EXPERIMENTAL STUDY OF HEAVY RADIAL DENSITY CURRENTS

Ibrahim S. El-Sebakhy
Alexandria University, Alexandria, Egypt.

ABSTRACT

Heavy density currents occur when the inflow is denser than the ambient fluids in a basin. These currents exist in most secondary sedimentation basins and in nature as reservoirs and estuaries. In this paper, the internal flow regimes, associated with the density currents due to diurnal heat loading in circular clarifiers, are investigated. The experimental studies included flow with unsteady influent temperature under different conditions of geometry, momentum and negative buoyancy. Velocity and temperature measurements of different flow regimes were measured throughout the basin. The flow phenomena progressed through a sequence of density flow regimes: the denser wall jet, internal hydraulic jump, rebound at the gate, and stratification. Temperature and photographic data are analyzed to determine the characteristic depths, velocities and isotherms for the radial density currents in a basin. The experimental results are compared with a simple model. This study shows that circular tanks subject to variable influent temperatures (or concentrations) experience internal surges in the form of moving hydraulic jumps. This phenomenon could result in degraded performance of clarifiers during transient density events.

INTRODUCTION

The typical flow in sedimentation basins is stratified, two-phase and turbulent. The diurnal variations of inflow, temperature and concentration can result in unsteady density currents. Previous studies of the hydrodynamics of sedimentation basins have not adequately considered the effects of unsteady density gradients on the flow patterns (e.g. Larsen [1977], Zhou et al [1992], Bretscher et al [1992]). The purpose of this work is to study the internal flow regimes associated with the density currents due to the introduction of a denser influent to an initially unstratified circular tank. The denser fluid is obtained by using colder water than that in the tank. The settling basin can be divided into inlet zone, outlet zone, settling zone and sludge zone but this paper does not consider the sludge zone.

A 'density current' is a flow of fluid into an ambient fluid of a different density. A density current that is heavier than the main body of fluid will tend to sink and flow along the bottom of the tank. If the density current is lighter it tends to rise and flows along the top. Density currents may result from thermal effects, concentration effects, and the release of gas bubbles.

If the influent velocity and flow are sufficiently high and steady, the influent will mix with the tank contents yielding only a small density effect on the flow pattern through the tank resulting a relatively rapid transition to a steady flow pattern. If the thermal density currents maintain their identity through a tank, the flow pattern will be unsteady [Camp, 1946]. The hydraulic efficiency is affected by these density currents but there is still no consensus on how the removal efficiency is affected [McCorquodale 1976, 1987]. Although thermal and concentration driven density currents are similar in their initial unsteady regimes, the concentration density currents can achieve a stratified steady state while the steady state condition for the thermal case may be a new unstratified (neutral density) condition.

Settling basins may have to be over designed to account for uncertainties of the hydrodynamics. There is now a considerable interest in the optimization of treatment plant design to achieve high removal efficiency at low cost. A number of studies have investigated non-ideal settling basin hydrodynamics. They have revealed that phenomena such as density currents, turbulent mixing and recirculation in plan and profile, among other factors are important in determining the hydraulic efficiency of a tank. The existence of bottom and surface density currents have been confirmed by observation in some wastewater treatment plants; surface density currents in particular, can give rise to extreme short circuiting and poor hydraulic efficiency [McCorquodale, 1976, 1987]. A sequence of density interfaces for bottom and surface currents have been observed; internal travelling radial hydraulic jumps can be induced by both types of density currents. Very little is known about the effects of these density regimes on the sedimentation process.

An insight into the density flow regimes in settling tanks can be obtained from the numerous studies that have been presented on density flows. The general principles of density stratified flow can be found in Long [1953], Yih and Guha [1955], Harleman [1960], Harleman et al [1958], Baddour and Chu [1975], and Chu and Baddour [1977]. Interfacial shear is discussed by Ippen and Harleman [1957], Abraham and Eysink [1970], French [1979] and Dermissis and Partheriades [1984]. Internal hydraulic jumps have been studied by Yih and Guha [1955], Baddour and Abbink [1983], Baddour [1987], Wilkinson et al [1970, 1971], Rajaratnam and Subramanyan [1986], Powley [1987], Godo et al [1991]. All of these studies have been made in rectangular channels; however Bretscher et al [1992] carried out full scale velocity measurements in rectangular and circular final clarifiers under different stratifications. Godo et al [1991] studied thermal density currents in model rectangular tanks.

The studies in this paper were undertaken to quantify the transient flow regimes associated with thermal density currents and to aid in mathematical modelling of settling tanks. This paper describes an experimental setup of a cool denser radial jet discharging into a warm ambient. Data were collected for different tank configurations and flow conditions. Velocity and temperature distributions were measured at several sections along the tank radius at different stages of the transient phenomenon. In addition, photographic dye tests were carried out under different flow regimes. The regime characteristics are determined, such as: jet depth, velocity, temperature, moving hydraulic jump sequent depths and surge velocity.

EXPERIMENTAL SETUP AND TEST PROCEDURE

The main purpose of the experimental program was to provide information on the internal flow regimes associated with the density currents and provide data for model development for the denser wall jets. The experiments were carried out in a physical sector model of a circular clarifier, as shown in Figure (1). The tank had a total angle of 20. The test section was 1.25m long, and the inlet to the test section was controlled by a radial gate. The flume was provided with a peripheral weir with a height of 230mm. The water entered the flume through an inlet port in a 50mm riser fed by a hose attached to a hot and cold water supply.

Twenty copper-constantan thermocouple were used in the experiment to monitor the temperature in the tank. Measurements were taken at eleven radial locations, using a traversing probe array of 8 thermocouple at specific elevations; the other 12 thermocouple were positioned at stationary locations along the flume wall, gate and the weir. The thermocouple outputs were scanned and digitized with the data acquisition system, which consisted of a Fluke model 2240B data logger, an A/D converter, and a microcomputer.

The velocity profiles were measured at different locations along the tank radius and under different flow regimes associated with the density current. The probe was made of 3.2mm diameter stainless steel tube, with 1.6mm diameter holes at 38mm spacing. To obtain the velocity about 50mL of a solution of Potassium permanganate dye was injected through plastic tubing connected to the probe. The experiments were recorded by an auto focus RCA video camera, running at 30 frames per second with a 88mm video zoom lens.

For the photographic dye study, a visual determination of the flow pattern was made and the results were documented by photographing the different flow regimes. A series of photographs during each test were taken with a 35mm Cannon A1 camera. A clock with a sweep second hand was photographed in the field of the camera to give a time reference.

The experimental program undertaken involved temperature tests, velocity tests and flow visualization tests. These three tests were repeated for similar test conditions. In the experiments, the variables were flowrate, gate opening, ambient fluid temperature and influent temperature of the jet.

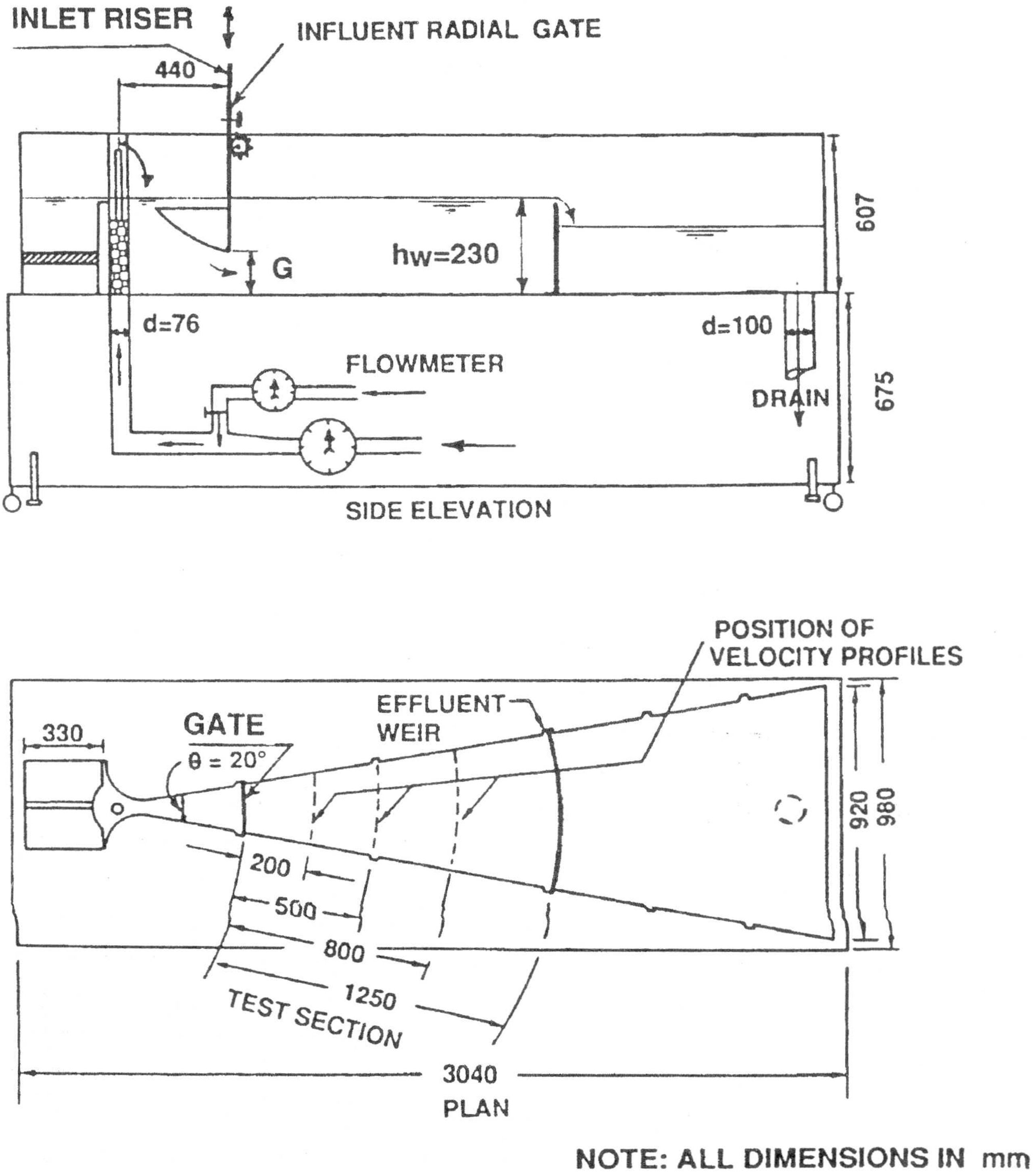
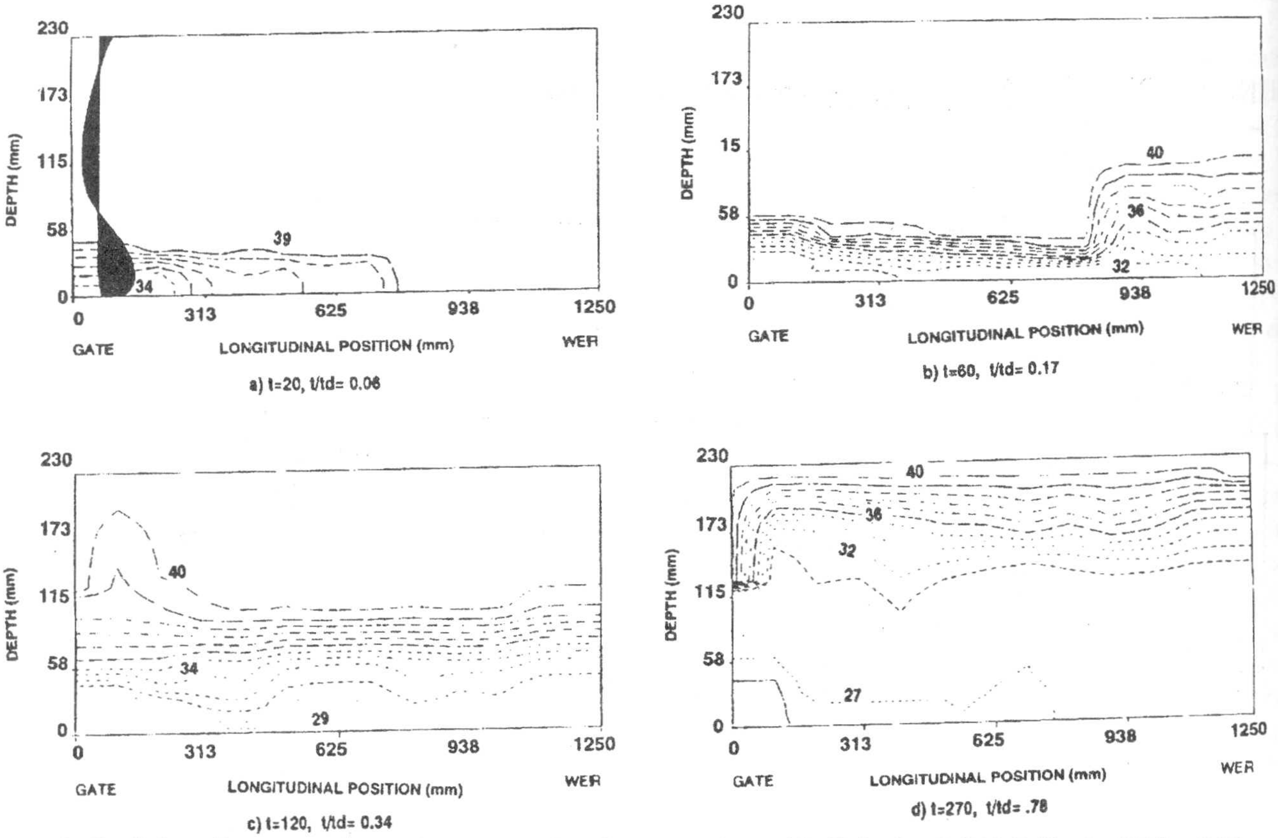


Figure 1. Schematic layout of sector model of the tank.



a) t=20, t/td= 0.06

b) t=60, t/td= 0.17

c) t=120, t/td= 0.34

d) t=270, t/td= .78

Figure 2. Radial wall get test thermal contour plot G=7 cm, hw=23 CM, Q=0.310 L/S td=V/Q=347.

Table 1. Temperature and photographic experiments.

Case number	G (cm)	Q (L/s)	T_o^+ (°C)	T_1^+ (°C)	F'_o	Source$^+$
1	5	0.514	39	25	2.5	t.t
2	5	0.318	40	26	2.25	t.t
3	7	0.310	41	25	2.9	t.t
4	3	0.501	42	25	3.1	t.t
5	7	0.493	41	25	2.1	t.t
6	3	0.314	41	27	3.7	t.t
7	5	0.550	42	21	2.5	p.d.t
8	5	0.368	44	22	1.9	p.d.t
9	7	0.350	44	22	1.5	p.d.t
10	3	0.550	43	21	2.9	p.d.t
11	7	0.550	43	22	2.1	p.d.t
12	3	0.350	44	22	2.2	p.d.t

The velocity measurements were obtained at three radial locations in the tank, i.e. near the gate, at the middle of the tank, and close to the weir as shown in Figure (1). The entire experiment was repeated three times for each of three sections and for different flow regimes associated with the density current. The test procedure was the same as the temperature study but the video camera was used instead of the data acquisition system. The video records were projected on a high resolution video monitor to determine the travel time of the dye.

Injection of dye into the cold influent allowed visual observations and photographic records to be made of the flow structure. The results obtained from the photographs of the dye tests were used to estimate density current depths and velocities.

EXPERIMENTAL RESULTS

The experimental data from 162 experiments were collected for a total of 18 tank configurations and conditions. Table (1) shows 12 conditions for the temperature and photographic experiments along with the initial reference densimetric Froude Number. The experimental results are discussed in three groups: the temperature study, the photographic dye study and the velocity study.

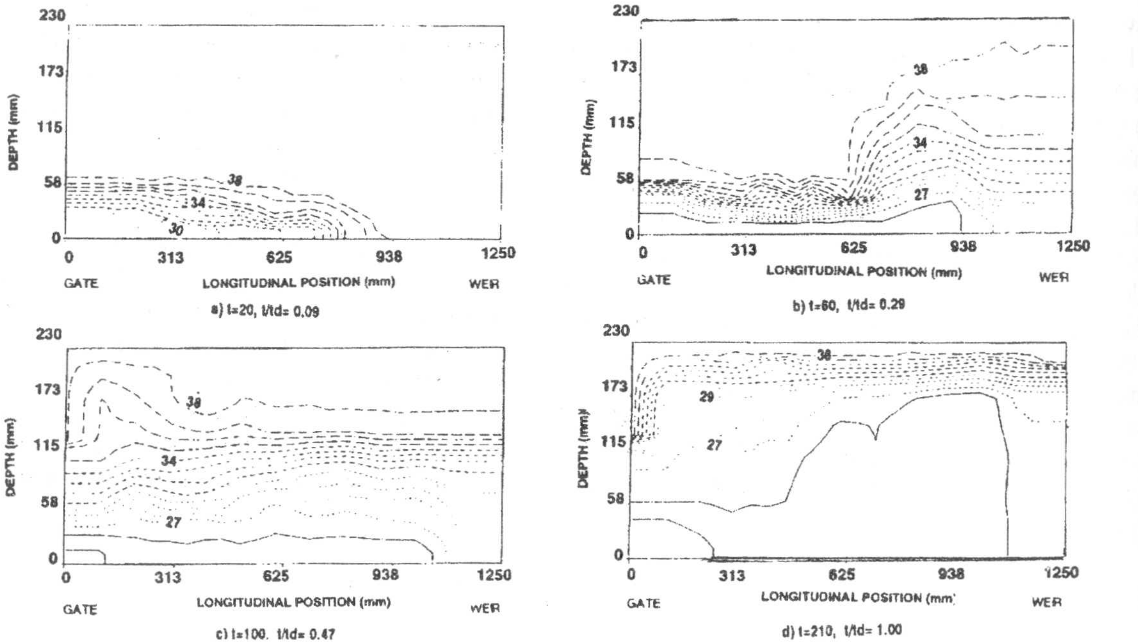
A total of 66 runs were made to survey the temperature field in the radial sedimentation tank. These experimental tests were conducted under six conditions. For each test condition, the results of the temperature measurements are presented in the form of contour plots (isotherms) such as Figures (2) to (7). All length dimensions are given in mm, the flowrate in L/s, temperature in C and time in seconds. The isotherms from the six test conditions reveal several different transient flow regimes: (i) denser wall jet, (ii) rebound at the wall, (iii) the travelling radial internal hydraulic jump, (iv) submergence and rebound at the baffle, (v) submerged internal hydraulic jump, (vi) stratification, and (vii) neutral density flow. Figure (8) shows a typical moving internal hydraulic jump.

Data for the velocity profiles were collected at different radial locations and under different flow regimes. Figure (9) presents the velocity distributions along the centreline of the flume at the three locations shown in Figure (1), and for specific flow regimes under certain test conditions. Table (2) gives the definitions for the different flow phases.

The values and ranges of the experimental data were: weir height, h_w = 23cm; flow rate, Q = 0.310L/s to 0.550L/s; Gate Opening (gap below baffle), G = 3cm, 5cm, and 7cm; ambient fluid temperature, T_o = 39 C to 43 C; minimum jet temperature, T_1=21 C to 23 C.

Table 2. Definition of velocity experiment phases.

Phase number	Definition
1 Regime i	The incoming jet just reaches the location of the testing profile. Regime i
2 Regime i-ii	The incoming jet becomes fully developed, i.e. reaches the end of the testing section. Regime i-ii
3 Regime i-iii	The moving internal hydraulic, jump just reaches the location of the testing profile. Regime iii
4 Regime iv-v	The moving internal hydraulic, jump becomes submerged at the gate. Regime iv-v



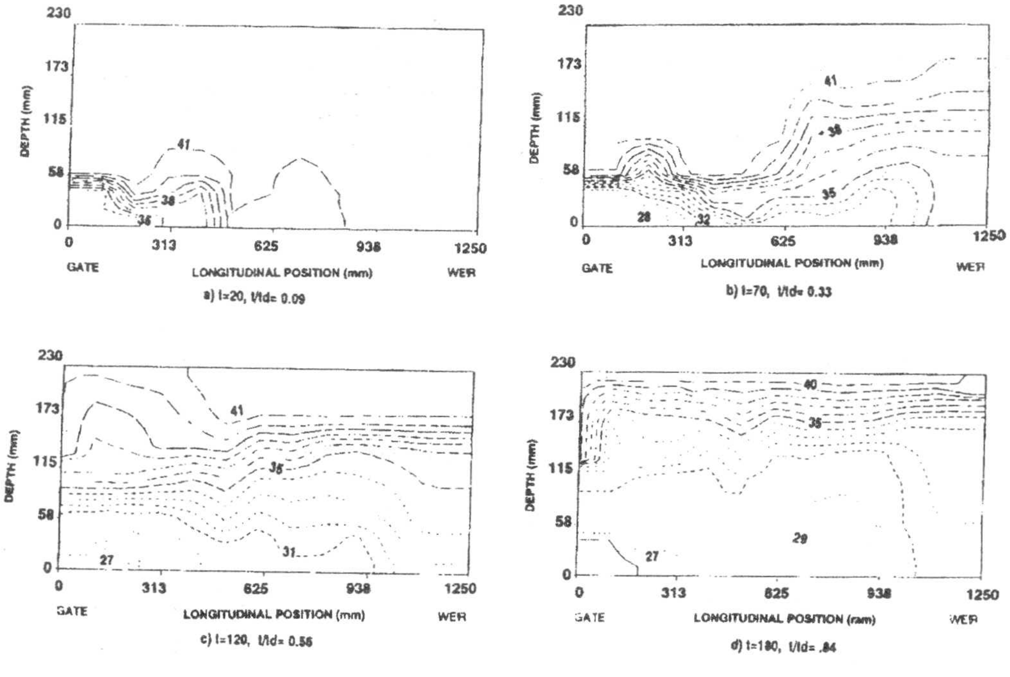
a) t=20, t/td= 0.09

b) t=60, t/td= 0.29

c) t=100. t/td= 0.47

d) t=210, t/td= 1.00

Figure 3. Radial wall jet test thermal contour plot G=5 CM, hw=23 CM, Q=0.514 L/S td=210.



a) t=20, t/td= 0.09

b) t=70, t/td= 0.33

c) t=120, t/td= 0.56

d) t=180, t/td= .84

Figure 4. Radial wall jet thermal contour plot G=5 CM, hw=23 CM, Q=0.318 L/S td=339.

ANALYSIS OF EXPERIMENTAL RESULTS

The Denser Radial Wall Jet

The total amount of entrainment of the ambient fluid and the frictional resistance ultimately govern the change of the jet depth with longitudinal position.

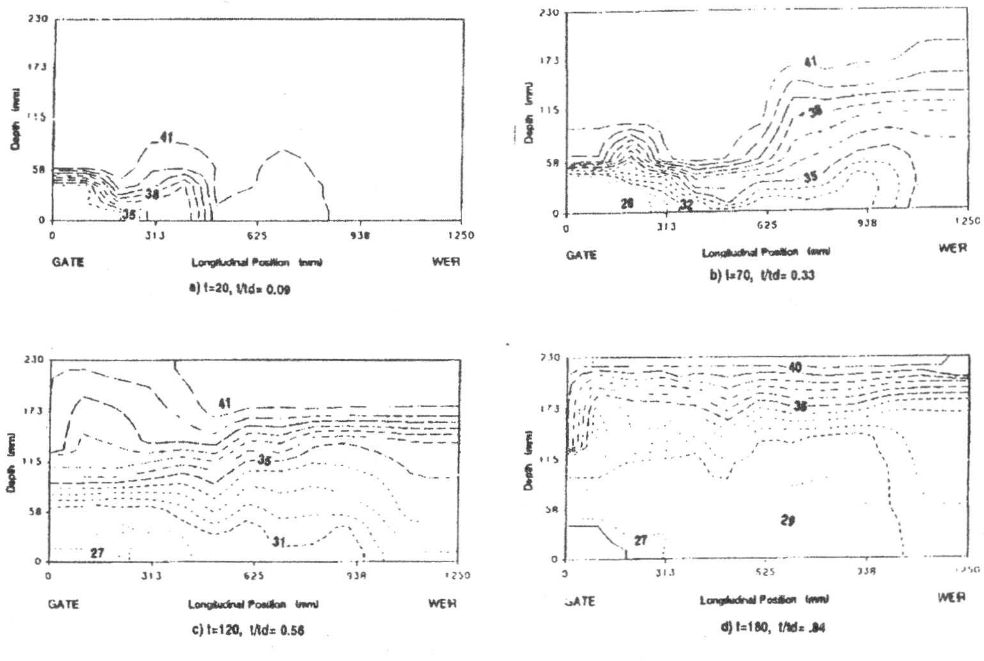
From the thermal contour plots and the photographs, it was found that, in the cases of large gate openings with low densimetric Froude numbers, the inflow does not impinge on the baffle; thus the inlet baffle does not effectively reduce the inlet momentum. This phenomenon is important because there is a large amount of entrainment upstream of or near the gate; this results in an increase in the flow in the bottom density current and the degree of recirculation in the settling zone. For large gate openings with high densimetric Froude numbers, the inflow impinged on the reaction baffle, and the entrainment upstream of the baffle is reduced significantly. Figure (10) shows typical experiment curves for the entrainment coefficient as a function of radial distance from the baffle.

The mean velocity profiles shown in Figure (9) were obtained from the dye velocity experiment. The experimental profiles are characterized by a three layer distribution: a strong bottom density current (denser wall jet) attached to the bottom of the tank: a reverse flow above the bottom jet induced by entrainment. Also the experimental profiles and a surface layer characterized by positive velocity (radially outward). The surface layer was related to: (a) the unsteady nature of the temperature stratification process which results in an internal 'interface' that rises towards the tank surface during the re-establishment of a new neutral density condition; (b) displaced fluid above the thermal 'interface' is withdrawn by the effluent weir; (c) water surface curvature produced by the presence of the effluent weir is responsible for an increase in surface velocity in the withdrawal zone, three-dimensional eddies produced some anomalies in the flow patterns.

Typical density currents modelled in this study had bottom velocities from 1.90cm/s to 8.26cm/s (or V_B/V_G from 0.49 to 0.80), where $V_G = Q_{in} / A_{gate}$, in which V_G is the initial bulk velocity of the jet at the gate and V_B is the velocity of the bottom current.

The reverse flow velocities varied from 0.46cm/s to 2.99cm/s (or V_R/V_G from 0.12 to 0.30); and surface flow velocities from 0.3cm/s to 2.7cm/s (or V_S/V_G from 0.10 to 0.25, where V_S is the velocity at the surface flow). It was found that the maximum velocity occurs close to the bottom, which with the injected dye from the vertical manifold probe, is visible as a sharp interface a few millimeters thick.

It was apparent from moving jump and stratified interfaces that most of the entrainment occurs in the jet phase, with the greatest entrainment at or near the gate Figure (10). This entrainment is reflected by the increased reverse flow. Figures (11) and (12) show a typical mean profile of velocity and thermal contour plot of the jet phase, for large opening (G = 7cm) and low discharge. It is noted that the strength of the reverse flow is related to the strength of the bottom current as shown in Figure (9).



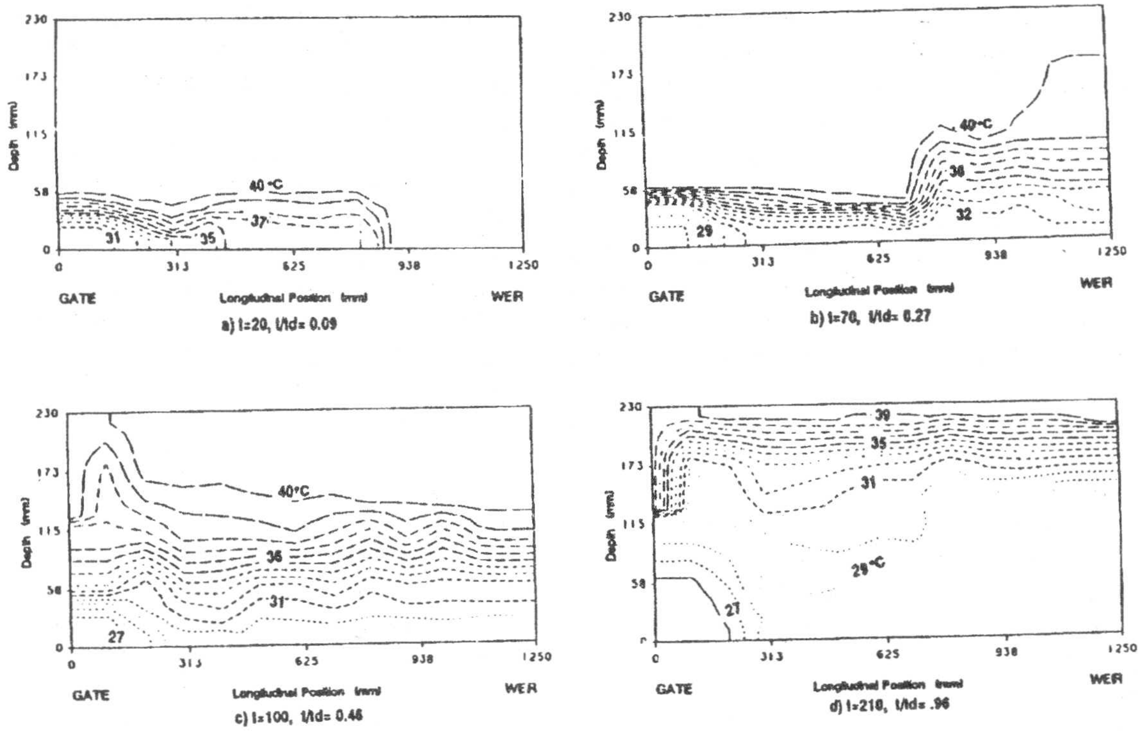
a) t=20, t/td= 0.09

b) t=70, t/td= 0.33

c) t=120, t/td= 0.56

d) t=180, t/td= .84

Figure 5. Radial wall jet test thermal contour plot G=3 CM, hw=23 CM, Q=0.501 L/S td=215.



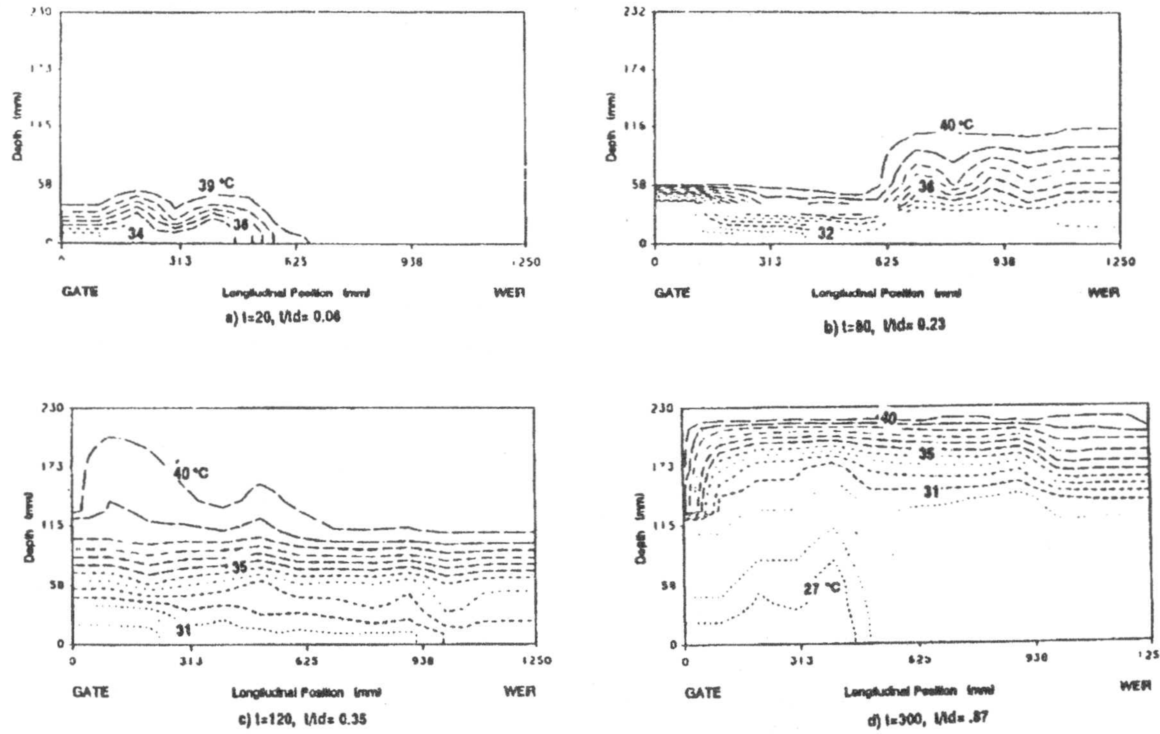
a) t=20, t/td= 0.09

b) t=70, t/td= 0.27

c) t=100, t/td= 0.46

d) t=210, t/td= .96

Figure 6. Radial wall jet test thermal contour plot G=7 CM, hw=23 CM, Q=0.493 L/S td=219.



a) t=20, t/td= 0.06

b) t=80, t/td= 0.23

c) t=120, t/td= 0.35

d) t=300, t/td= .87

Figure 7. Radial wall jet test thermal contour plot G=3 CM, hw=23 CM, Q=0.314 L/S td=V/Q=343.

Table 3. The general trend of the internal hydraulic jump phase for temperature study.

Case number	Q (L/s)	G (cm)	y_2 (cm)	V_s (cm/s)	F'_{r1}	L_i (cm)
1	0.514	5	8.0-13.0	3.8-1.2	2.50	14
2	0.318	5	9.5-7.0	1.5-1.2	2.41.2.92	14
3	0.310	7	10.5-8.5	2.5-1.5	2.80	7
4	0.501	3	8.4-5.9	2.3-1.1	3.0	11
5	0.493	7	8.4-5.9	2.3-1.1	1.79-2.20	11
6	0.314	3	8.75-7.0	2.3-1.4	2.96-2.43	11

Table 4. The general trend of the internal hydraulic jump phase for photographic dye study.

Case No.	Q L/s	G m	y_2 cm	V_s cm/s	F'_{r1}	L_i cm
7	0.550	5	12.0-10.0	3.50-1.68	2.88-2.28	14
8	0.368	5	13.0-4.0	4.50-0.83	2.22-0.59	11
9	0.350	7	16.9-9.3	3.50-1.10	2.40	20
10	0.550	3	12.8-7.7	4.20-1.60	1.92-2.63	14
11	0.550	7	5.0-7.7	2.70-1.58	2.00	12
12	0.350	3	7.0	2.80-1.58	2.50	12

The Moving Internal Hydraulic Jump

The moving internal hydraulic jump is characterized by its length, L_j, the surge velocity, V_s, the sequent depth, y_2, and the relative densimetric Froude number, F'_{r1}. Tables (3) and (4) give the general trends observed in the flow parameters associated with the moving internal hydraulic jump for the temperature surveys and photographic studies.

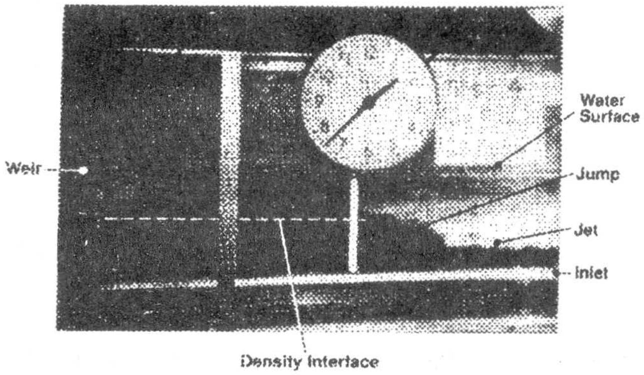


Figure 8. Photographic dye test.

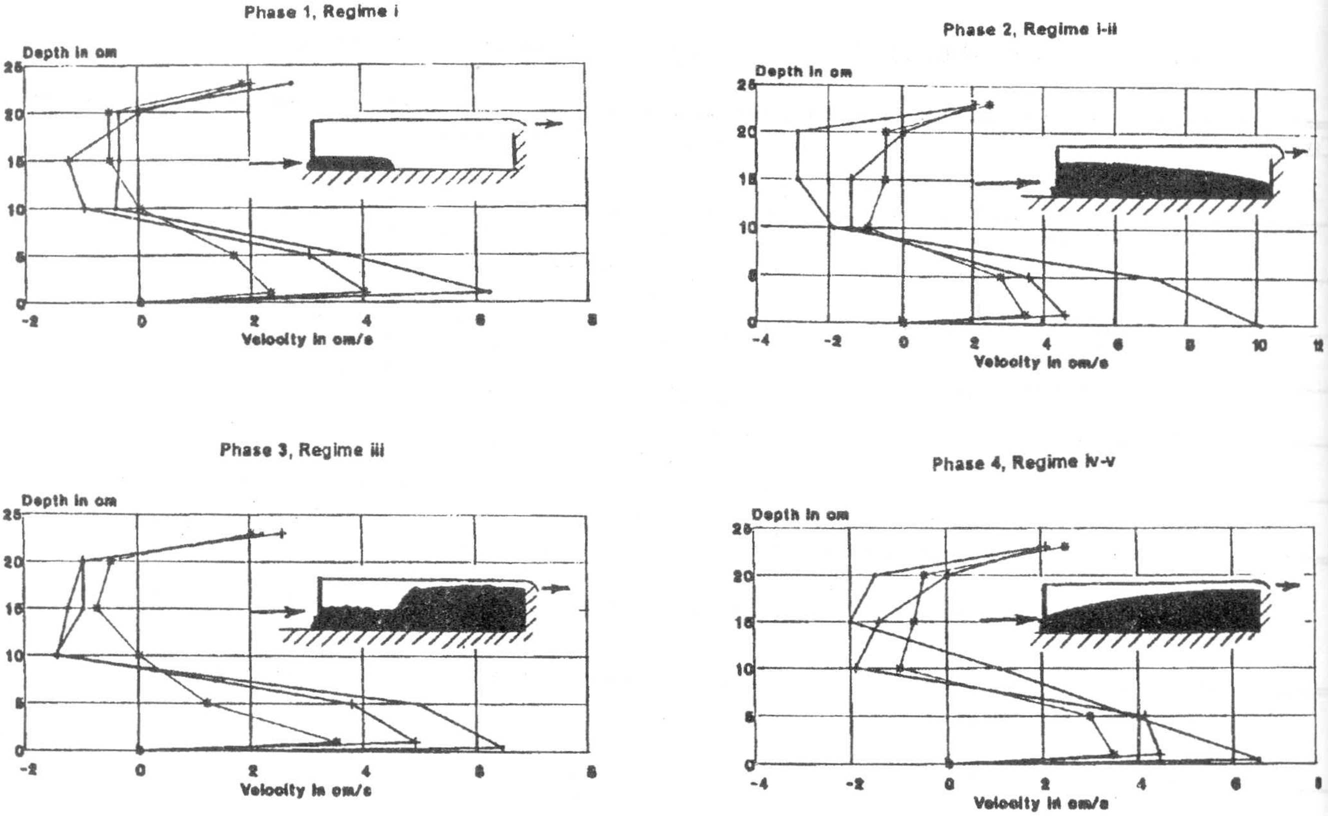


Figure 9. Velocity profiles for density flow.

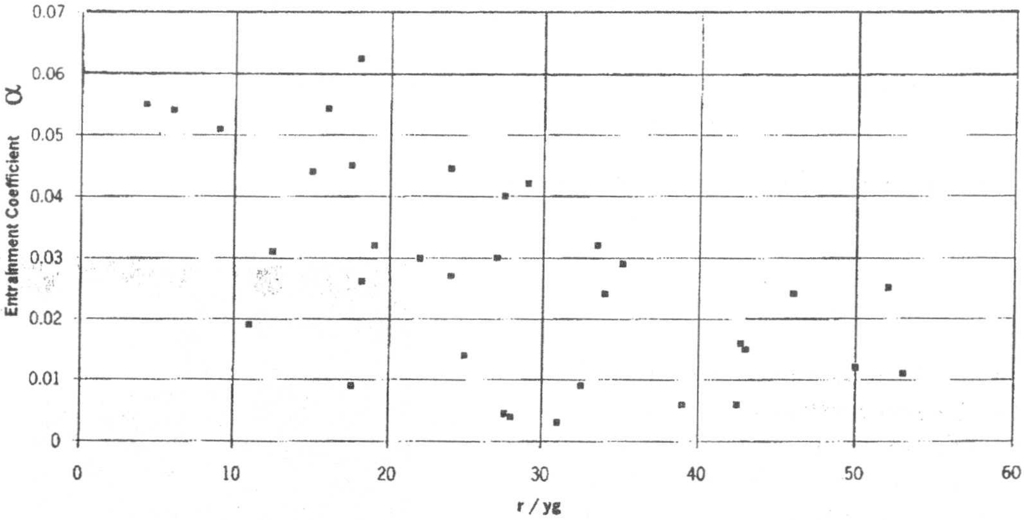


Figure 10. Entrainment coefficient versus distance.

The experimental results for the sequent depth ratio, y_2/y_1, with relative densimetric Froude number, F'_{r1}, are compared with the radial hydraulic jump theory of Khalifa and McCorquodale [1992]. The experimental results are generally lower than that of the theory as shown in Figure (13) but this difference is less than the standard error in the data which is about 15%.

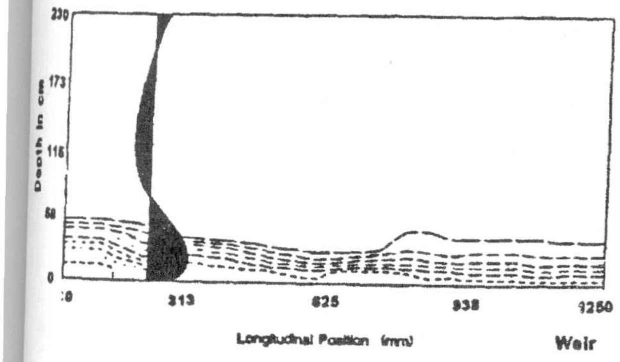


Figure 11. Radial wall jet and thermal contour plot G=7 CM, hw=23 CM, Q=0.31 L/S.

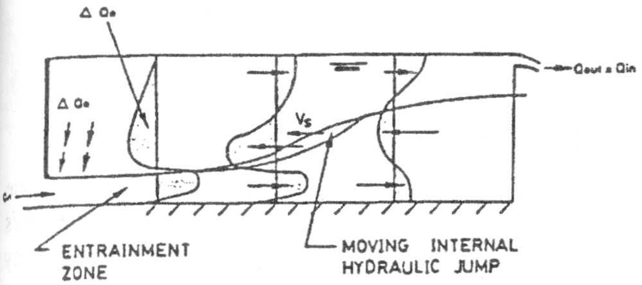


Figure 12. Velocity profiles associated with the internal moving jump.

The Velocity Study

Figure (14) shows typical neutral density velocity distributions at three radial positions in the tank for the same flow and geometry as in the density flow velocity experiments shown in Figure (9). A sketch of the hydraulic behaviour of the ambient fluid and the moving internal hydraulic jump is presented in Figure (12) (based on video records and Figure (9)). Velocity profiles sketched in Figure (12) show three types of flows associated with the moving internal hydraulic jump: the denser radial wall jet with relatively strong entrainment of ambient fluid, the travelling radial hydraulic jump which is characterized by a roller or reverse flow in its upper zone, and a positive surface flow influenced by withdrawal of displaced water over the effluent weir.

The velocity measurements close to the baffle for the jet phase (Figure (9)) show that most of the entrainment takes place in the jet phase or upstream of the baffle; a typical velocity profile close to the gate is given by Figure (12). The entrainment is reflected in the increased reverse flow in relation to the strength of the bottom current. The entrainment coefficient shown in Figure (10) also confirm that entrainment is greatest near the baffle.

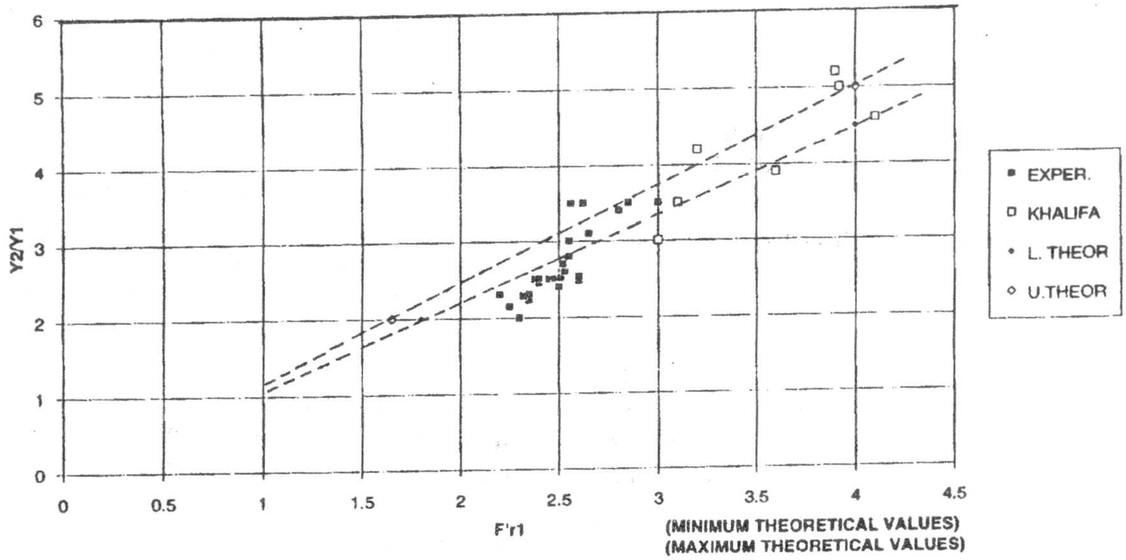


Figure 13. Comparison between the experimental and theoretical results.

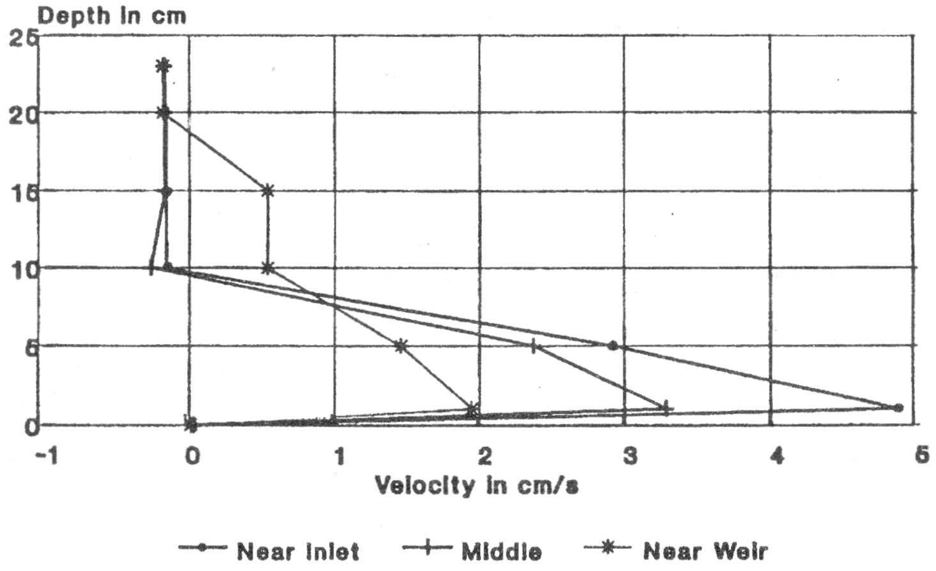


Figure 14. Velocity profiles for neutral density Q=0.5/S, G=5 CM, hw=23 cm.

The internal jump had a relatively stable interface, i.e. there was low mixing with the ambient fluid above it. The internal jump had a weak roller or reverse flow in its upper zone. The velocity gradients in the roller were small and apparently not strong enough to produce a sufficiently turbulent interface to overcome the stabilizing density gradients and entrain the ambient flow. Typical maximum reverse velocities measured in the jump phase were from 0.5cm/s to 2.0cm/s (or V_R/V_G from 0.13 to 0.20, where V_R is the velocity of the reverse flow, and V_G is the initial velocity of the jet at the baffle). The velocities in the surface layer at the jump location were similar in magnitude to those in the reverse flow region (internal hydraulic jump) as indicated in Figure (9).

The experimental flow patterns observed close to the weir were similar to the velocity distribution at the jump location, except near the surface where the velocity was dominated by the withdrawal by the weir. The three-dimensional eddies and water surface curvature produced by the presence of the effluent weir influence the velocity in the surface layer in the withdrawal zone. In the withdrawal zone, the bottom current gradually loses its momentum but in the upper layer the flow near the effluent weir is accelerated. The three layer flow pattern persists after the submergence of the hydraulic jump at the baffle. The length of the roller of the submerged radial hydraulic jump (phase 4, regime v) occupied the whole length of the settling zone and part of the withdrawal zone typical reverse flows close to the weir had velocities from 0.05 cm/s (orV_R/V_G from 0.10 to 0.18, where VR is the velocity of the reverse flow region).

CONCLUSION

In this paper, the internal flow regimes associated with transient density currents due to diurnal heat loading in a radial sedimentation tank were examined. From the experimental analysis conducted on the denser wall jet, the internal hydraulic jump and the velocity fields, the following conclusions can be drawn:

1. The entrainment coefficient of the initial denser jet decreased as radial position increased (see Figure (10)). This can be attributed to the stable density difference between the jet and the ambient fluids which dampens the vertical mixing; this damping is less effective in the inlet zone where this flow has a significant downstream component.
2. In the case of a large opening under the baffle with low densimetric Froude Number, there is a large amount of entrainment upstream of the baffle. It was found that the highest value of the entrainment coefficient occurs close to the beginning of the jet for low flows with large openings below the baffle. This phenomenon is important because it results in an increase in the bottom density current, greater

recirculation and possibly increased upward currents in the effluent zone.

3. The moving internal hydraulic jump surface was fairly smooth with no evidence of strong interfacial mixing which is consistent with the characteristics of hydraulic jumps for Froude Numbers less than 3.5. As the surge moved upstream (towards the baffle), the sequent depth, y_2, and the surge velocity, V_s, were observed to decrease;
4. The length of the internal hydraulic jump, L_j, was found to be almost constant for the range of test conditions;
5. The sequent depth ratio of the jump versus relative densimetric Froude number was generally lower than that predicted by the radial hydraulic jump theory of Khalifa and McCorquodale [1992];
6. The existence of density gradients has a pronounced effect on the flow pattern in the clarifier. It was found that the velocity profiles driven by density gradients were significantly different from those of neutral density flow. The maximum velocity of the bottom current with density flow was about 30% higher than the neutral case, while the initial depth of the jet was 10% less. Also, the maximum velocity of the reverse flow was more about 100% higher for density flow than for neutral density flow.

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