CHAPTER 124

USE OF MIXING TUBES ON MARINE OUTFALLS

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ABSTRACT

To optimise dispersion from marine outfalls multiport diffusers have been developed. The addition of mixing tubes to such outlets can create an ejector action and so cause pre-mixing before discharge to the receiving mass of water. The characteristics of such water jet-pumps in this submerged condition have been derived elsewhere, but are applied herein to the dilution of effluents. For a range of jet to mixing tube area ratios optimisation has been carried out on a computer, thus indicating the densimetric Froude numbers and depth ratios at which dilution exceeds that for the plain jet. Even for a stagnant ambient medium dilution in experiments exceeds that predicted, possibly because of macro-turbulence not accounted for in the theory available. Turbulons developed in a mixing tube are larger than any emerging from a plain smaller jet and may thus promote better mixing from its exit to the sea surface. Mixing tubes have obvious applications in shallow water and where an effluent is particularly obnoxious.

INTRODUCTION

With the increased concentration of industry and population on coasts and waterways, for the sake of cooling water and sea transport, greater demands are being made on the coastal waters for the disposal of liquid effluent. At the same time these beach areas are required for recreation of the populace, so that higher standards of purity are being demanded for river, estuarine and coastal waters. This situation has promoted the use of multiple ports in outfalls(1), so that warm water or effluent alike can be well mixed with the receiving liquid. Because such diffusion takes some time and distance to be effective the hydraulics of mixing tubes will be outlined.

Although the waters of coastal zones and estuaries are in continual motion, due to tidal currents, the diffusion analyses generally assume a stagnant ambient fluid. A design based upon this adverse condition is reasonable since at high- or low-water-slack the receiving liquid is stagnant for a period of 2 or 3 hours, in which time a sizable volume of effluent could accumulate.

An outfall may have ports which discharge horizontally or vertically or both. At the outlet the jet contains a certain kinetic energy in the form of momentum. Due to the normal density difference of the effluent and the medium a certain potential energy is exerted on the jet in the form of buoyant uplift. As the jet travels through the stagnant liquid it draws some of it in, so increasing the area through the jet and diluting its contents. The further from the port the greater is the proportion of buoyant force to vertical momentum, any horizontal momentum remaining steady, although the velocity associated with this approaches zero as the area of the jet increases.

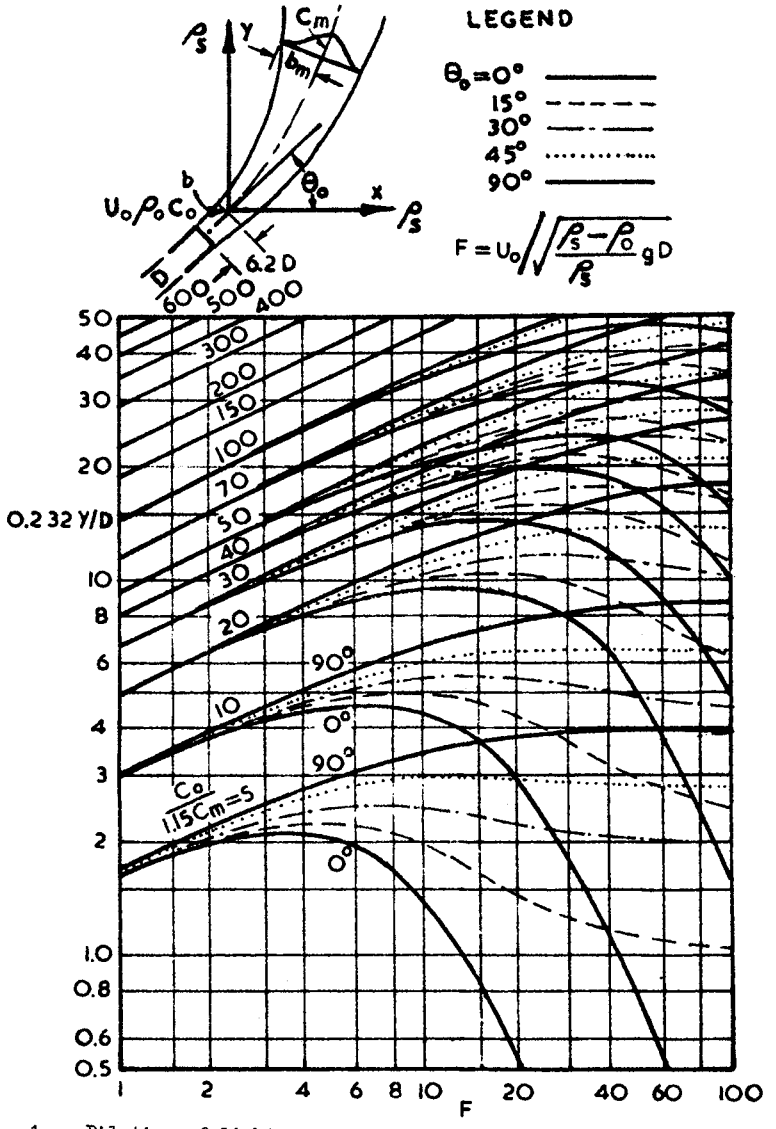
Many workers have supplied analyses and experimental data on this topic, but those who have provided comprehensive reports suitable for ready application are Abraham(2) plus Fan and Brooks(3). Both of these are mathematical treatments which include constants derived from experimental work of their own or of other workers. Abraham treats vertical and horizontal jets in ambient fluid of constant or variable density. Fan and Brooks have generalised the analysis to cover discharge at any angle and to vary the constants over the depth, rather than a step change at mid-depth. Both reports contain graphs for circular orifices or continuous slots, only the former will be discussed here.

CIRCULAR JET IN UNIFORM DENSITY MEDIUM

A jet of diameter D is depicted in Fig. 1 issuing with a velocity U_o at an angle θ_o to the horizontal into an ambient liquid of uniform density ρ_s. At the nozzle the density and concentration of the effluent is ρ_o and C_o respectively. At the end of flow establishment (6.2 D from the nozzle) the centre-line concentration C is given by

$$C_o / C = 1.15 \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

whilst at a height y above this point the centre-line concentration C_y



1. Dilution of lighter circular jet in ambient fluid of uniform density.

is given by the curves in Figure 1. These vary with y/D, θ_o and densimetric Froude number F defined by

$$F = U_o \Big/ \sqrt{\frac{\rho_s - \rho_o}{\rho_s} gD} \qquad \text{.....(2)}$$

The graphs of Fan and Brooks[3], from which Figure 1 has been prepared, were presented with an abscissa of dimensionless momentum flux which at the nozzle (M_o) is related to F by

$$F = \frac{\lambda}{2^{\frac{1}{4}} \alpha^{\frac{1}{2}}} M_o^{\frac{5}{4}} \qquad \text{.....(3)}$$

where α is the coefficient of entrainment, assumed from Rouse et al[4] to be 0.082. This is noted since Fan and Brooks[3] state that if new values of α and λ emerge from future tests then a new multiplying factor can be derived for use with the same graphs. For the sake of simplicity the values of $\alpha = 0.082$ and $\lambda = 1.16$ have been employed, resulting in the abscissa of F, also used by Fan and Brooks as an alternative scale. For $F = \infty$ a value of $\alpha = 0.057$ is suggested.

To obtain the vertical height from the nozzle to the trajectory point where the concentration is C_m the component of the distance for flow establishment must be added, that is

$$y_m/D = y/D + 6.2 \sin \theta_o \qquad \text{.....(4)}$$

The dilution curves ($C_o/C_m = S_m$) in Figure 1 for $\theta_o = 90^\circ$ rise consistently with F, whereas those for $\theta_o \leq 45^\circ$ reach a peak y/D and then fall, thus giving two locations at which the same dilution or concentration occurs. At small F the jet rises almost vertically from the nozzle and reaches a given dilution at a specific height (e.g. F = 1, $C_o/1.15\ C_m = 10$ at 2.32 y/D = 3). As the jet discharge is increased, and so F, so is the height of y/D for the same dilution until F is large enough for the trajectory length to permit enough mixing for the dilution to become similar at the same height (e.g. F = 20 gives the same conditions as before).

Sharp[5] has described the mechanism for small F as that of "starving" the jet. In this situation the buoyant force predominates and stretches the system, so causing gusts which expedite mixing. The condition for minimal dilution is therefore the Froude number at which the jet reaches the surface on the point of being starved. Operation at these maxima on the curves of Figure 1 should be avoided. Conditions should be chosen either side of these F values, preferably smaller ones as these demand less power. It is seen that for any given Froude number the greatest dilution is achieved by the horizontal jet, but other angles must be considered so as to prevent interaction of jets.

The co-ordinates of the trajectory with respect to the origin of established flow are given in Table I in terms of x/D and y/D. The width ratio b_m/b (see Figure 1), where b is the half jet width at the

end of flow establishment ($\approx D/\sqrt{2}$), and b_m is the half width where the central concentration is C_m is also listed. The concentration at any radius r from the centre-line is given by the Gaussion distribution

$$C_r/C_m = e^{-r^2/(\lambda b_m)^2} = e^{-0.74(r/b_m)^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots (5)$$

MIXING TUBES

Several devices were used by Hansen and Schroeder[6] to break the jet into parts, in order to effect greater dilution. They concluded: "Dilution of a jet can be increased by use of a special nozzle design, but the possibilities in this direction are reduced considerably when complicated devices are avoided and little or no additional loss of energy is allowed." In multiport diffusers deflection of one jet into the path of another serves little purpose. Also, such appendages must be added to the outfall when it is in place, which can be a costly operation.

However, under certain conditions of insufficient depth, or improving the dilution of an existing outfall, the addition of a mixing tube may be found economical. This consists of a cylinder, larger in diameter than the port or 'nozzle' which is placed in line with the jet, with its flared entrance in close proximity to the outfall (see Figure 2). The jet then draws seawater into the tube and mixes with it before discharging at a lower velocity at the outlet. Design graphs have been presented[7] for this water-jet-pump action and its application to sewage outfalls presented by Silvester[8].

The initial dilution S_i effected in the mixing tube is in proportion to the water drawn in (Q_s) and the discharge of the driving jet (Q_n), so that

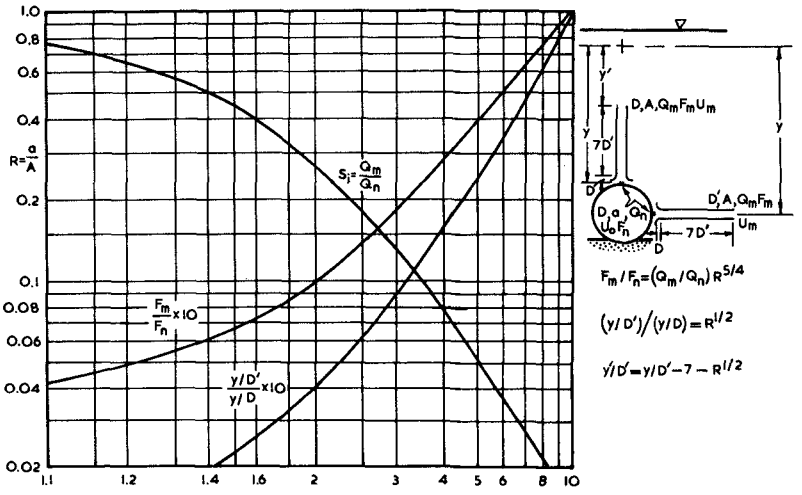
$$S_i = \frac{Q_n + Q_s}{Q_n} = \frac{Q_m}{Q_n} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

The ratio Q_m/Q_n depends upon the ratio (R) of the area of the nozzle ($a = \pi D^2/4$) to the area of the mixing tube ($A = \pi D'^2/4$). For the specific condition of a plain cylindrical mixing tube with flared entrance a characteristic curve as in Figure 2 can be derived[7]. This is based upon the criterion that the mixing tube length is 7 times its diameter (i.e. = 7D'), which has been found to be that for maximum mixing with least friction loss [9].

The discharge velocity from the mixing tube is much lower than that from the nozzle and, in spite of the increased diameter, the densimetric Froude number is decreased, such that

$$F_m/F_n = (Q_m/Q_n)R^{\frac{5}{4}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

where $$F_m = U_m / \sqrt{\frac{\rho_s - \rho}{\rho_s} gD'} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$



2. Initial dilution, change of densimetric Froude number, and change of dimensionless height by using a mixing tube on horizontal or vertical circular jets.

where U_m is the discharge velocity from the mixing tube ($= 4Q_m/\pi D'^2$)

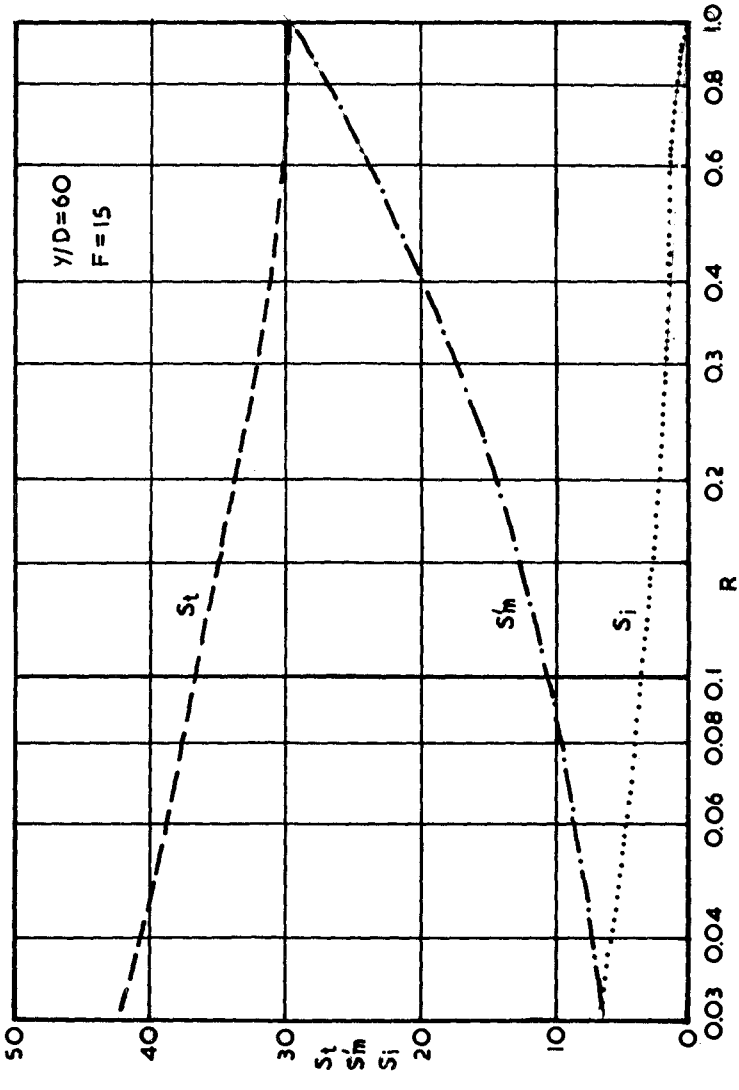
ρ is the density of the diluted effluent leaving the mixing tube.

Equation (7) has been plotted against R in Figure 2.

The mixing tube now serves as the nozzle for the further dilution (S'_m) of the jet as it rises to the surface. The height ratio for the design chart of Figure 1 must now be based on the mixing tube diameter D', which can readily be determined from Figure 2, for any chosen R value. When the mixing tube is vertical the remaining height for dilution (y'/D') is the height from the nozzle (y/D') less the height from the end of the mixing tube to the nozzle ($7D' + D = 7D' + D'R^{\frac{1}{2}}$). The nozzle exit is placed one diameter (D) from the entry point of the cylindrical mixing tube for optimum efficiency(9).

A typical variation of initial dilution (S_i), dilution beyond the mixing tube (S'_m), and total dilution ($S_t = S_i \times S'_m$) is given in Figure 3. This is for a specific area ratio R and specific depth ratio y/D. It is seen that as R increases (i.e. mixing tube smaller) initial mixing decreases whilst dilution from the exit to the surface increases. The product of these two dilutions decreases as R increases, approaching ultimately the dilution from the original nozzle as R reaches 1.0. Thus for all values of $R < 1.0$ the total dilution is greater than that from the single nozzle, for the case of F = 15 and y/D = 60.

It should be noted that as greater dilution is effected so will the volume or depth of ambient liquid taken up by effluent. This necessarily



3. Variation of initial dilution (S_i), buoyant dilution (S'_m) and total dilution ($S_t = S_i \times S'_m$) with area ratio R for a specific F and y/D.

decreases the active height (y) available for diffusion. However, currents and waves influence this thickness of polluted water in ways yet to be determined, so that refinements in assessment of this decreased depth ratio is not warranted at present except qualitatively.

Similar curves to Figure 3 can be derived for other area and depth ratios, from which an improvement factor can be derived ($= S_t/S_m$). A multitude of area ratios (R) could be selected for such a comparison, making the choice of a mixing tube tedious unless other design criteria limit this choice. In order to optimise the total dilution (S_t) for a horizontal jet a computer study was carried out[10], the result of which is presented in Figure 4.

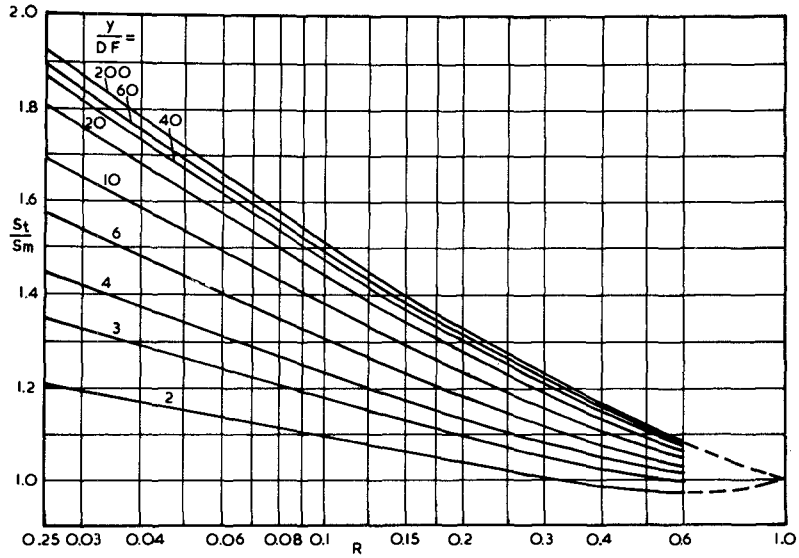
It may seem strange that placement of an apparent obstruction in the flow path of a jet will achieve greater dilution with the surrounding medium. However, it should be realised that a plain jet effects mixing by drawing in ambient fluid through shear stresses at its boundaries. This process is maximum near the nozzle where velocities are greatest. When this stress is exerted within the confines of a mixing tube the stagnant fluid is accelerated and mixed completely within a short distance of the nozzle. The ejector tends to pump ambient fluid into the jet rather than leave it to the peripheral shear stress to accelerate some boundary layer thickness to the speed of the plume.

Equation (2) may be re-written as

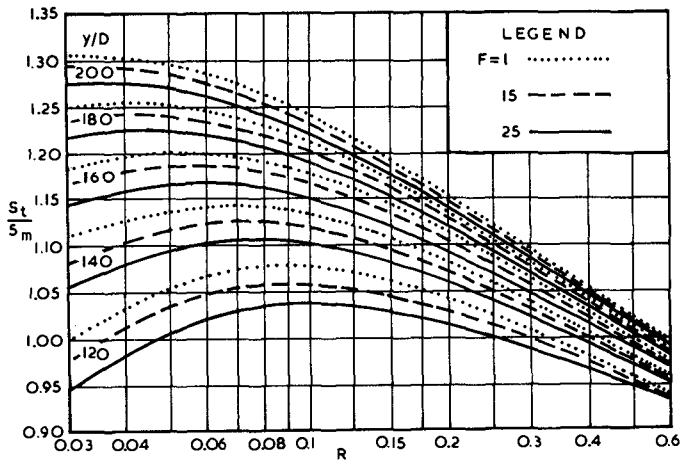
$$F = Q \Big/ \frac{\pi}{4} D^2 \sqrt{\frac{\rho_s - \rho_o}{\rho_s} gD} \qquad \text{.....(12)}$$

Thus for a specified dilution (C_o/C_s) in Figure 1 and an F value on the left of the maximum of the horizontal jet curve, any reduction of F to effect greater dilution (for a given discharge Q) implies a larger D and hence smaller y/D. This traverse to the left and downwards would probably mean arriving back on the same dilution curve, or below it, so that optimum design can be reached. When a mixing tube is used a similar change of D and F occurs, but an initial dilution is also produced. As seen above the product of S_i and S'_m can be greater than dilution (S_m) from the plain jet, when y/D, F and R are within certain limits. It is seen that greatest gain derives for large y/d, small F and small R. These are rather conflicting demands since smaller F and smaller R may result in a condition where the jet from the nozzle is insufficient to drive the "jet-pump". The smaller R also implies a relatively large D' and hence length 7D'. But Figure 4 could serve as a starting point for the design of an outfall, which should then be tested in the laboratory.

A similar optimization curve is presented in Figure 5 for a vertical jet, in which y/D has been separated from F, because no benefit accrues until y/D = 120. This is because the height for dilution S'_m is reduced as the mixing tube length increases vertically. The major benefit from this type of installation is that F is reduced to the stage where "Starvation" of the plume occurs and hence mixing promoted. If insufficient height is left for this to take place no increase in dilution over that from the plain jet results.



4. Design chart for selecting size of mixing tube for a horizontal jet.



5. Design chart for selecting size of mixing tube for a vertical jet.

EXPERIMENTAL VERIFICATION

Tests on plain horizontal jets have been reported by Cederwall[11]. Using a semi-empirical relationship derived by Bousanquet et al[12], he has reported them as explicit analytical solutions

$$S_m = 0.54\ F(y/DF)^{7/16} \qquad \text{.....(9)}$$

for $y/D < 0.89F$, and

$$S_m = 0.54\ F(0.38\ y/DF + 0.68)^{5/3} \qquad \text{.....(10)}$$

for $y/D > 0.89F$

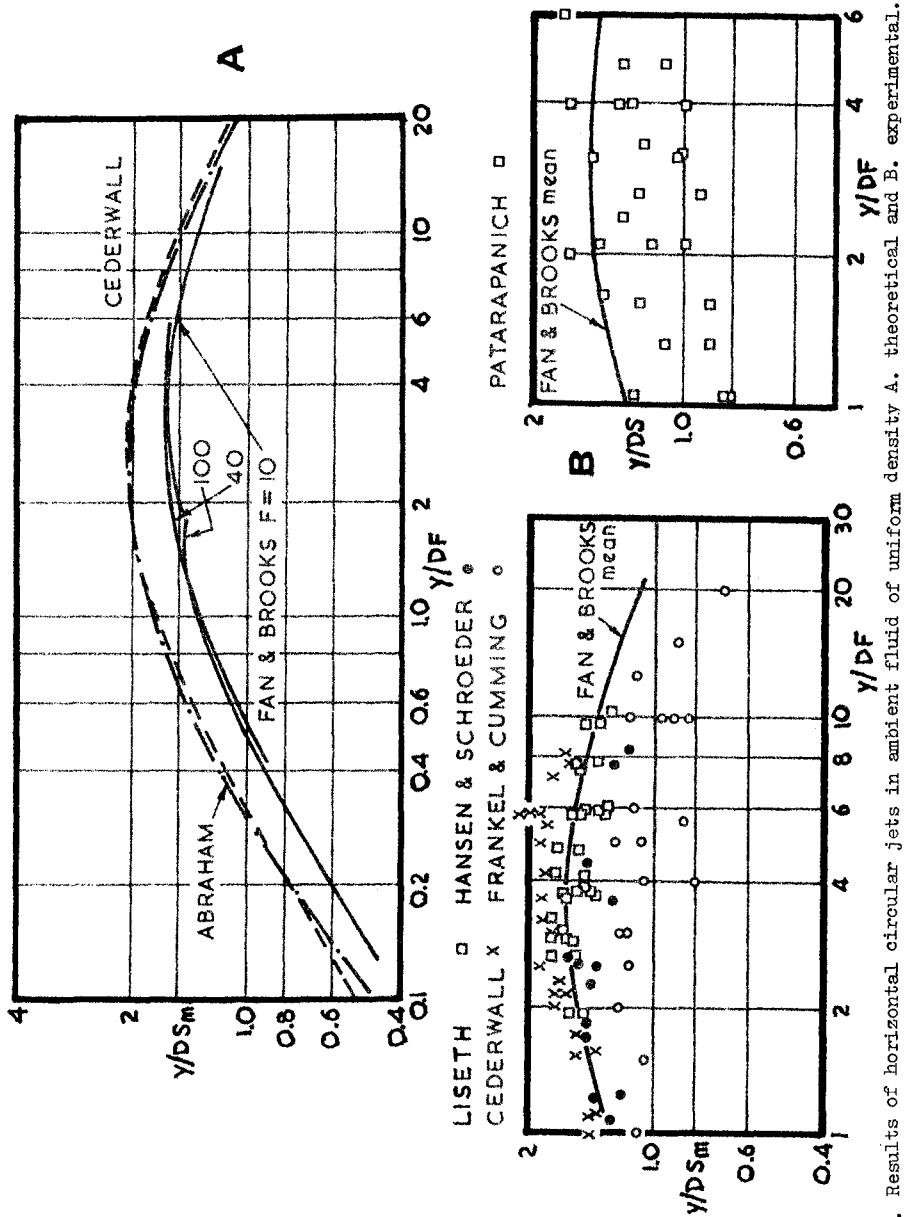
where $$S_m = C_o/C_m \qquad \text{.....(11)}$$

Equations (9) and (10) have been graphed in Figure 6A, together with a similar presentation of $y/D\ S_m$ verses y/DF for the solutions of Abraham[2] and Fan and Brooks[3]. The latter includes the dilution factor for flow establishment, which correction could be applied to the curves of Cederwall and Abraham, since their solutions apply to established flow only.

The parameters as outlined above are the best for comparing the experimental results from several workers[6][10][11][13][14]. This has been done in Figure 6B and indicates that better mixing is obtained even in the laboratory than that predicted by theory. In this respect the theoretical solution is conservative. With the aid of further macro-turbulence available in the prototype (through scale effects alone) it would be expected that greater dilution could ensue. Hansen and Schroeder[6] accepted the deviation from theory as a "factor of safety".

In respect to laboratory experiments it has been noted[10][13] that time is required in experiments for the dilutions to reach a steady state. For jets of $\frac{1}{8}$ to $\frac{1}{4}$ inch diameter about 10 to 20 minutes is required at $y/D \geq 50$. Closer to the outlet equilibrium is reached much sooner.

Laboratory tests for jets with mixing tubes[10] have shown that total dilution as indicated in Figures 4 and 5 is possible. In fact, dilution in excess of the theoretical prediction was obtained, as has been experienced with plain jets. It could be anticipated that this improvement, which probably emanates from the macro-turbulence not accounted for in the theory, might be greater due to the larger turbulons generated in the mixing tube. The tests referred to utilised nozzles of $\frac{1}{8}$ to $\frac{1}{5}$ inch diameter and mixing tubes of $\frac{1}{4}$ to $\frac{1}{2}$ inch diameter[10]. Further experiments are warranted, since economical improvements on existing outfalls may be possible, especially where discharge is from a plain end or a few large ports.



6. Results of horizontal circular jets in ambient fluid of uniform density A. theoretical and B. experimental.

APPLICATION OF MIXING TUBE CONCEPT

The addition of mixing tubes to the ports of an outfall does not impose any extra pressure head load on the system. The discharge from each outlet could, in fact, be increased due to the slight suction created at the entrance of the mixing tube.

One installation in a river has been reported[15], although the mixing tube in this case was not of correct proportions for optimum mixing[8]. The concept is particularly applicable when an effluent as supplied for discharge is very obnoxious to marine fauna and flora, making swift initial mixing desirable. It could also serve in density-stratified situations, to reduce the mixture density to a value where the effluent could be retained below the surface.

Pearson[16] made a comprehensive survey of sewage outfalls and provided details of 148 installations throughout the world. This report contains some 250 references on this topic. These outfalls were investigated by the authors to see what improvement in dilution could be effected by the addition of mixing tubes. Only 42 could be analysed due to lack of information or inappropriate nozzle shape (slots etc). Of these 26 could be so improved by percentages ranging from 25 to 245%. The largest percentage gains applied to discharges direct from the end of an outfall into shallow water, for which an R ratio of 0.1 was used, implying a mixing tube diameter of about three times the port outlet or a length of around 20 times this dimension. The addition of mixing tubes to a newly constructed outfall presents the same problem as modifying an outfall that has been in commission for some years. A little thought would soon devise a plastic or fibre glass appendage which could be readily clipped on to each port with the minimum of handling by divers. By such pre-mixing, existing outfalls could be made to carry larger loads, or new outfalls could be of shorter length.

CONCLUSIONS

1. Greater demands on coastal waters for recreation has raised their pollution standards and caused marine outfalls to be taken further seawards and multiple ports diffusers to be utilised.

2. A mixing tube with a flared entrance placed co-axially with a port or nozzle of an outfall will promote initial mixing and produce greater overall dilution in certain circumstances.

3. Graphs have been prepared which indicate the densimetric Froude numbers and depth ratios required for a mixing tube, of specific area ratio to the initial jet, to optimise dilution.

4. Experiments with small scale mixing tubes have shown that dilution is greater than that predicted by semi-empirical relationships, in a similar way to those for plain jets.

5. Larger scale tests may confirm the supposition that discharge from a mixing tube can produce better dispersion because of the larger

sized turbulons they could produce.

6. Pre-mixing might be useful for an obnoxious effluent, whether of chemical or temperature nature, so that its concentration is reduced sufficiently for it not to affect the marine biota.

7. Pre-mixing could produce sufficient immediate dilution to retain an effluent within the body of a fluid medium with a density gradient.

8. Application of mixing tubes to many existing outfalls could increase their capacity for diluting effluents, particularly in the case of single, or a few, large ports in shallow conditions.

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TABLE I

Coordinates of trajectory and jet width for circular jet in uniform density medium.

Values of 0.232x/D (upper) and b_m/b (lower)

θ_o	0.232 y/d	F = 1	2	4	8	16	32	64	128
0	5	0.5	1.5	2.5	4.5	7.5	12.5	20.5	33.5
		3.5	4.0	4.5	6.0	8.5	13.0	20.5	33.0
	10	0.7	1.6	3.0	5.5	9.7	16.2	26.5	42.0
		6.5	7.0	7.5	8.5	11.0	17.0	26.5	41.5
	20	1.0	2.0	3.5	6.5	11.9	20.0	33.5	53.7
		12.0	12.5	13.0	14.5	17.0	22.5	33.5	52.0
	30	1.0	2.0	3.5	7.5	13.0	22.5	37.6	61.2
		19.0	19.5	20.0	21.0	23.0	29.0	39.0	60.0
	40	1.0	2.0	3.5	7.6	14.0	24.5	41.0	67.0
		25.0	25.5	26.0	27.0	29.5	34.0	45.0	64.0
	50	1.0	2.0	3.5	7.9	14.5	26.4	44.0	72.0
		30.5	31.0	31.5	33.0	35.0	40.5	51.0	68.0
15	5	0.5	1.4	2.4	4.0	6.6	10.0	12.6	16.5
		3.5	4.0	4.5	5.5	8.0	11.0	14.0	18.0
	10	1.0	1.5	3.0	5.0	8.5	13.4	19.2	27.0
		6.5	7.0	7.5	8.5	11.0	15.0	20.0	29.0
	20	1.0	1.8	3.5	6.0	10.5	17.5	27.2	40.0
		12.0	13.0	13.5	14.5	17.0	21.0	29.5	41.5
	30	1.0	2.0	3.6	6.9	11.8	20.0	32.0	48.5
		18.0	18.5	19.0	20.5	22.0	27.0	36.0	50.0
	40	1.0	2.0	3.8	7.1	13.7	21.9	35.6	55.2
		25.0	25.5	26.0	27.0	29.0	33.0	41.5	58.0
	50	1.0	2.0	3.9	7.4	13.5	23.2	37.5	60.5
		30.5	31.0	31.5	33.0	34.0	38.0	46.0	63.0

(Continued)

TABLE I (continued)

ϕ_o	0.232 y/d	F = 1	2	4	8	16	32	64	128
30	5	0.5	1.0	1.9	3.1	4.5	6.2	7.5	8.5
		3.5	4.0	4.5	5.5	6.5	8.5	9.5	10.5
	10	0.6	1.1	2.3	4.1	6.6	10.0	13.4	16.0
		6.5	7.0	7.5	8.5	10.0	13.0	17.0	20.0
	20	0.6	1.2	2.7	5.3	8.9	14.0	20.8	27.2
		12.5	13.0	13.5	14.5	16.0	20.0	26.0	32.0
	30	0.7	1.3	3.0	5.7	10.1	16.5	25.5	35.7
		18.0	18.5	19.0	20.5	22.0	26.0	32.0	42.0
	40	0.8	1.4	3.1	6.0	11.0	18.4	29.0	42.2
		25.0	25.5	26.0	27.0	28.5	32.0	39.0	50.5
	50	0.9	1.5	3.2	6.4	11.5	19.5	31.5	47.0
		30.5	31.0	31.5	32.0	34.0	38.0	44.0	55.0
45	5	0.3	0.9	1.5	2.4	3.2	4.2	4.8	5.2
		3.5	4.0	4.5	5.0	6.0	7.0	8.0	8.5
	10	0.4	1.0	1.9	3.2	5.1	7.0	8.8	9.6
		6.5	7.0	7.5	8.0	9.5	12.0	14.0	15.0
	20	0.5	1.1	2.3	4.0	6.9	10.6	14.7	17.5
		12.5	13.0	13.5	14.0	15.5	18.0	22.0	26.0
	30	0.6	1.2	2.4	4.7	7.9	12.7	18.6	24.5
		18.0	18.5	19.0	20.0	21.5	25.0	30.0	35.0
	40	0.7	1.3	2.5	5.0	8.5	14.2	21.5	29.7
		25.0	25.5	26.0	26.5	27.5	30.5	36.0	43.0
	50	0.7	1.4	2.6	5.1	9.0	15.2	24.0	34.1
		30.5	31.0	31.5	32.0	33.0	36.0	42.0	51.0