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Withdrawal Behaviour Through a Single Round Hole In a Cross Flow

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ABSTRACT

Experimental measurements of drawdown, the critical withdrawal rate and the mean temperature profiles in the near field region of a withdrawal system in a two-layered thermally stratified cross-flow are presented. Flow visualisation is also reported which provides detail information on the structure and dynamics of the warm/cold water interfaces for different intake flow rates. The present experimental data on the critical intake flow rate are compared with the measurements of Goldring (1984). The drawdown results indicate an inverse dependency on density gradient unlike the case without cross-flow.

NOMENCLATURE

D	hydraulic diameter, 4* area / wetted perimeter
DD	drawdown fraction, $(T_o - T_2)/(T_1 - T_2)$
DD_m	peak drawdown fraction
Fr_o	Inlet Froude number, $U/(g'H)^{1/2}$
g	gravitational acceleration
g'	reduced gravitational acceleration, $g\,\Delta\rho/\rho_1$
h_1	depth of warm water layer
h_2	depth of cold water layer
H	$h_1 + h_2$
Q_o	intake flow rate
Q_o^c	critical intake flow rate
U	cross flow velocity
Re	Reynolds number, UD/ν
T	mean temperature of the field
T_1	temperature of warm water
T_2	temperature of cold water
T_o	mean temperature of the intake flow

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X,Y,Z	cartesian coordinates measured from the axis of the intake hole
Φ	normalised temperature, $(T - T_2)/(T_1 - T_2)$
ρ_1	density of warm water
ρ_2	density of cold water
$\Delta\rho$	density difference, $(\rho_2 - \rho_1)$
ν	kinematic viscosity

INTRODUCTION

In natural water bodies density stratification is caused by the presence of a varying temperature with depth due to variation of observed solar radiation, also by a vertical profile in the concentration of dissolved and suspended solids. This naturally occuring stratification is sometimes enhanced by the rejection of large volumes of waste heat from costal power stations in the from of a warm water discharge which tends to form a low den-sity floating surface layer. This type of stratification is usually of stable nature and is important in several flow problems of engineering interest, e.g. management systems for water quality control in reservoirs, waste or warm water discharges into natural water bodies and cooling water intake from reserviors, seas and rivers. In many of these flows the density variation combines with gravity to produce buoyancy effects which can crucially influence the fluid dynamic behaviour. The buoyancy force inhibits vertical motion and in some engineering problem, specially the management of water quality of reservoirs and the intake of cooling water, the flow is coming from a spatially limited selective layer or region. This phenomena is known as selective withdrawal.

Selective withdrawal phenomenon has often been studied for two dimensional laminar flow cases. Brooks and Koh (1969) and Imberger (1980) have provided a very good review of these cases. In practice, specially for the intake of cooling water, this phenomena is of three-dimensional (3D) nature, and needs an extensive study. This paper deals with this type of 3D problem. A single round hole is considered for the intake geometry to withdraw selectively cold water from a two layered thermally stratified cross flow.

EXPERIMENTALI SETUP AND PROCEDURE

The expriments were carried out in a flume of 0.4m width, 0.5m depth and 8m length. The withdrawal hole was situated on the smooth wooden bottom surface at the symmetry axis of the flume, 2.5m downstream of the entry section. The warm and cold water were introduced into the flume from two constant head tanks and the heights of the warm and cold water layers were maintained by means of a splitter plate. Figure 1 shows a schematic view of the experimental flume.

Goldring (1984) obtained experim-ental correlations for critical drawdown conditions for different cross-flow and intake hole diameter conditions. In the present study, Goldring's experiment was extended with single round hole to study the mixing behaviour in the near field region of the intake system. The diameter of the hole was d=42.5 mm and the cross-flow velocity was U=31.25 mm/sec for both layers. Seven experimental runs were made to map the temperature field at two Reynolds numbers, 8330 and 9850 and the inlet Froude number, Fr_o ranges from 0.72 to 1.3. Table 1 gives the details of the parameters of these seven experimental runs.

The water temperature was measured by means of nine miniature bead (1.5 mm dia) thermistors (R-S Data 151-142) calibrated to an accuracy of $\pm 0.01°C$; six

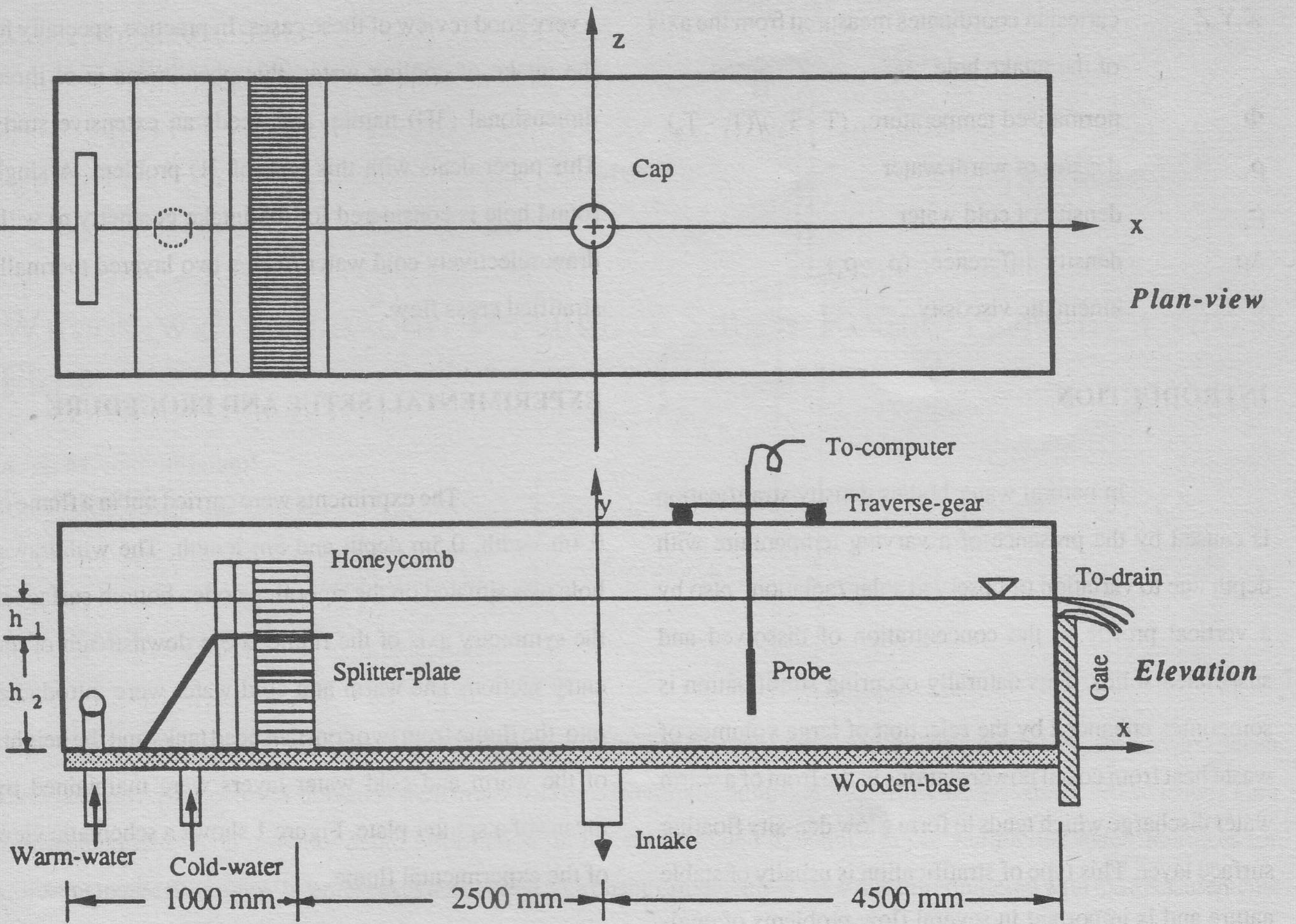


Fig. 1 The cross-flow flume.

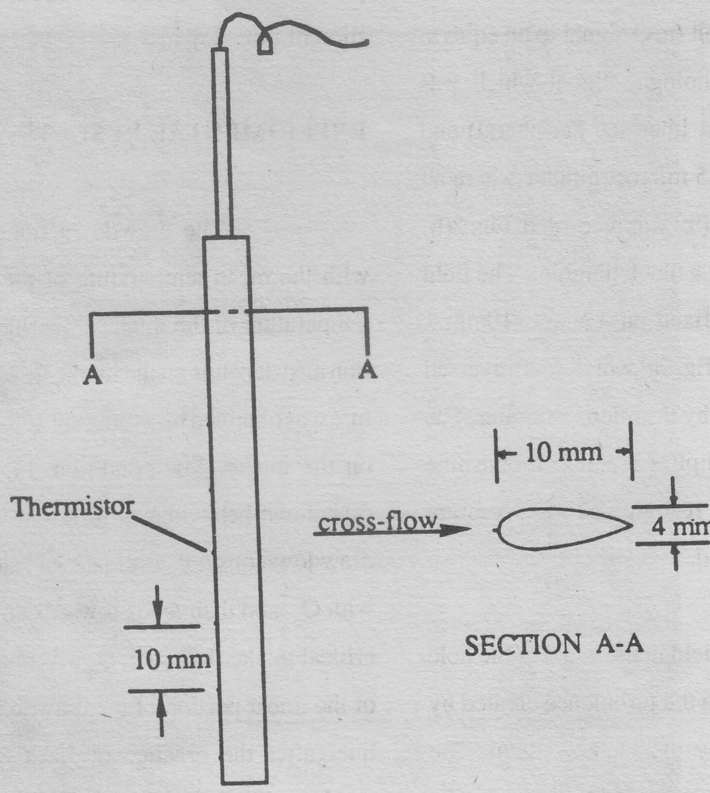


Fig. 2 (a) The probe for field temperature measurements.

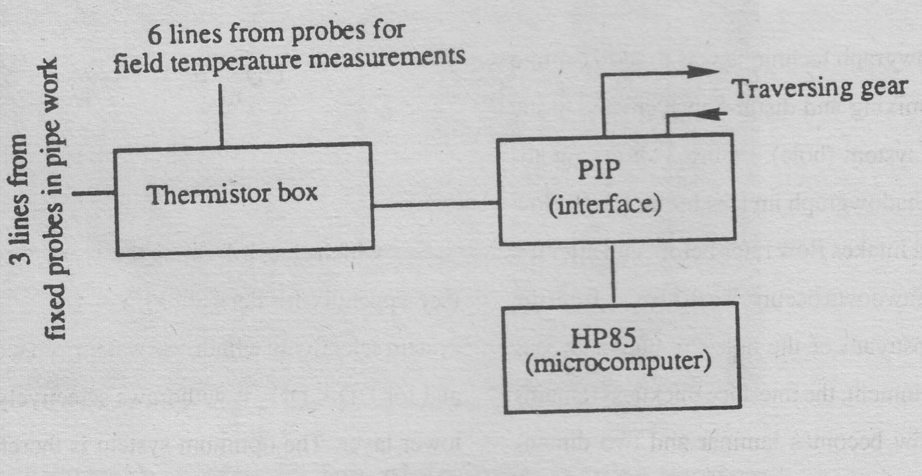


Fig. 2 (b) Block diagram for electrical connection of thermistor probes and traversing gear to the microcomputer.

of which was for field temperature mapping. The thermistor box which converts the millivolt (mv) signal to an equivalent resistance and then an anologue signal which was digitised by an interface (Plant Interface Peripheral) and sent to a Hewlett Packard HP85 microcomputer where an equivalent temperature reading (°c) was reco-rded. Fig. 2(b) illustrates these connections by a block diagram. The field temperature thermistors were fixed on a small (10mm x 5mm) stream lined plastic rod, (fig. 2a) which was traversed by a traversing gear monitored by the microcomputer. The time taken by the system for sampling readings for the nine thermistors and converting the readings into temperature (°c) was approximately 1 second.

The temperature field in the wake of the hole was observed to fluctuate due to the turbulence created by the flow disturbance caused by the intake system. The amplitude of these fluctuations increased with the intake flow rate. To averaging out this fluctuations, different sample sizes ranging from 30 to 300 depending upon the flow condition were taken.

FLOW VISUALISATION

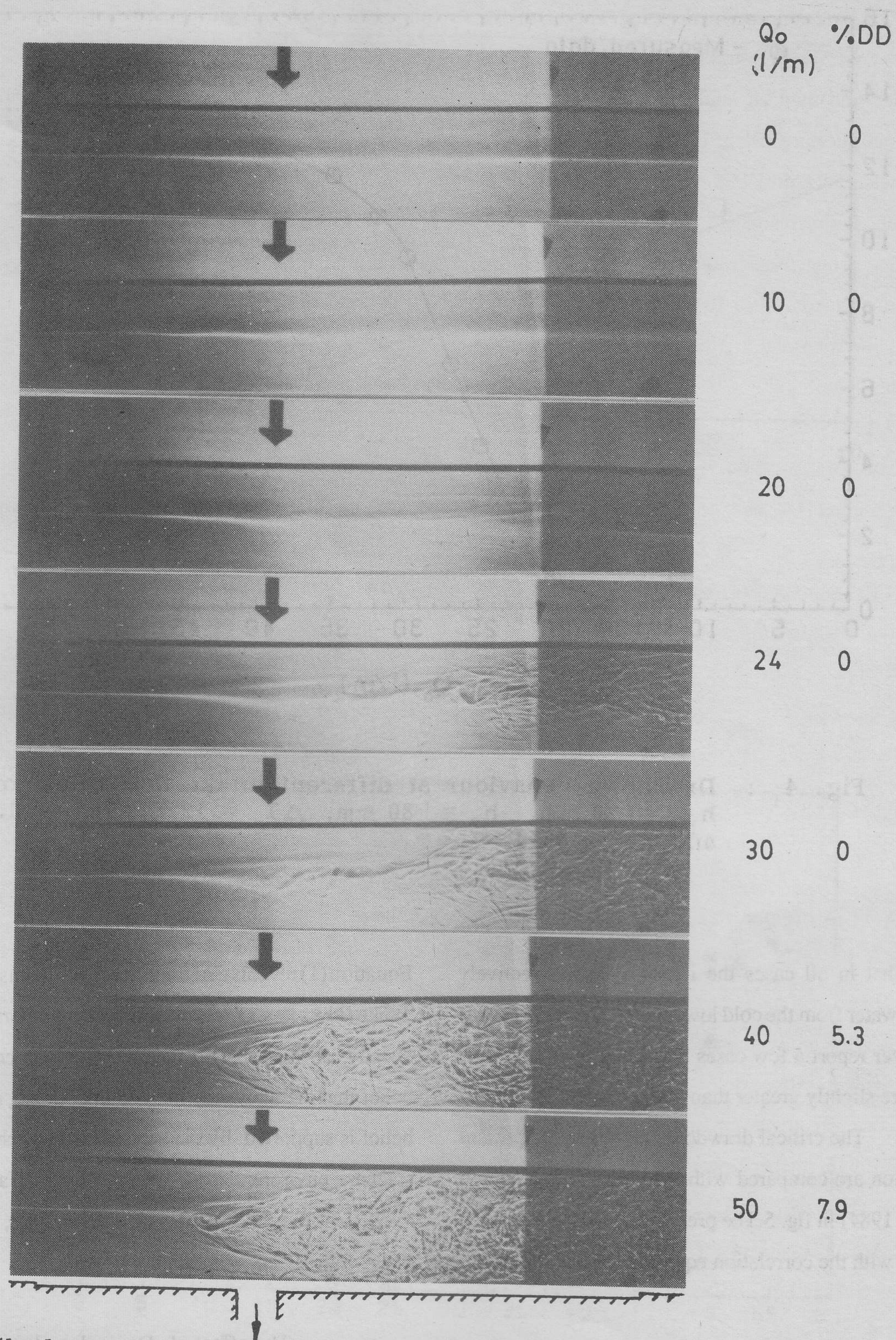
Shadowgraph technique was used to capture the features of the mixing and distur-bance created in the wake of the intake system (hole). Figure 3 shows photographs taken from shadowgraph images for no intake flow rate and six different intakes flow rates before and after the incipient (critical) drawdown occurs. It can be seen from the photographs that upstream of the hole the buoyancy has damped out all entrainment, the interface thickness remains constant and the flow becomes laminar and two dimensional. As the intake flow rate increases the turbulence generated at the hole breaks up the interface and in the wake region the two layers are mixed up and the mixed layer is pulled down towards the hole, causing a significant proportion of drawdown.

EXPERIMENTAL RESULTS AND DISCUSSION

The drawdown fraction (DD) is calculated with the mean temperature of the intake flow. Since the temperature of the intake flow fluctuates and this fluctuation also depends on the intake flow rate, the mean temperature was obtained by averaging 100-600 samples depending on the intake flow condition. Figure 4 shows a typical drawdown behaviour at different intake flow rates. After drawdown onset the drawdown fraction increases linearly with Q_o and then tends towards an asymptofic value. The critical intake flow rate, Q_o was obtained by the projection of the linear portion of the drawdown curve to the DD = 0 line (after the practice of Jirka & Katavola, 1979 and Goldring 1984). The asymptotic (or peak) value observed in the drawdown curve has a great practical importance in the context of intake system design. For example, for the case of fig. 4, for well mixed conditions at the upstream the drowdown will be

$$DD_m = \frac{h_1}{h_1 + h_2} = 20\%$$

which gives a defining limit for selective withdrawal (see appendix for derivation). For $DD > DD_m$, the intake system selectively withdraws water from warm upper layer and for $DD < DD_m$ it withdraws selectively from the cold lower layer. The optimum system is therefore that which leads to a maximum reduction in the peak drawdown value below DD_m. During the present experimental studies, the peak DD observed were always substantially below DD_m



Shadowgraph pictures for plain hole intake system at different intake flow rates. $h_1 = 50$ mm, $h_2 = 80$ mm, $T_1 = 9.4°C$, $T_2 = 4.6°C$

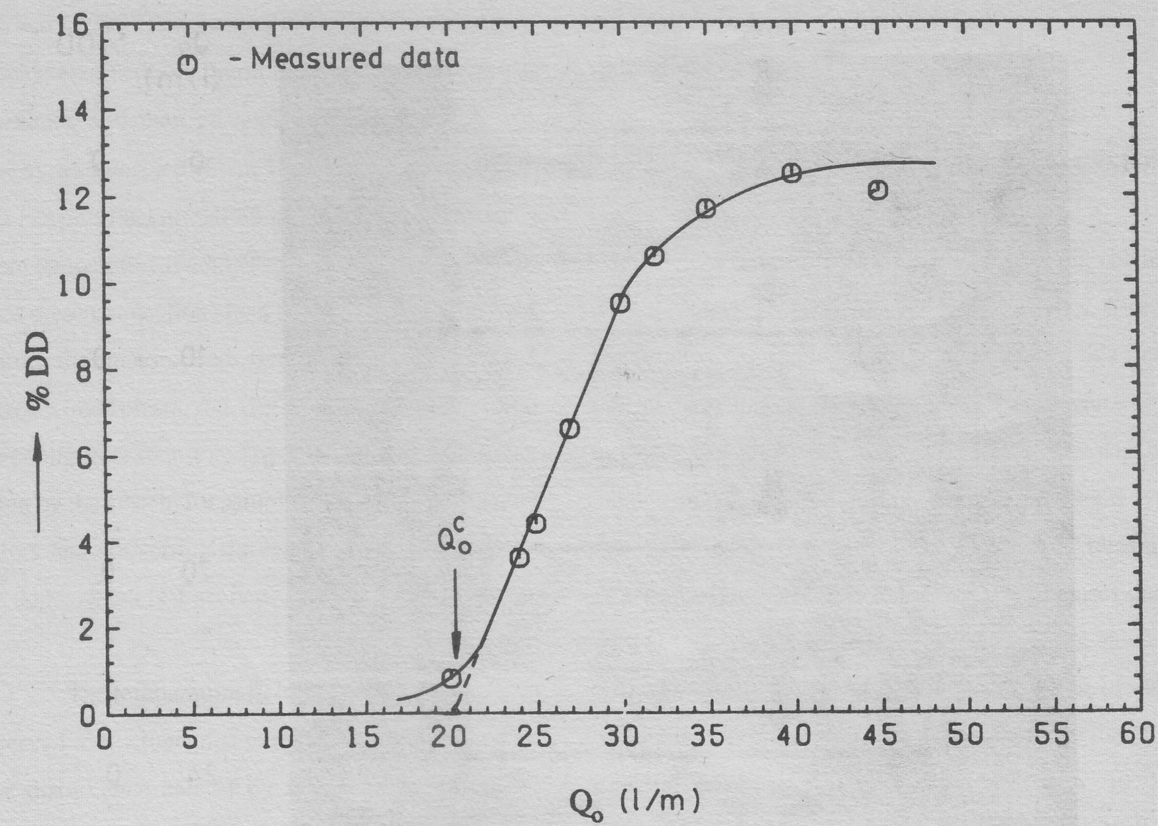


Fig. 4 : Drawdown behaviour at different intake flow rates for h_1 = 20 mm, h_2 = 80 mm, ΔT = 12°C, Fr_o = 0.72 and Re = 8330.

showing that in all cases the intake system selectively withdrew water from the cold lower layer. Goldring (1984) did however report a few cases where the maximum DD values were slightly greater than DD_m.

The critical drawdown results of the present investigation are compared with the correlation equation (Goblring 1984) in fig. 5. The present measurements agree quite well with the correlation equation (1).

$$\frac{h_2}{d}\left(\frac{U}{\sqrt{g'h_2}}\right)^{0.575} = 0.763\left(\frac{Q_0^C}{\sqrt{g'd^5}}\right)^{0.386} \quad (1)$$

Equation (1) reveals that for the cross-flow cases the critical intake flow rates, Q_o^c shows an inverse proportionality with density difference Dr, which is in direct contrast to the belief that the buoyancy inhibits drawdown, although this belief is supported by the axisymmetric withdrawal from stagnant environment (see, Craya 1949, Harleman et al 1959, Goldring 1981, Ivey & Blake 1985, McGuirk & Islam 1987).

The effect of Dr on drawdown at different supercritical intake flow rates ($Q_o > Q_o^c$) are also presented in figure 6. By increasing Dr, the drawdown is increased.

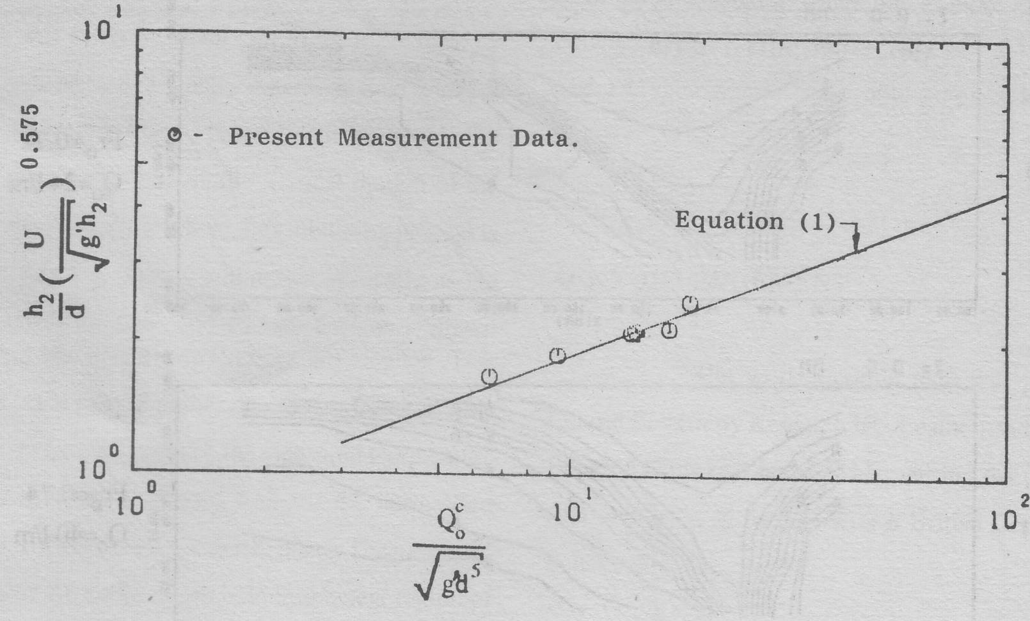


Fig. 5 : Critical drawdown.

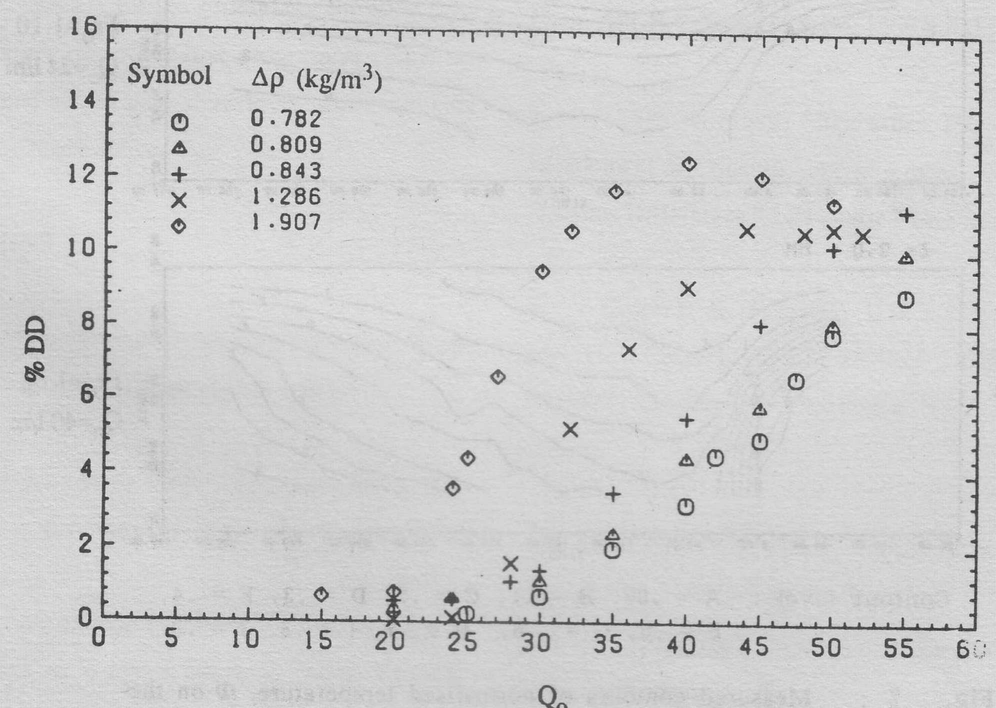
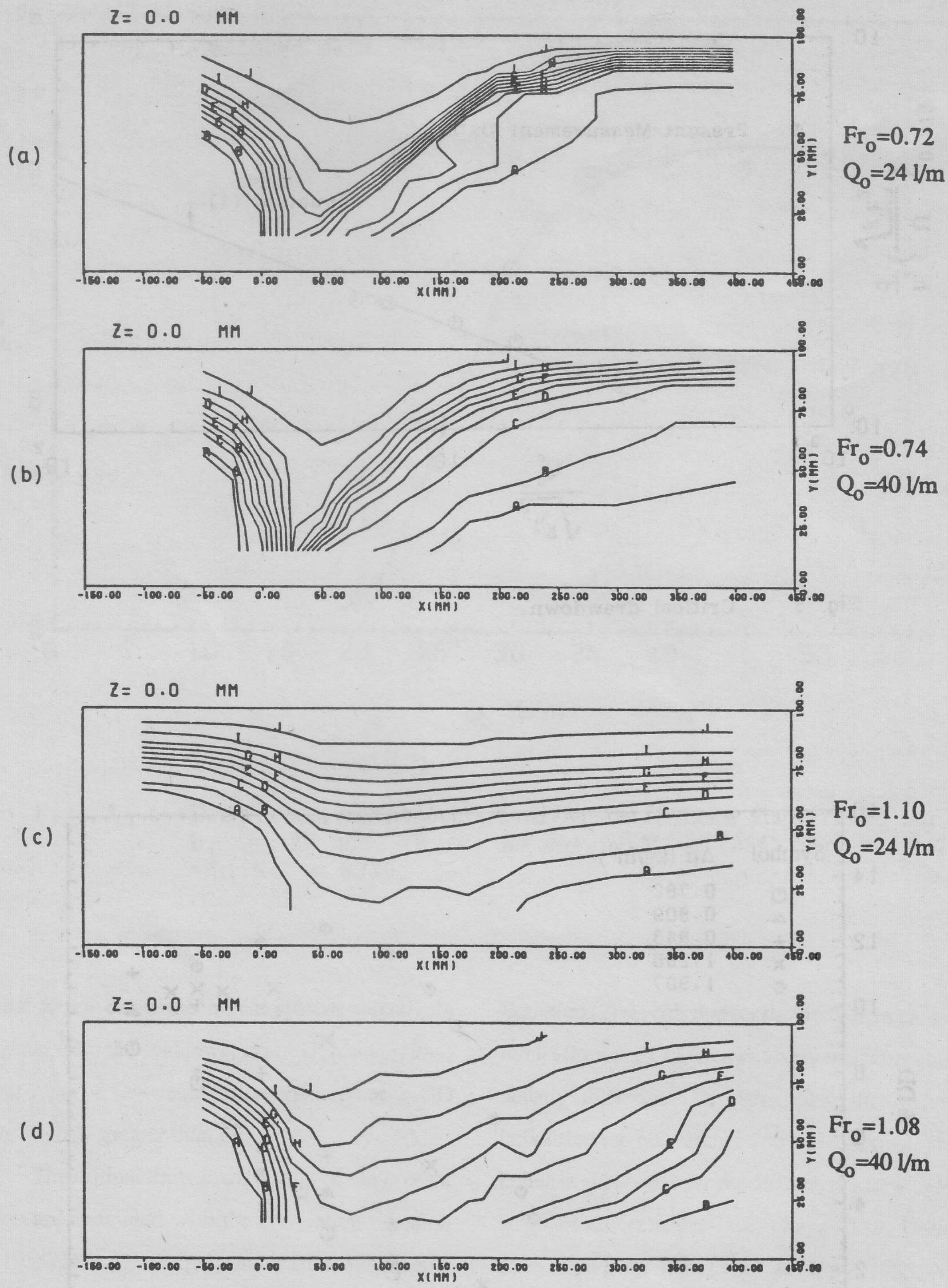


Fig. 6 **Effect of buoyancy on drawdown. h_1=20mm, h_2=80mm**



Contour level : A = .05, B = .1, C = .2, D = .3, E = .4,
F = .5, G = .6, H = .7, I = .8, J = .9.

Fig. 7 : Measured contours of normalised temperature, Φ on the symmetry plane.

The peak value of DD observed also increases with Dr. An explanation was given by Islam (1988) for these facts by observing the predicted flow and temperature field for these cases. The buoyancy forces, proportional to the density gradient at the thermocline inhibit vertical motion of the fluid. For higher density gradient, this inhibiting process is stronger, so that less fluid is withdrawn vertically as the layer passes over the hole, and a larger fraction is drawn hence mixing the density differences are smaller. This mixed fluid leads then to higher drawdown fraction. This explanation is also supported by the measured temperature field shown in figure 7. Figure 7 shows the normalised temperature, F field on the sysmmtry plane. The measured perturbation of the temperature field in the near region of the hole is presented for approximately two different inlet Froude numbers and for two different intake flow rates. As Q_o increases, the vertical perturbation of a given temperature contour increases for the same Fr_o cases and causes more drawdown. For the same Q_o cases, the warm water floats up more quickly for the strong buoyant cases (less Fr_o), but in the vicinity of the hole more warm waters are pulled down and causes more drawdown, which supports the explanation made above.

CONCLUSIONS

The major conclusions from the present experimental observations may be summarised as follows :

(i) Flow visualisation served as a good guide to understand the flow behaviour in the near field region of an intake system.

(ii) The present drawdown data are in good agreement with the correlation equation (1) of Goldring's (1984) experimental data.

(iii) An inverse dependency of density difference on from the downstream, where due to more turbulence and critical intake flow rate, Q_o^c, drawdown behaviour and peak DD value was observed, unlike the case without cross-flow.

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REFERENCES

1. Brooks N. H. & Koh. R. C. Y. (1969) "Selective Withdrawal from Density Stratified Reservoirs", J. Hydr. Divn, ASCE Vol.95, HY4, pp. 1369-1400.

2. Craya A. (1949) "Recherhes Theoriques Sur L' Ecoulement de Couehes Superposees de Fluides de Densites Differentes," La Houille Blanche, pp. 44-55.

3. Goldring B. T. (1981) "The effect of a hood on drawdown Criteria in Zero Crossflow", Report No RD/L/2031/N81, Central Electricity Research Lab., Leatherhead, U.K.

4. Goldring B. T. (1984) " Selective Withdrawal by Capped and uncapped intakes in a Tidal flow", Report No TPRD/2/2678/N84, Central Electricity Research Lab., Leatherhead, U. K.

5. Harleman D. R. F., Morgan R. L. & Purple R. A.

(1959) " Selective Withdrawal from a Vertically Stratified Fluid ", Paper 10-c, Proc. 8th Congress of IAHR, Montreal, Canada.

6. Imberger, J. (1980) "Selective Withdrawal : A Review", 2nd Int. Symp. on Stratified Flows, IAHR, Norway, pp. 381-400.

7. Ivey G. N. & Blake S. (1985) "Axisymmetric Withdrawal and Inflow in a Density Stratified Container", J. Fluid Mech., Vol. 161, pp. 115-137.

8. Jirka G. H. & Katavola D. S. (1979) "Supercritical Withdrawal from Two-layered Fluid Systems, Part-2 ", J. Hydr. Res., Vol. 17, pp. 53-62.

9. McGuirk J. J. & Islam A. K. M. Sadrul (1987) "Numerical Modelling of the Influence of a Hood on Axisymmetric Withdrawal from a Density Stratified Environment", Proc. 3rd Int. Symp. on Stratified Flows, Caltech, Pasadena, U.S.A.

10. Islam A.K.M. Sadrul (1988) "Prediction of Selective Withdrawal Phenomenon in Stratified Cross Flowing Streams", Ph.D. Thesis, Imperial College, London, U.K.

Table 1

Experimental Parameters for Intake Flow Through a Single Plain Hole:

Run No	h_1	h_2	T_1 °C	T_2 °C	Q_o l/m	Fr_o	Re
1	50	80	12.4	7.6	24	1.28	9850
2	50	80	12.1	7.3	30	1.3	9850
3	50	80	12.3	7.6	40	1.29	9850
4	20	80	22.0	9.7	24	0.72	8330
5	20	80	21.3	9.3	40	0.74	8330
6	20	80	16.2	9.8	24	1.1	8330
7	20	80	16.3	9.7	40	1.08	8330

Appendix

Drawdown fraction is defined as the ratio of the amount of the warm upper layer withdrawn to that of the total mixed fluid withdrawn and is expressed as :-

$$DD = \frac{m_{0,1}}{m_0} = \frac{m_{0,1}}{m_{0,1} + m_{0,2}} \quad ..... \quad ..... \quad (A.1)$$

where m_o is the mass of the fluid withdrawn and the subscripts 1 and 2 refer to the masses of fluid withdrawn from the warm upper layer and cold lower layer respectively.

Now from mass balance,

$$m_o = m_{o,1} + m_{o,2} \quad (A.2)$$

and from energy balance,

$$m_o T_o = m_{o,1} T_1 + m_{o,2} T_2 \qquad (A.3)$$

assuming C_p of the fluid is constant in the range of temperature considered here.

Equating equations (A.2) and (A.3) we have,

$$DD = \frac{T_0 - T_2}{T_1 - T_2}$$

For well mixed conditions at the upstream of the intake hole, the intake mass flow rate will be,

$$m_o = k(m_1 + m_2) \qquad (A.4)$$

where k is any constant and m_1 and m_2 are the mass flow rates of the warm upper layer and cold lower layer fluids. Then the peak drawdown fraction is given by,

$$DD_m = \frac{km_1}{m_0} \quad \ldots\ldots\ldots \quad (A.5)$$

Since,

$$\frac{m_1}{m_2} = \frac{h_1}{h_2}$$

for the flume considered here and equating equations (A.4) and (A.5), we have,

$$DD_m = \frac{km_1}{m_0} = \frac{h_1}{h_1 + h_2}$$