Twelfth Australasian Fluid Mechanics Conference
The University of Sydney, Australia 1995

BUOYANT DISCHARGE FROM A LINE DIFFUSER INTO A CURRENT WITH VERTICAL STRATIFICATION

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ABSTRACT

The paper describes a series of laboratory experiments which examined the discharge of buoyant fluid from a line of diffusers into a stratified cross-flow. It is shown that the structure of the plume can be characterised by two non-dimensional parameters, one based on the cross-flow velocity and the buoyancy flux and the other on the ambient stratification and the momentum and buoyancy fluxes emerging from the diffusers.

INTRODUCTION

Increasing public concern for the quality of coastal waters has resulted in the construction of the deepwater ocean outfalls for the disposal of waste water from a number of major coastal cities. Los Angeles, Boston, Hong Kong and of course Sydney are cities which are using, or plan to use this disposal option. The depth of the diffusers attached to these outfalls has meant that for much of the year the effluent is discharged below the thermocline in which case the plume may be trapped and may never reach the surface. While this may seem appealing in that the effluent field may not be assessable to wind driven surface currents which might otherwise advect the effluent on-shore, it also means that the effluent is less diluted than would be the case if it were able to accend through the full water column. Additionally coastal waters are seldom quiescent. Offshore from Sydney at the 80 m contour, current speeds exceed 10 cm/s for over 75% of the time and 20 cm/s for 45% of the time. Therefore currents play an important role in the behaviour of effluent plumes.

The effluent plumes produced by deepwater outfalls are complex. Individual diffusers may have up to 8 nozzles discharging radially into the surrounding environment and a typical outfall may have from 20 to 50 separate diffuser heads. Figure 1 gives a schematic view of the diffuser section of a typical deepwater outfall. The complexity of the resulting flow field makes numerical modelling of the flow field a challenging exercise and until there is a clearer understanding of the physical process involved hydraulic model studies remain the more reliable means of assessing the plume structure and dilution produced by these outfalls. Flows from multiport diffusers have been classified by Jirka and Akar (1993). Roberts et al. (1989) have experimented with the nearfield merging of plumes from multiport diffusers. However little is known about the plume field at larger distances from the diffusers and more importantly the net dilution of the effluent released from the outfall in the presence of currents and stratification.

This paper describes the results of a series of experiments in which a negatively buoyant discharge of brine was released from a towed diffuser into a tank containing a stationary but vertically stratified body of water. The aim of the study was to identify the key parameters which determine the behaviour of buoyant plumes in flowing, stratified environments typical of deepwater outfalls and to examine how plume spread and dilution is affected by those parameters.

NATURE OF THE FLOW

The flow issuing from the diffusers of deepwater outfalls is initially momentum dominated however as this diffuses due to the entrainment of ambient fluid, buoyancy forces become increasingly important. In addition forces imposed by any cross-flow also affect the behaviour of the plume. The initial flow from the diffusers is highly three dimensional due to the radial placement of the diffuser nozzles around the diffuser. However both buoyancy and the cross flow combined with the growth of the individual buoyant jets causes them to merge. In the absence of any cross flow this merging occurs vertically above the diffuser at a height which depends on the radial spacing of the diffuser nozzles and the momentum and buoyancy of the flow. The cross-flow will cause the plume to deflect laterally and in the absence of vertical stratification in the ambient fluid, will ultimately dominate both buoyancy and the plume momentum so that the plume becomes close to horizontal.

Density stratification in the ambient fluid causes the plume to loose buoyancy with increasing elevation. Due to the entrainment of ambient fluid into the plumes at lower levels the density of the plume will ultimately reach that of the ambient fluid, provided the water is of sufficient depth. The plume will then spread laterally as a submerged field.

SCALING RELATIONSHIPS

The buoyant jets emerging from the diffusers are characterised by their kinematic fluxes of momentum (m) and buoyancy (B) defined by:

$$M = u_{o2}A_o \qquad (1)$$

and

$$B = g'_o u_o A_o \qquad (2)$$

where

u_o = the velocity of the jet the nozzle exit
A_o = the cross-sectional area of the nozzle exit
g'_o = the effective gravitational acceleration of the jet at the nozzle exit

The source geometry is characterised the number of nozzles attached to each diffuser (N) and by the spacing of the diffusers (s). The ambient fluid is characterised by its velocity (U) and the vertical gradient of the effective gravitational acceleration ($\varepsilon = dg'/dz$) in which z is the vertical co-ordinate.

At distances from the diffusers which are large compared with the spacing between them, the buoyant jets from the different diffusers merge and the flow becomes two dimensional over the central region of the plume. The symmetry of the jets discharging from a single diffuser causes the net momentum of the emerging flow to be zero. However the initial flow from each nozzle is momentum dominated and this therefore plays a role in determining the final structure of the flow. A two dimensional momentum flux (m) is therefore defined as:

$$m = NM / s \qquad (3)$$

and the two dimensional buoyancy flux (b) by:

$$b = NB/s \qquad (4)$$

where N is the number of nozzles attached to each diffuser.

The other factors affecting the motion of the plume are the velocity of the cross flow (U) and the ambient stratification characterised by (ε). These four variables yield two non-dimensional parameters which characterise the behaviour of a two dimensional buoyant jet and are given by:

$$F = U / b^{1/3} \qquad (5)$$

which is a cross flow parameter first identified by Roberts (1979) and a plume rise parameter (R) given by:

$$R = b / m\varepsilon^{1/2} \qquad (6)$$

The influence of the cross flow is seen through the cross flow Froude Number (F) and the role of buoyancy and stratification through the rise parameter (R). The terminal height of rise is characterised by the length scale $L_z = b^{1/3} / e^{1/2}$.

EXPERIMENTS

The experiments were performed in a tank 5 m square and 1 m deep. The scale of the model was set at 1:123 based on the depth of the test tank. For experimental convenience the flow was inverted so that a brine solution was discharged from four diffusers into a tank which contained fresh water for experiments without ambient stratification or was salt stratified for experiments with ambient stratification. The vertical stratification was scaled to be representative of the oceanic thermocline off-shore from Sydney. Four diffuser heads were modelled and the side wall was employed as a line is symmetry to increase the effective length of the diffuser array.

The ambient cross flow was simulated by towing the diffusers across the tank. The dilution of the discharge was monitored by means of an array of conductivity probes. Six probes were employed along a vertical line aligned with the axis of the 2nd diffuser head and a second similar array was aligned with the centreline between the 1st and 2nd diffusers from the wall. Preliminary experiments demonstrated that the plume structure was not affected by end or wall effects along the monitoring planes. In experiments where there was no cross flow the diffusers were held stationary and the probe arrays were towed across the tank.

Because of the finite length of the tank steady state conditions relative to the diffusers could only be achieved over a limited distance from the diffusers. Care was also taken to avoid starting transients. Because of these constraints it was not possible to average out the larger coherent structures in the flow and these remain evident in the dilution profiles. The mean structure of the flow could not be resolved with precision from a single experiment however the basic characteristics are evident.

RESULTS

Influence of Cross-flow

Figures 2a, 2b and 2c show plume structures in terms of dilution contours based on the density of ambient fluid at the same level. These figures correspond to cross-flow Froude numbers of 0 (stagnant conditions), 0.35 (10 cm/s prototype) and 0.72 (20 cm/s prototype). All lengths have been normalised with respect to L_z. The boundary of the shaded region corresponds to a dilution of 500 or alternatively the density along that contour differs from the ambient density by 1/500. Fluid within the shaded region is therefore diluted with ambient fluid to a ratio of less than 1/500.

In the absence of cross-flow (Figure 2a) the effluent rose to a maximum level of about $3L_z$ and then spread as a horizontal intrusion. Within a distance of approximately $4L_z$ from the diffuser, the plume was highly 3-dimensional however beyond this distance the structure was 2-dimensional and dilution contours taken along a diffuser centreline were similar to those taken between two diffusers. Minimum dilution in the region of horizontal outflow was found to be $1.6L_z$ above the level of the diffusers.

In the presence of a weak cross flow Figure 2b shows that the intrusion was blocked on the upstream side of the diffuser. The boils visible above the diffuser when there was no cross-flow are no longer evident. The plume formed an intrusive layer on the downstream side of the diffuser with the level of minimum dilution about $1.7L_z$ above the diffusers.

Figure 2c shows the plume when the cross-flow Froude number was increased to 0.72. The vertical extent of the plume was significantly reduced and the plume remained attached to the bottom. The level of minimum dilution was reduced to about $0.7L_z$ above the diffusers. The steep vertical density gradients observed along the upper boundary of the plume at lower values of F were no longer evident.

Influence of Ambient Stratification

The effects of ambient stratification can be seen through the plume rise parameter (R) which expresses the ratio of the terminal height of rise of a 2-dimensional simple plume to the momentum-buoyancy length of buoyant jets from a single diffuser. Figures 3a, 2b and 3b show the structure of the plume for increasing values of R when F is held constant and equal to about 0.35.

Low values for R correspond to flows from the diffuser with high initial momentum into an ambient fluid with strong stratification. The strong mixing induced by the jets close to the diffuser produces a plume in which minimum dilutions are found close to the bottom. Figure 3a shows such a plume in which $R = 2.0$ and minimum dilutions at found at a height of $0.7L_z$. Figure 2b shows the plume structure when $R = 3.5$. It will be noted that plume dilution has increased and the level of minimum dilution has risen to about $1.6L_z$. A further increase in R to 11 in Figure 3b, corresponding to a plume rising in a relatively weak density gradient, shows a more confined outflow and significantly increased dilution.

Plume Dilution

Figure 4 shows the minimum dilution of the plume averaged between $5L_z$ and $10L_z$ downstream from the plume. It is clear that minimum dilution increases with increasing R. The reason for this is evident from Figures 3a and 3b that increasing R results in a relatively longer region of buoyancy domination so that the plume is more dilute when it reaches its equilibrium level. Somewhat surprisingly the cross-flow Froude number has minimal influence of plume dilution at its terminal height. Three ranges of F are indicated for the experiments shown in Figure 4 and there is no systematic trend with cross-flow Froude number.

CONCLUSIONS

A systematic study of the behaviour of buoyant jets discharging from a line of diffusers has shown that their general structure can be described in terms two dimensionless parameters. One is a Froude number based on the velocity of the ambient cross-flow and the 2-dimensional buoyancy flux from the diffusers. The other is a plume rise parameter based on the ratio of the terminal height of rise of a 2-dimensional plume in a density stratified environment (L_z) and the momentum-buoyancy length of the diffuser discharge.

Increasing the cross-flow Froude number caused the level of minimum dilution within the outflow to be depressed towards the bed however there was no significant change to the actual dilution. Increasing the value of the rise parameter was found to increase the dilution of the outflow and also caused a reduction in the relative thickness of the intrusion. The total vertical penetration of the plumes was found to be approximately 3Lz and was independent of either R or F.

REFERENCES

Jirka, G.H. and P.J. Akar (1991) *Hydrodynamic Classification of Submerged Multiport Diffuser Discharges*, J. Hydraulic Engineering HY9, ASCE 117, No.9, 1113-1128.

Roberts, P.J.W., W.H. Snyder and D.J. Baumgartner (1989) *Ocean Outfalls I: Submerged Wastefield Formation*, J. Hydraulic Engineering, ASCE 115, No.1. 1-25.

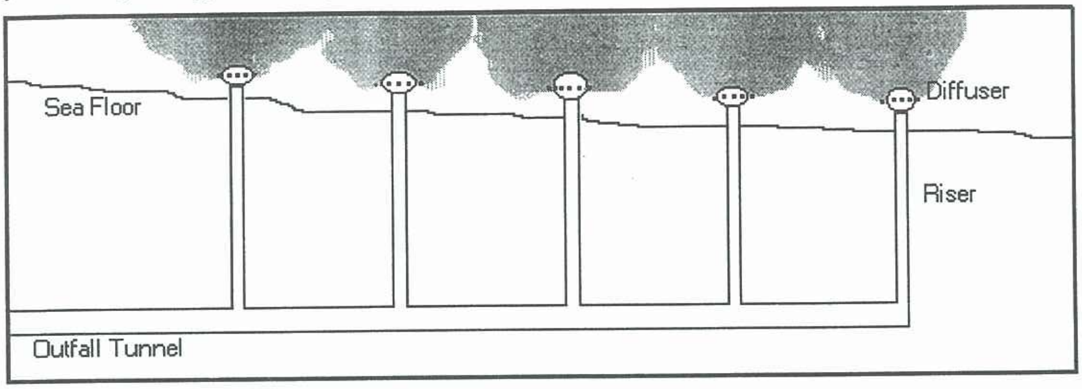

Figure 1. Schematic View of a Deepwater Outfall

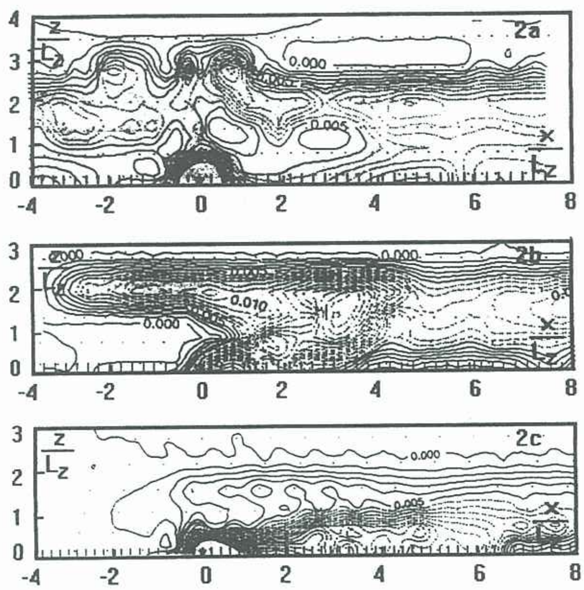

Figure 2. Dilution contours for buoyant discharges with increasing cross-flow and constant stratification.
(2a): F = 0 & R=3.5, (2b): F=0.35 & R=3.5,
(2c): F=0.72 & R=0.41

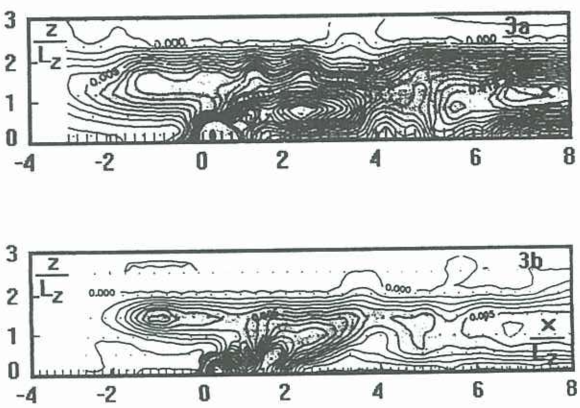

Figure 3. Dilution contours for buoyant discharges with weakening stratification and constant crossflow.
(3a): F=0.30 & R=2.0, (3b): F=0.43 & R=11.3

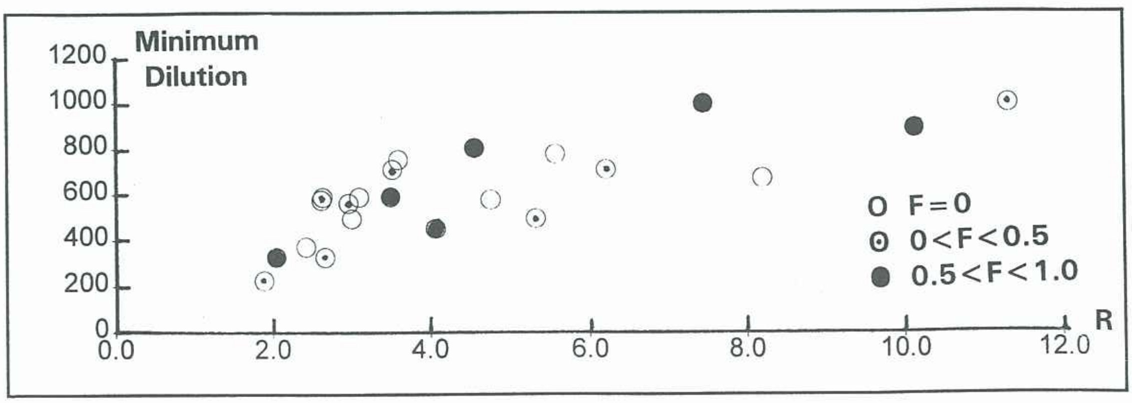

Figure 4. Minimum Dilution as a Function of the Rise Parameter