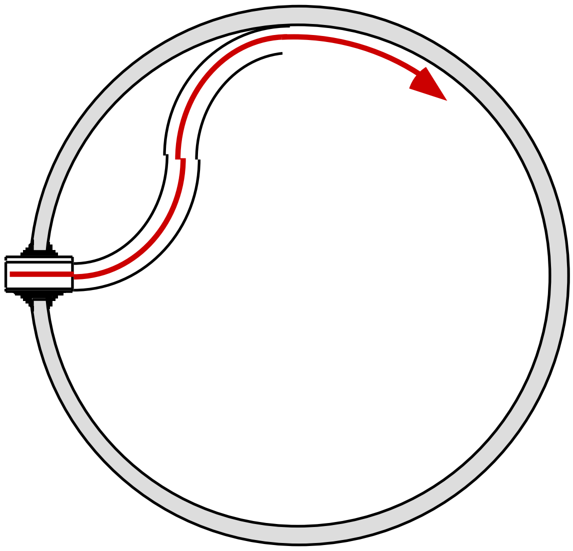
This relation appears robust against changes in diameter, discharge, buoyancy and water level so the results should be scaleable.

4.5 CIRCULATING INLET

INTRODUCTION

The major cause of upward movement with a horizontal inlet is the jet impinging on the far wall. If the water is designed in such a way as to avoid this, it is possible that the mixing height will be reduced. One way of achieving this is to encourage the inlet to circulate around the perimeter of the tank as in figure 4.7. This should both avoid direct impingement on the wall but should also provide a surface on one part of the jet to slow the jet down more quickly and with less mixing than with free turbulence. Circulation also has a natural stratifying effect.

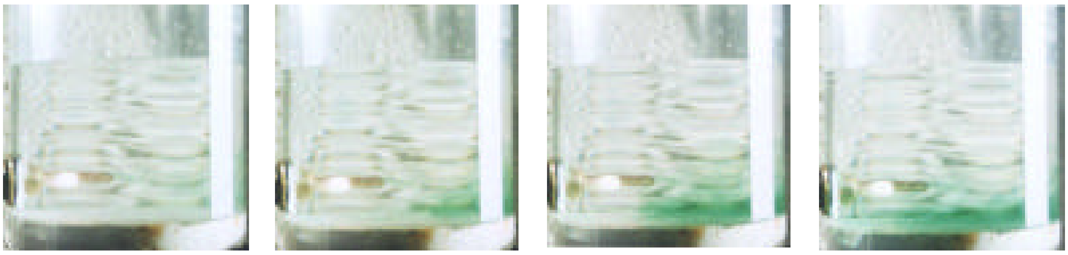
FIGURE 4.7 – CIRCULATING INLET



RESULTS

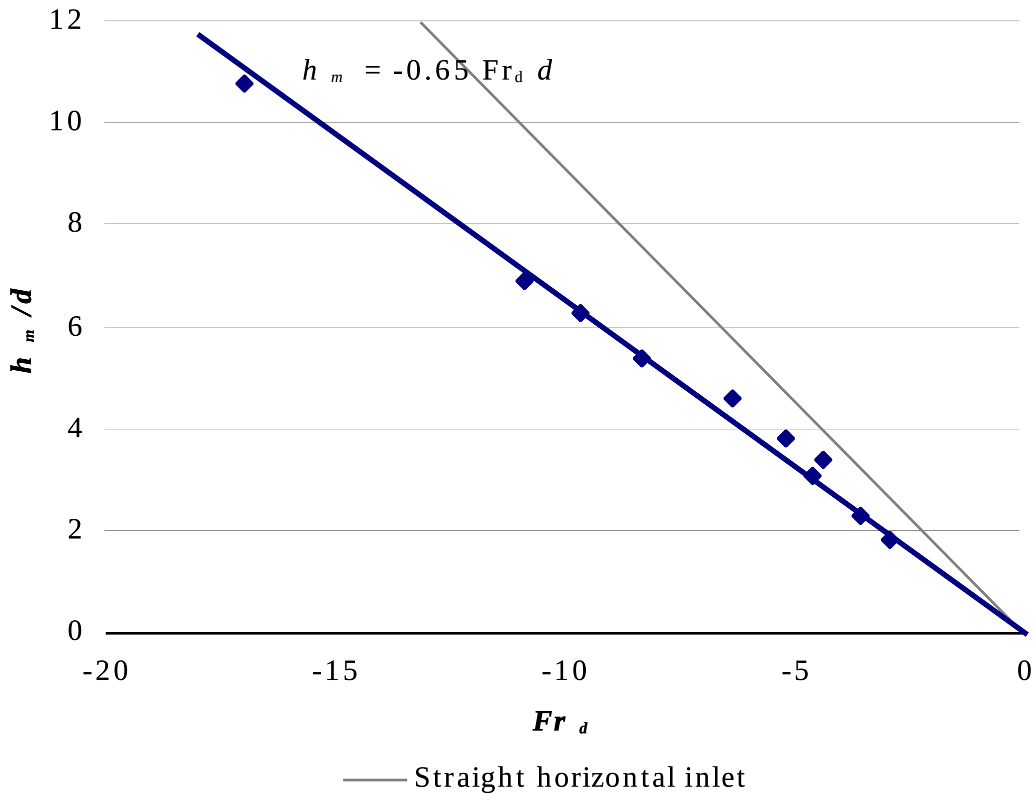
The jet performed much as expected. There was no impingement and the jet simply fell gradually to the bottom as it circulated around the tank. As it hit the bottom it spread out and behaved in much the same manner as with a straight jet.

FIGURE 4.8 – PROPAGATION OF CIRCULATING JET



The results from the circulating jet again fell on a straight line through the origin but the coefficient of stratification of 0.65 was significantly lower than a straight horizontal jet. The results are plotted in figure 4.9.

FIGURE 4.9 – FROUDE NUMBER VS. MIXING HEIGHT/INPUT DIAMETER HORIZONTAL CIRCULATING INLET

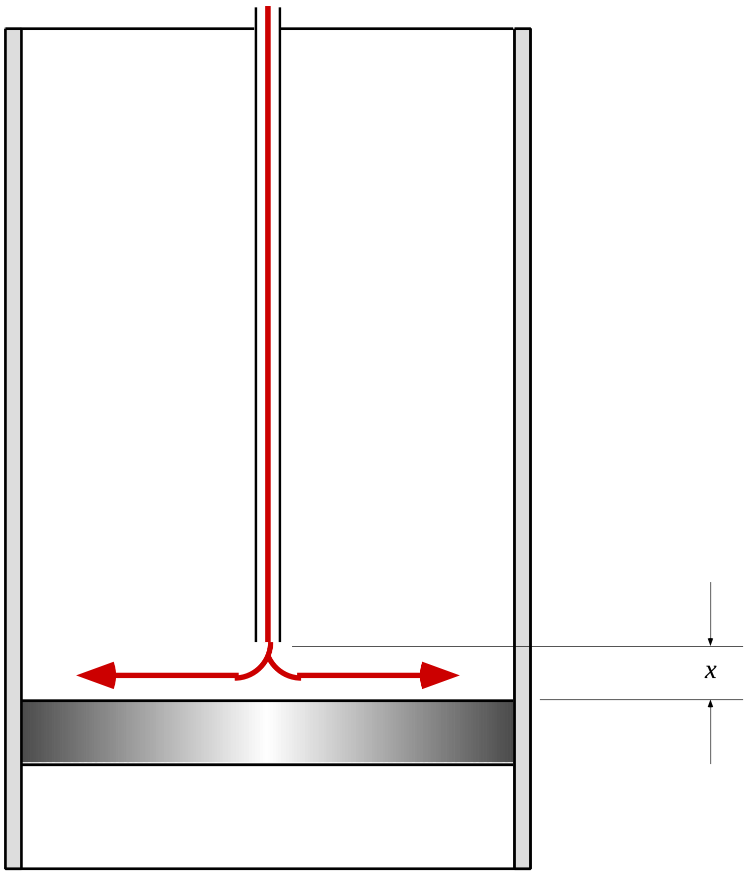


4.6 DOWNWARD POINTING VERTICAL INLET

INTRODUCTION

Another option to avoid impingement on the sides is to simply aim the jet downwards as in figure 4.10. the jet will then first impinge on the floor and only then move up the sides. This is a very different situation to simply dropping the water in from the top as the diameter of the inlet is controllable and all air will float out before the water is introduced into the tank. it will, however, disturb the sludge on the bottom of the tank, but, as the water needs to be left for pathogen die off, this should also provide ample time for sedimentation to take place. It is also possible that sedimentation could reduce the necessary residence time through flocculation.

FIGURE 4.10 – DOWNWARD POINTING VERTICAL INLET

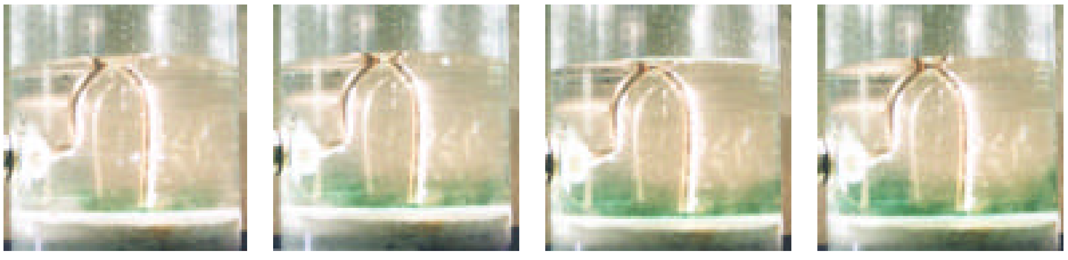


Tests were made with the inlet at several heights above the base (*x*), centrally and near to the tank wall

RESULTS

The jet moved outwards along the bottom of the tank and then climbed the walls with a similar pattern as had been noted with the straight jet.

FIGURE 4.11 – PROPAGATION OF DOWNWARD POINTING VERTICAL JET



Once again the results fell on straight lines however the coefficients of stratification ranged as the height of the nozzle changed. The resultant coefficients are in table 4.2. The actual results are graphed in figure 4.12

The results for central positioning and positioning next to the wall fall on the same line. So mixing appears insensitive to the horizontal placement of the jet.

FIGURE 4.12 – FROUDE NUMBER VS. MIXING HEIGHT/INPUT DIAMETER
DOWNWARD POINTING VERTICAL INLET

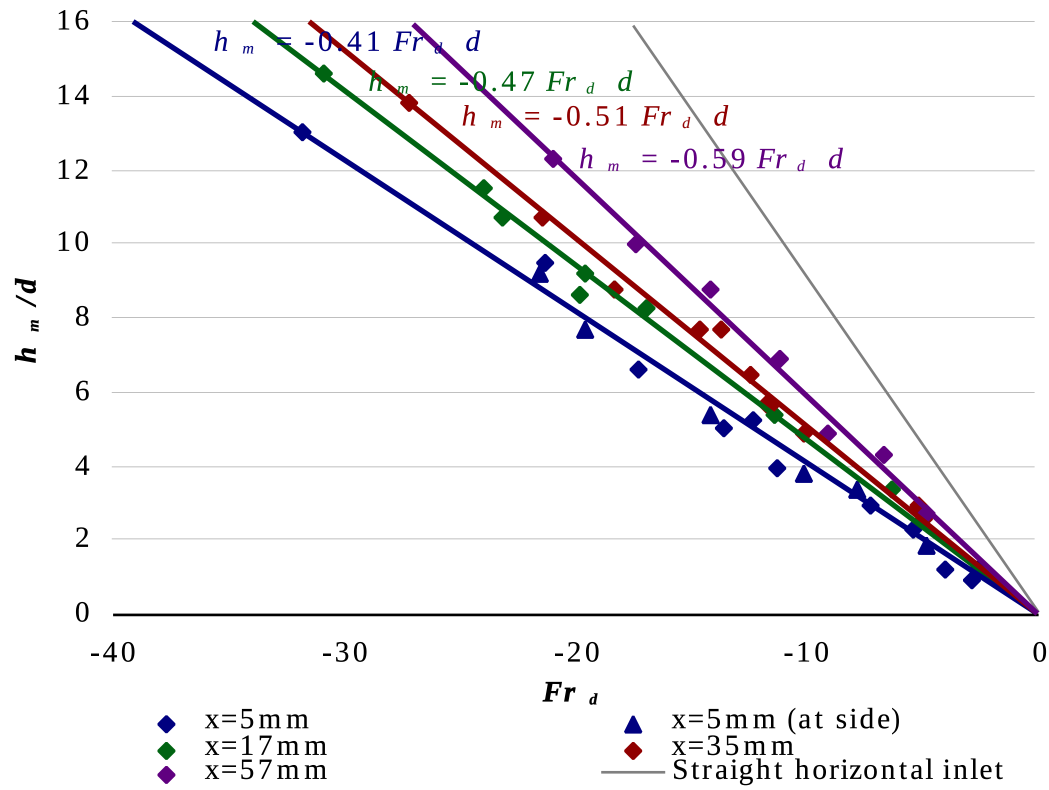
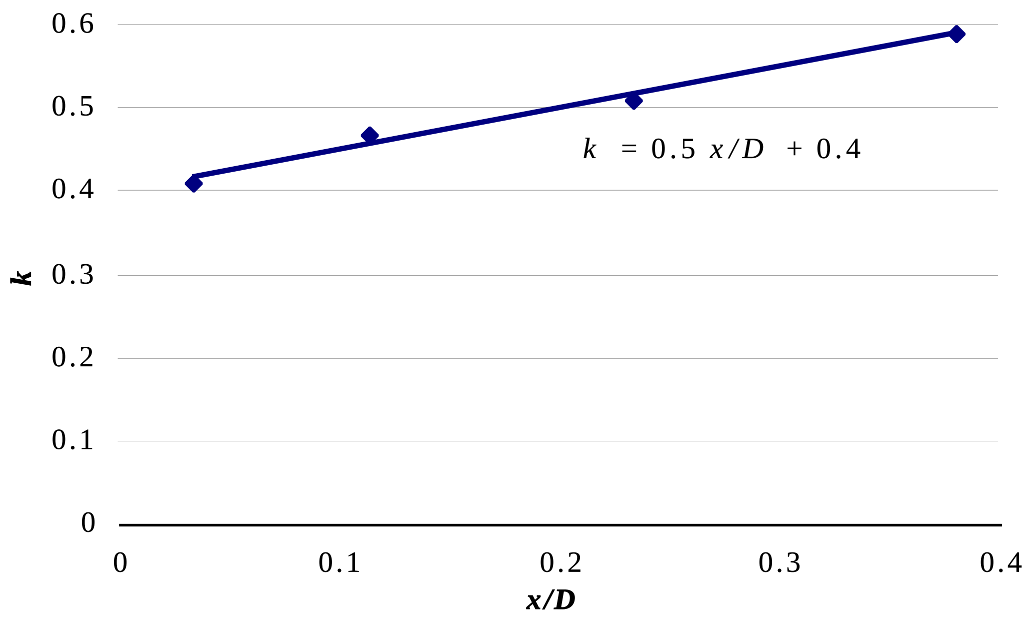


TABLE 4.2 – COEFFICIENTS OF STRATIFICATION FOR DOWNWARD POINTING VERTICAL INLET

x	k
5 mm	0.41
17 mm	0.47
35 mm	0.51
57 mm	0.59

The results for *k* were charted against the height of the nozzle which was non-dimensionalised by dividing by the diameter of the tank. They also fall on a straight line as shown in figure 4.13

FIGURE 4.13 – STRATIFICATION COEFFICIENT VS. VERTICAL INLET HEIGHT

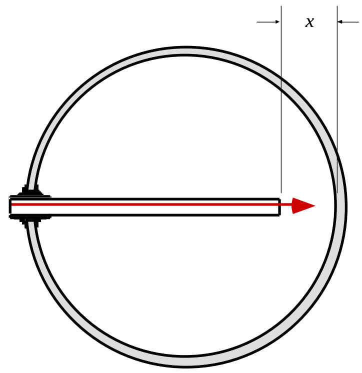


4.7 EXTENDED HORIZONTAL INLET

INTRODUCTION

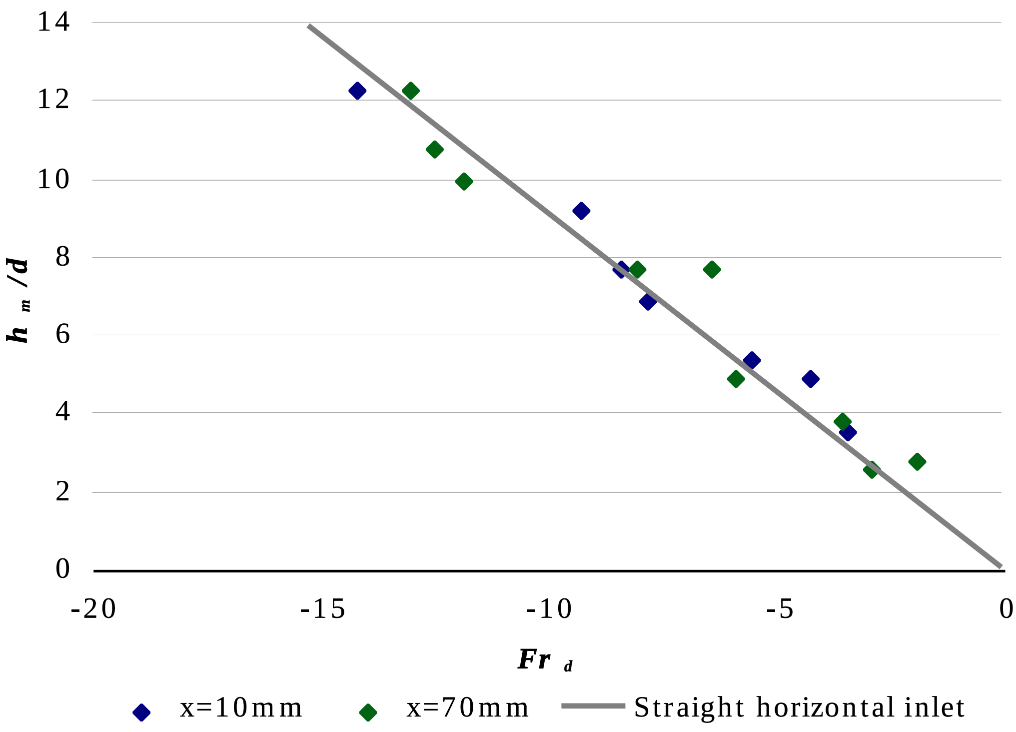
These results beg the question of how much effect the distance before the jet impinges upon the far wall makes. To this end several tests were done with different lengths of extension to the horizontal inlet (see figure 4.14).

FIGURE 4.14 EXTENDED HORIZONTAL INLET



the results fell on the same line as those from the other horizontal inlet tests. Mixing height appears to be completely independent of distance from the impinging wall.

FIGURE 4.15 – FROUDE NUMBER VS. MIXING HEIGHT/INPUT DIAMETER
STRAIGHT HORIZONTAL INLET

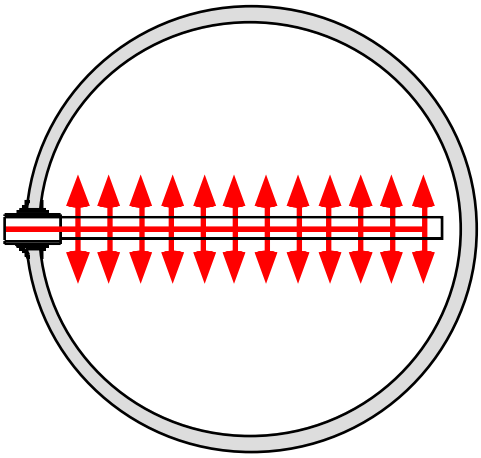


4.8 STRAIGHT HORIZONTAL MANIFOLD

INTRODUCTION

One way of increasing the total cross sectional area of inlet and consequently lower the velocity is to use a manifold design such as that shown in figure 4.16. Each jet will have a Froude number and a consequent terminal height, however the total height should be less than for a single jet of the same cross section as each jet has a much smaller diameter. The calculation of the manifold considered the effects of each jet in the manifold individually and divided the discharge by the number of jets consequently reducing the velocity.

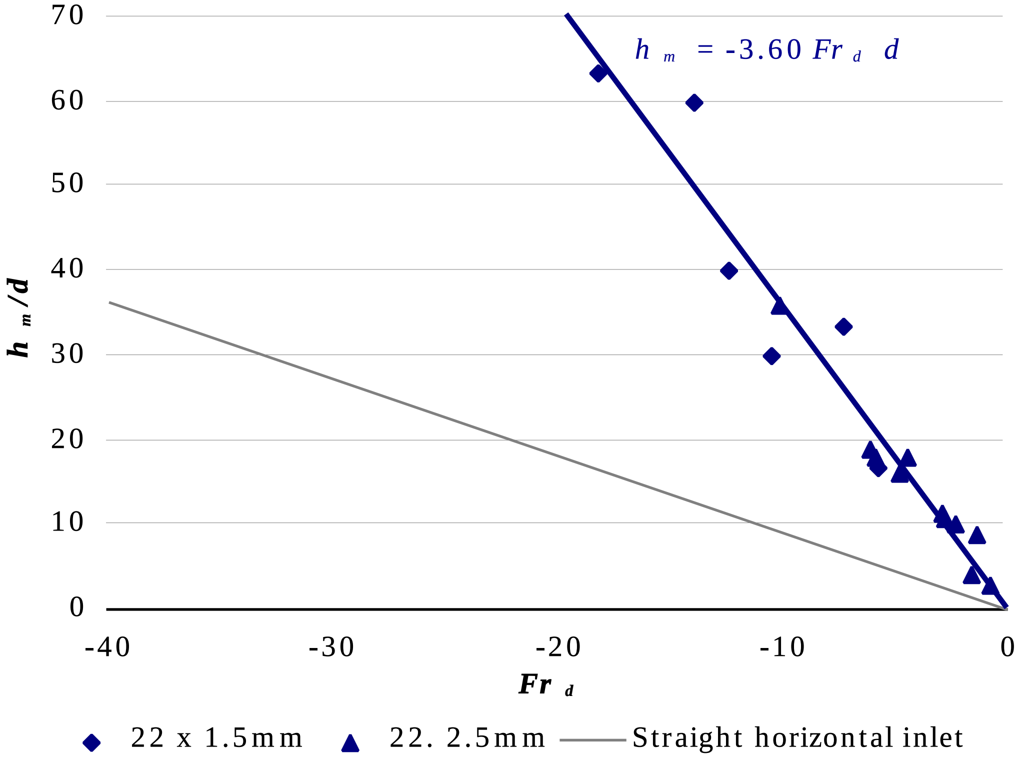
FIGURE 4.16 – STRAIGHT HORIZONTAL MANIFOLD



RESULTS

The horizontal manifold gave a poor performance with a coefficient of stratification some four time higher than for a single jet.

FIGURE 4.17 – FROUDE NUMBER VS. MIXING HEIGHT/INPUT DIAMETER
STRAIGHT HORIZONTAL MANIFOLD



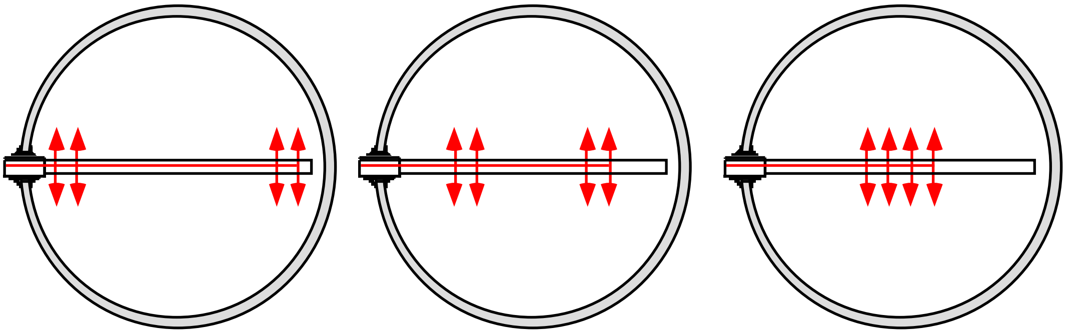
4.9 MODIFIED STRAIGHT MANIFOLD

INTRODUCTION

The promising results of circulating inlets prompted trials with a number of configurations of manifold in an attempt to ascertain whether proximity to the tank wall has any significance,

FIGURE 4.18 – MODIFIED STRAIGHT MANIFILDS

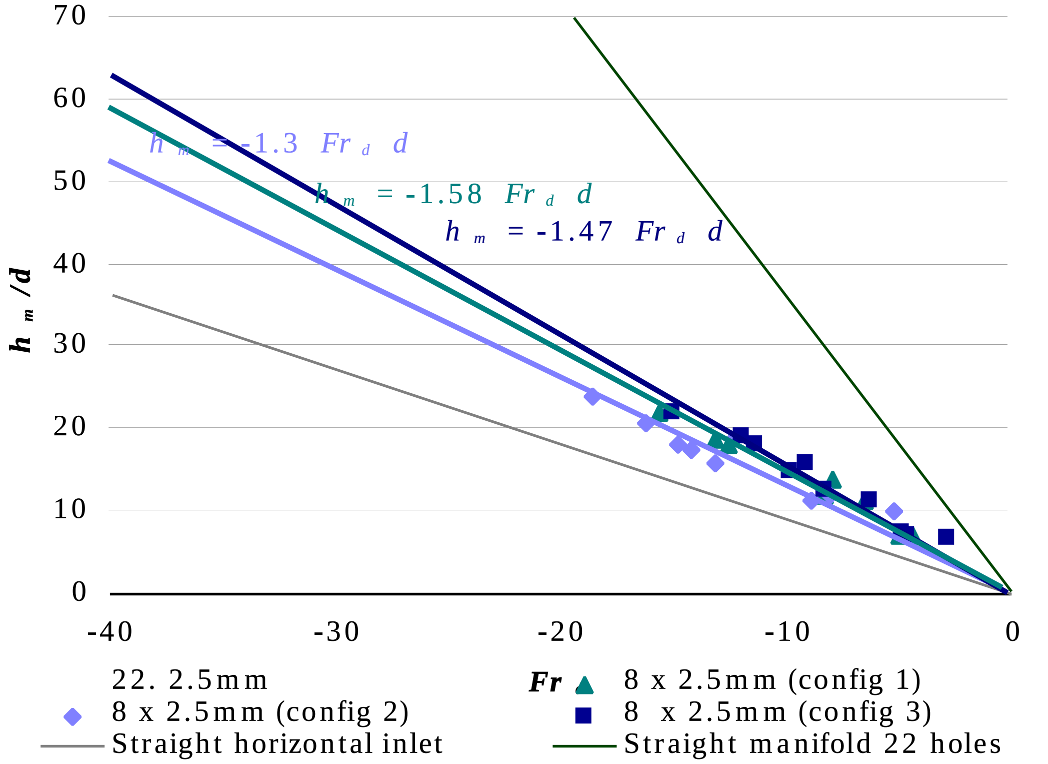
CONFIGURATION ONE	CONFIGURATION TWO	CONFIGURATION THREE



RESULTS

The results are fairly inconclusive, All configurations gave a better result than the longer manifold but worse results than a straight inlet. The actual gradients are within a small range and favour configuration two. The improvement is probably due to the lower number of jets interfering with each other however, the lack of overall promise of the straight configuration does not really warrant further investigation.

FIGURE 4.9 – FROUDE NUMBER VS. MIXING HEIGHT/INPUT DIAMETER MODIFIED STRAIGHT MANIFOLD

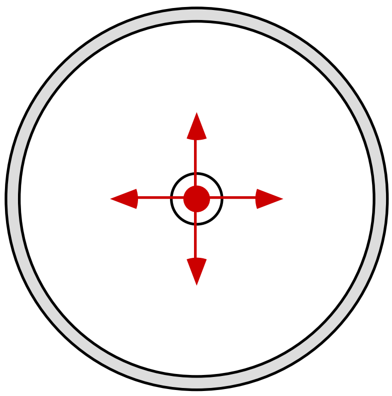


4.10 RADIAL MANIFOLD

INTRODUCTION

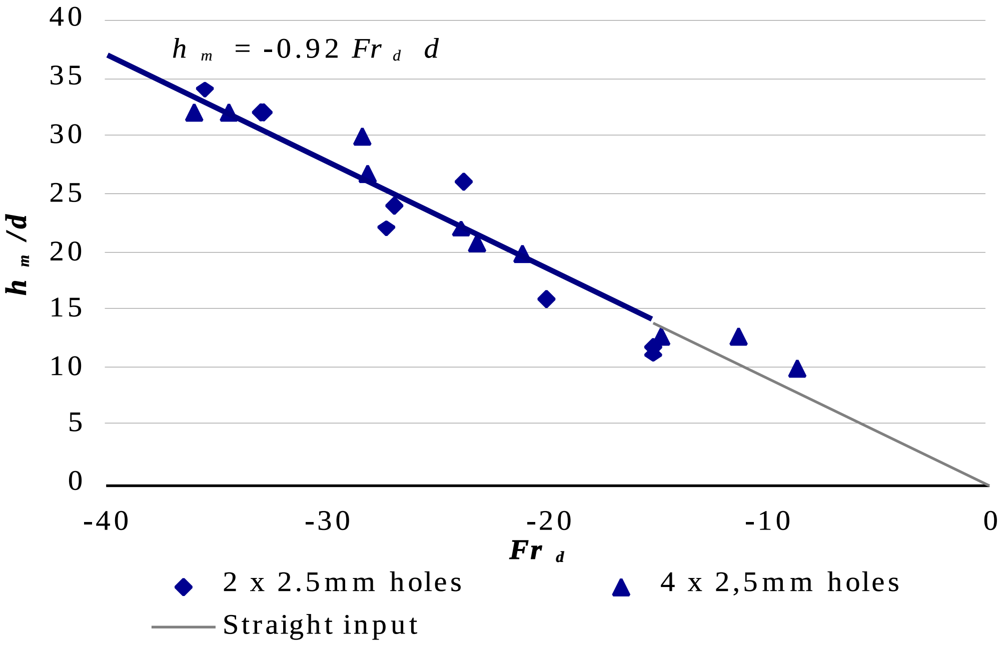
Manifolds can also originate from a central point. This should result give less interference between each jet. Trials were made with a radial manifold with twin jets in opposite directions from a central position and one with four equally spaced jets.

FIGURE 4.20 – RADIAL MANIFOLD



All results fall on the same line. This line has a gradient within 1% of that for a straight inlet which is what is to be expected if the jets have no contact with each other. The difference is almost certainly due to measurement errors.

FIGURE 4.21 – FROUDE NUMBER VS. MIXING HEIGHT/INPUT RADIAL MANIFOLD

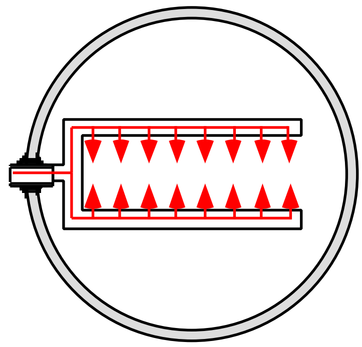


4.11 Horizontal manifold with collision

INTRODUCTION

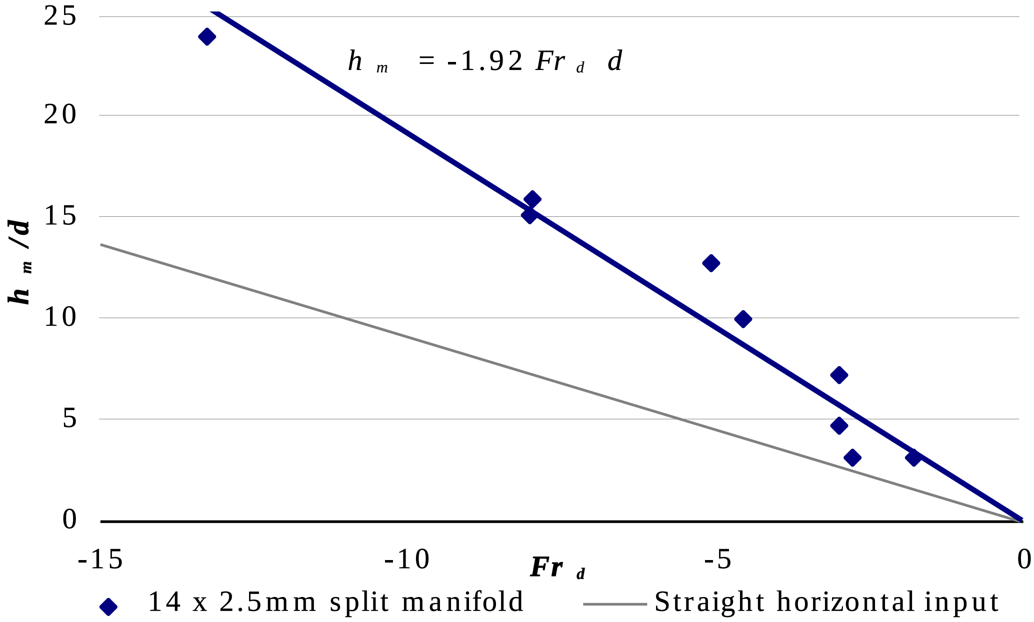
Another possible geometry is to have the jets collide with each other.

FIGURE 4.22 – COLLIDING MANIFOLD



The result from the colliding inlet are slightly better than those for a simple straight manifold. They are, however still much worse than those for a straight inlet and could simply be due to the lower number of jets.

FIGURE 4.23 – FROUDE NUMBER VS. MIXING HEIGHT/INPUT COLLIDING MANIFOLD



PLUNGING JET

INTRODUCTION

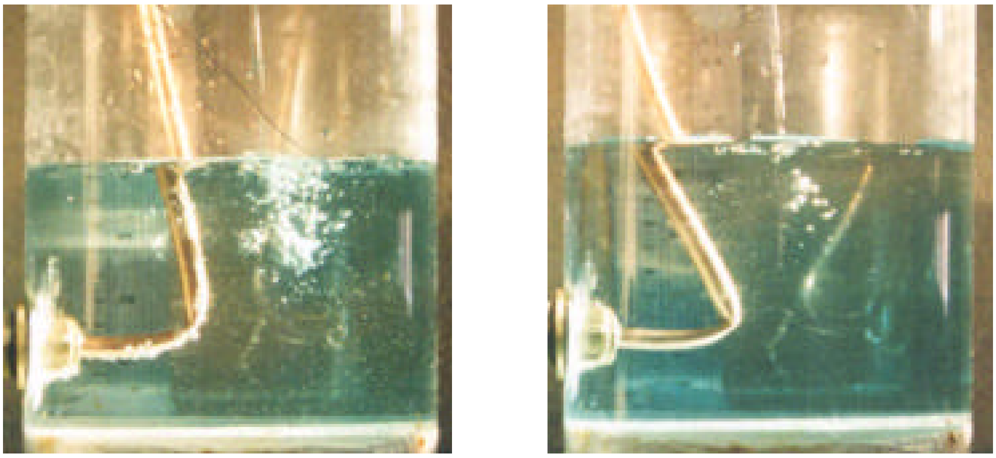
For comparison, several tests were done with the inlet above the water level as in a traditional tank configuration

RESULTS

The velocity gain due to the fall from the inlet meant that the cross section of the jet was less than 3mm by the time it hit the surface of the tank. The jet also had a great deal of entrained air which was released below the surface. This effect was even seen with quite “clean” jets that had not developed into droplets. The effect can be clearly seen in figure 4.24. At the small scale of these experiments, surface tension was more of an issue than would be the case on a larger scale so the results may not be completely accurate, however most turbulent jets will have entrained air and droplets as they develop. It was impossible to create a stratified result at the scale of these trials due to the dropletting of the jet as it fell, the small cross section and surface splashing.

FIGURE 4.24 – PLUNGING JETS

DEVELOPED DROPLETTING JET UNDEVELOPED "CLEAN" JET



SUMMARY OF RESULTS

TABLE 4.3 COEFFICIENTS OF STRATIFICATION

Inlet type	**Coefficient of stratification**
Horizontal	0.91
Circulating	0.65
Vertical	0.41 – 0.59
Straight manifold (22 outlet)	3.6
Modified manifold (8 outlet)	1.3–1.47
Radial manifold	0.92
Colliding manifold	1.92

5. CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK

GENERAL DESIGN RULES

Some general design rules have emerged from this work

- Placement of the input is best under the surface of the water
- Make the input as large as possible
- The best configuration for the inlet is horizontally downward followed by along the tank wall to encourage circulation
- Manifolds can be useful but should be radial not linear
- Output should either be floating or at such a height that only water that has been depleted can be drawn
- When a horizontal inlet is used, the best place for a fixed output is on the same side as the input as the mixing height is higher at the opposite side

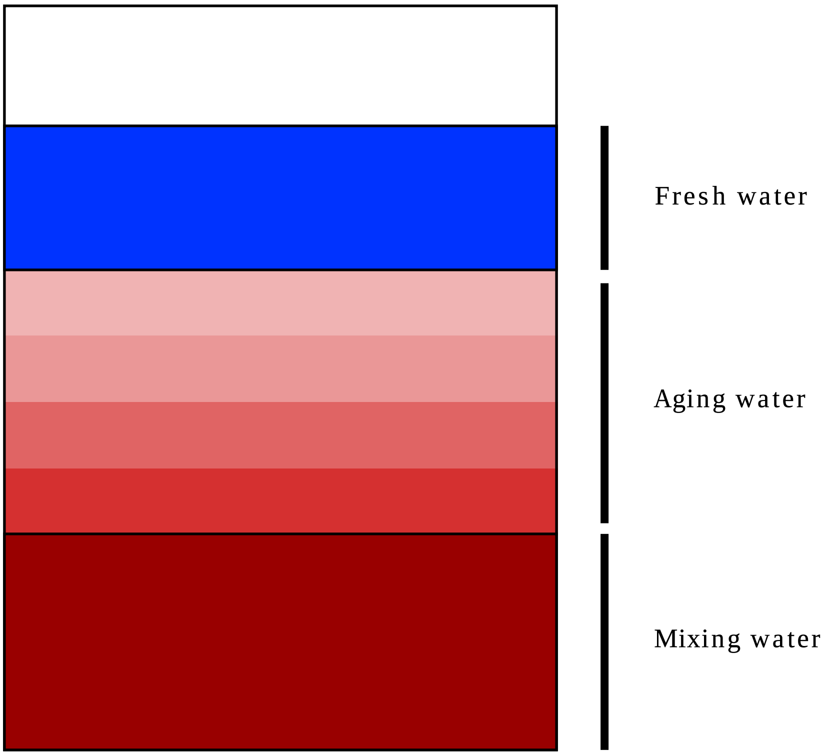
SCALING AND EQUATIONS FOR CONTAMINATION HEIGHT

The tank will consist of three layers.

- On the top will be fully aged fresh water forming a buffer
- Underneath there will be water that is ageing which will have been added in a number of discreet storm events. It's quantity, however will depend on the longer term rainfall over the period need to age the water

- At the bottom is the mixing front which forms the "floor" of the ageing water. Water below this is subject to mixing and cannot be considered as having started ageing

FIGURE 5.1 – LAYERS IN A WATER TANK



The height of the ageing water is determined by the prevailing rainfall which forms the basis of the upward velocity. Practically, the average rainfall can be used to find the average velocity.

$$\bar{v} = \frac{4 A_{roof} \bar{R} C_r}{\pi D^2} \tag{5.1}$$

Where

$\bar{v}$ is the average velocity

A_{roof} is the roof area

$\bar{R}$ is the average rainfall

C_r is the runoff coefficient

D is the tank diameter

The height will be determined by the time necessary to age the water. This will depend on the die off coefficient and initial and safe concentrations. Equation 2.3 provides the necessary time.

$$t = \frac{\ln\left(\frac{c_0}{c}\right)}{k}$$

Combining equations (2.3) and (5.1) finds the height

$$h = \frac{4A_{roof}\overline{R}\ln\left(\frac{c_0}{c}\right)}{\pi D^2 k} \tag{5.2}$$

The mixing height is an instantaneous phenomenon which is found by using equation (3.11)

$$h = k\,F_d\,d$$

As Froude number is dependent on velocity, diameter and buoyancy, an equation can be developed by combining equations (3.8), (3.9), (3.10) and (3.11) along with the rainfall intensity and the roof area. When this is simplified and insignificant terms are removed we obtain:

$$h = 182\,k\frac{IAC_r}{d^{\frac{3}{2}}\left(T_t^{\,2} - T_f^{\,2} + T_t - T_f\right)^{\frac{1}{2}}} \tag{5.3}$$

Where:

h is the height

k is the constant of stratification

I is the rainfall intensity

A is the roof area

C_r id the runoff coefficient

d is the inlet diameter

T_f is the feed temperature (in °C)

T_t is the tank temperature (in °C)

This equation is reliable ± 0.5% between 0 and 50°C and depends only on the highest expected rainfall intensity, tank and rain temperatures and known physical factors.

SOME EXAMPLES OF APPLICATION

Early indications from field work indicate that a 4 – 5° temperature difference is fairly reliable. and short term rainfall intensities of 4mm/minute are common. We can use this data to calculate the mixing height in some real tanks such as those in table 5.1[1]

TABLE 5.1 – SIZES OF WATER CATCHMENT SYSTEMS

	Roof Area	**Tank Capacity**	**Tank Diameter**
	m2	*m3*	*m*
Botswana "ALDEP" catchment	40	11	2.7
Thai household jar	100	2	1.56

[1] From Gould and Nissen-Petersen

TABLE 5.2 – MIXING HEIGHTS FOR TANKS

	Mixing Height (m)				
	110 mm Inlet	**25mm Inlet**	**110 mm Bent Inlet**	**110 mm vertical inlet**	**Radial Manifold 6 x 25mm**
"ALDEP" catchment	0.80	7.35	0.57	0.44	1.22
Thai household jar	1.99	18.37	1.42	1.09	3.06

When the heights are greater than the tank height, total mixing will take place, however with judicious choice of inlet, both types of tank will gain some benefit from stratification. Larger tanks such as those found on public buildings in Africa have very large roof areas and require large and complex inlets to achieve stratification. For example a typical school set up in Botswana[1] with a 1300m roof area and two water tanks requires a radial system of 6 150mm pipes to achieve stratification at 1.35m or a downward inlet of 300 mm to achieve a mixing height of 1.58m.

FURTHER WORK

WEATHER

The height of the output above the input is dependent on several local factors:

- Rainfall intensity
  - Determines discharge and velocity
- Rainfall temperature

[1] Gould and Nissen-Petersen p210

- Tank temperatures
  - Determine buoyancy

MICROBIOLOGY

The residence time is also reliant on a number of unknown local factors:

- The maximum concentration recommended by local health authorities
- The initial concentration
- The die off rate

At present, the latter two of these must be found by local sampling. Further work could yield guidelines according to roof type, tank size, rainfall intensity etc.

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