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DENSITY CURRENTS IN RECTANGULAR SETTLING TANKS

by

Anna Marie Godo
B.A.Sc.

A thesis
Submitted to the Faculty of Graduate Studies through the Department of Civil and Environmental Engineering in Partial Fulfilment of the Requirements for the Degree of Master of Applied Science at the University of Windsor

Windsor, Ontario, Canada

1990
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This work is dedicated to the memory of my father,

the late Emil F. Godo,

and to my mother,

Mary A. Godo.
ABSTRACT

In this thesis, the density currents in a rectangular sedimentation tank are investigated. Experimental studies were made of the flow under different conditions of geometry, momentum and buoyancy. A mathematical model was developed to simulate the characteristics associated with the denser wall jet condition.

The experimental program involved temperature tests, flow visualization dye tests and fluorescent dye tests. The variables in the experiments were flowrate, gate opening, weir height, ambient fluid temperature and influent temperatures in the initial tank. Both denser wall jet and buoyant surface jet conditions were considered. The characteristic depths, velocity and temperature of the jet and moving internal hydraulic jump were determined.

The mathematical model developed was divided into two parts: a jet submodel and a moving internal hydraulic jump submodel. An equation was developed to relate the submerged depth to the initial depth and sequent depth of the submerged internal hydraulic jump.

The mathematical model results are compared with the experimental data for the jet, moving internal hydraulic jump and the submerged hydraulic jump.
ACKNOWLEDGMENTS

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1. INTRODUCTION

1.1. OBJECTIVE

The objective of this thesis is to study density currents in a rectangular sedimentation tank. To achieve this, experimental studies of the flow under different conditions of geometry, momentum and buoyancy were necessary. A mathematical model to simulate the characteristics associated with the denser wall jet condition was also developed.

1.2. APPLICABILITY

Sedimentation is a common process in the treatment of water and wastewater. A diurnal temperature variation in the influent at the West Windsor Pollution Control Plant has been observed. Density currents can develop density gradients resulting from temperature differences and/or differences in concentration of suspended solids; these density currents may affect the efficiency of the sedimentation tank.

In a two phase mixture, such as water and suspended solids flowing under relatively quiescent conditions, the solids, having a higher specific weight than that of the liquid, will tend to settle due to gravitational effects. Sedimentation is used to remove particulate matter, flocculated impurities and precipitates which are formed in
water treatment operations such as coagulation, water softening and iron removal. In wastewater treatment, sedimentation is used in grit chambers, particulate matter removal in primary clarifiers and biological floc removal in secondary settling tanks.

Sedimentation is affected by the characteristics of the solid and liquid phases and the hydraulic conditions within the clarifier. The suspension is described by the physical and chemical characteristics of the liquid phase and the solids phase. The significant characteristics of the liquid phase are temperature, density and viscosity. The characteristics of the solids phase are particle size distribution, density, shape and concentration. The influent concentration of solids and their flocculant characteristics influences the settling velocity of the suspended matter. Factors imposed by field conditions such as wind effects, flow variability and the temperature difference between the tank inflow and the ambient air temperature should be considered when designing the clarifier.

The process is affected by the physical and chemical characteristics of the liquid phase and the solids phase. The influent concentration of solids and their flocculant characteristics also influence the settling velocity of the suspended matter.
1.3. METHODOLOGY

In the project reported here, the hydrodynamics of rectangular sedimentation tanks under stratified conditions are investigated in a physical model for different tank configurations. A total of seven tank configurations and flow conditions were tested. These included both denser wall jet and buoyant surface jet conditions. The data were collected during temperature tests, photographic dye tests and fluorescent dye tests. Estimates of jet depth, velocity and moving hydraulic jump sequent depths, surge velocity and temperature were made. Estimates of submerged hydraulic jump sequent depths and temperature were also made.

A computer model was developed for the denser wall jet case. This model is comprised of a jet submodel and a moving hydraulic jump submodel. Calibration and verification of the model were made using the experimental data collected in the physical model.
2. LITERATURE REVIEW

2.1. INTRODUCTION

The term stratified flow characterizes fluid motions in a gravitational field which are originated or influenced by variations in density within the fluid. The conventional usage refers to the motion of fluid masses of the same state. Therefore a heavier fluid flowing beneath a lighter one will be subjected to gravitational effects which depend upon the difference between the two specific weights rather than upon the absolute magnitude of the specific weight of the heavier fluid [Harleman, 1960]. According to Harleman [1960], the less dense fluid is considered as weightless and the more dense fluid is considered to be subjected to a modified gravitational acceleration, \( g' \), where

\[
g' = g \frac{\Delta \rho}{\rho}
\]

in which \( \Delta \rho \) is a typical density difference of the two layers. In two-layered stable flow systems, the denser fluid always tends to occupy the lowest position. For analysis, the interface is assumed to be a streamline separating the two fluids and coincident with the density discontinuity and represents the velocity discontinuity.

Long [1953,1954,1959] suggested that the study of fluids with stable density variation have universal applications. Examining the ionosphere, he described it
using equations of motion for a fluid, which are identical to those for a perfect gas if the gas is steady, frictionless, nonconductive, nonradiating and two-dimensional. The ratio of the inertial force to the buoyancy force of gravity is represented by the internal, or densimetric, Froude number, \( F' \), where

\[
F'^2 = \frac{U^2}{g' L}
\]

in which

\[
U = \text{the velocity}
\]

\[
L = \text{the length}
\]

The inverse of the square of the densimetric Froude number is the definition of the Richardson number. Long considered a general theoretical analysis of a two-dimensional flow of a stratified liquid in a gravity field [1953] and conducted an experimental investigation with a two fluid system [1954].

Chu and Baddour [1977] considered a two layer system and applied the general concepts of specific energy, \( E \), specific force, \( M \) and specific buoyancy, \( F \), to a two-layer stratified system. For a two layer system,

\[
e = \frac{E}{\rho} = \left( \frac{1}{2} u_1^2 + \frac{p_2}{\rho} + g' h_1 \right) u_1 h_1 + \left( \frac{1}{2} u_2^2 + \frac{p_2}{\rho} \right) u_2 h_2
\]

\[
m = \frac{M}{\rho} = u_1^2 h_1 + u_2^2 h_2 + \frac{1}{2} g' h_1^2 + \frac{p_2 h}{\rho}
\]
\[ (2.5) \quad f = \frac{F}{b} = g' \ u_1 \ h_1 \]

in which

- \( b \) = the width of the system
- \( u_1 \) = the velocity of the lower layer
- \( u_2 \) = the velocity of the upper layer
- \( h_1 \) = the depth of the lower layer
- \( h_2 \) = the depth of the upper layer
- \( h = h_1 + h_2 \)
- \( \rho \) = the density of the fluid
- \( \Delta \gamma \) = the specific weight in excess of the value in the upper layer
- \( g' = \) the reduced gravity
  \[ = \Delta \gamma \rho \]
- \( p_2 \) = the excess pressure in the upper layer

2.2. JETS, PLUMES AND ENTRAINMENT

Jets and plumes are examples of free flows. In turbulent jets and plumes, the turbulent region grows with distance downstream as the non-turbulent fluid becomes entrained in it. This entrainment implies a flow of ambient fluid into the turbulent layer. A fluid motion is considered to be a jet if its primary source of kinetic energy and momentum flux is a pressure drop through an orifice and a plume if that source is body forces [Rodi, 1982]. The transition from a jet to a plume is referred to
as a forced plume or buoyant jet.

2.2.1. JETS

Hayashi and Shuto [1967] conducted experiments of the spreading and diffusion of warm water jets discharged horizontally at the surface of an initially quiescent water body. In their experiments the temperature of the discharged water was 0.2 to 28 °C higher than the receiving water; the densimetric Froude number was in the range of 16.1 to 1.4, and the Richardson number was in the range of 0.00 to 0.54.

Koh [1971] investigated the mixing and dispersion of a two-dimensional surface buoyant jet discharged horizontally into a stagnant environment. Unlike the case of a submerged buoyant jet or a surface non-buoyant jet, the source characteristics are not the only dominant governing parameter. The downstream condition played an important role. His investigation dealt with an infinite ambient fluid. The surface heat exchange mechanism replaced the necessary downstream condition. The relative magnitudes of Froude number, Reynolds number and dimensionless surface heat exchange coefficient played a role in detailed quantitative description and classification of the flow field.

Rajaratnam and Subramanyan [1986a] studied plane
surface jet of warm water with thickness $b_0$, of almost uniform velocity, $U_0$, and density, $\rho_0$, entering a rectangular channel of width $B$, into a large depth of stagnant cold water with density $\rho_a$. The Reynolds number was large and the flow in the surface jet became turbulent very quickly. The Richardson number at the source was in the range of 0.0002 to 0.7 and was given as

$$\text{(2.6)} \quad Ri_0 = \frac{g b_0 \Delta \rho_0 / \rho_a}{U_0^2}$$

where

$$\text{(2.7)} \quad \Delta \rho_0 = (\rho_a - \rho_0)$$

In the experiment, four possible situations occurred as illustrated in Fig. 2.1 and a diagram which predicted when a surface jet, surface jet followed by surface jump, surface jump and drowned jump formed as a function of Richardson number and the ratio of the asymptotic value of the thickness of the surface jet, $\bar{b}_m$, and the gate opening, $b_0$. The surface jet grew in thickness like a non-bouyant surface jet. The surface jet with hydraulic jump grew in thickness for some longitudinal distance and then became either a stratified surface layer or formed a surface jump. If the surface jet was non-bouyant, the Richardson number was zero and the depth of the jet grew linearly with distance. For bouyant surface jets, if Richardson number was small, the surface jet grew in thickness initially linearly and then $\frac{db}{dx}$
continued to decrease due to the reduced entrainment of the ambient fluid. The thickness of the jet became approximately constant at the cessation of the ambient fluid entrainment. For a non-buoyant surface jet, the limiting curve of the thickness at Richardson number equal to zero is
\[
\frac{\delta}{b_\infty} = 1.0 + 0.2 \left( \frac{x}{b_0} \right)
\]
in which
\( \delta \) = the jet thickness at the longitudinal distance \( x \) from the outfall
\( b_0 \) = the jet thickness at the outfall
The variation of \( \frac{\delta}{b_\infty} \) and \( \frac{x}{b_\infty} \) with Richardson number was described by the following equations which agreed reasonably well with the experimental results:
\[
\frac{\delta}{b_\infty} = 1.02 \, \text{Ri}_0^{-0.36}
\]
and
\[
\frac{x}{b_\infty} = 80 - 65 \log \text{Ri}_0
\]
in which
\( \delta_\infty \) = the asymptotic value reached by the jet for large \( x \) distance
\( x_\infty \) = the \( x \) distance where \( \delta_\infty \) is attained

Rajaratnam and Subramanyan (1988b) also studied plane turbulent denser wall jets. The main difference between the buoyant surface jet and the denser wall jet appeared to be
the existence of skin-friction in the denser wall jet case. Also the presence of the free-surface for the surface jets allowed for direct buoyancy adjustments. The Richardson number was in the range of 0.02 to 0.2 and was given by Eq. 2.6. Data points followed a straight line for non-buoyant plane turbulent wall jet up to some value of \( x \) beyond which the rate of growth, \( \frac{d\delta}{dx} \), continued to decrease due to the reduced entrainment of the ambient fluid. The thickness of the jet became approximately constant at the cessation of the ambient fluid entrainment. The variation of \( \frac{\delta}{\delta_0} \) with Richardson number was described by the following equation which agreed reasonably well with the experimental results:

\[
(2.11) \quad \left( \frac{\delta}{\delta_0} \right)_\infty = 10.7 \, \text{Ri}_0^{-0.51}
\]

in which

\( \delta \infty = \) the asymptotic value reached by the jet for large \( x \) distance

\( x \infty = \) the \( x \) distance where \( \delta \infty \) is attained

Jirka and Harleman [1979] considered a plane turbulent buoyant jet discharging vertically into a two-dimensional channel of confined depth. Their analysis was aimed at the stability and bulk mixing characteristics of the discharge. The discharge stability was dependent on the interaction of three near-field regions (a buoyant jet region, a surface impingement region and a internal
hydraulic jump region). The jet was characterized by given flux of momentum, volume, buoyancy and mass of a conservative species.

2.2.2. PLUNES

Stefan [1972] conducted experiments designed to simulate heated water discharged from a channel into a deep lake or reservoir without allowing for lateral spreading. The walls of the experimental apparatus prohibited lateral mixing and lateral spreading. Only outlet flows which resulted in unstable interfaces and possibly turbulent mixing were studied. The flows had Reynolds numbers in the range of 40 to 2000. The mean water temperature in the upper layer was used to determine the amount of cold-water entrainment. The ratio of the flowrate of heated influent to flowrate after entrainment was

\[
\frac{q_i}{q_0} = \frac{T_0 - T_i}{T_1 - T_i}
\]

in which

- \( T_0 \) = temperature of heated water at outlet
- \( T_1 \) = temperature of heated water downstream from outlet after mixing
- \( T_i \) = temperature of cold water in tank
- \( q_i \) = flow rate of heated water per unit width downstream from the outlet after entrainment
\[ q_0 = \text{flow rate of heated water per unit width of flume} \]

Wallace and Wright [1984] examined a two-dimensional buoyant jet discharged vertically into a stratified fluid with no crossflow. Using a dimensional analysis, they predicted the location and concentration of the effluent as it began to spread horizontally from the jet axis. The gross characteristics studied were the maximum height of rise, \( Z_m \), the thickness of the spreading layer, \( h_s \), the thickness of the underlying layer, \( Z_a \), the minimum dilution of the effluent in the spreading layer, \( S_m \), and its vertical location, \( Z_s \). The fully turbulent jet issued from a slot of width, \( b_0 \), with velocity, \( w_0 \); density, \( \rho_0 \), and tracer concentration, \( c_0 \). Both the initial velocity and buoyant forces were directed vertically upward. The ambient fluid was assumed stagnant except for the motion induced by the buoyant jet. A linear density stratification was assumed so that the density profile was described by \( \rho_{a0} \) at elevation \( Z = 0 \) and a constant valued density gradient \( \frac{d\rho_a}{dz} \). The stratification parameter was defined as

\[ (2.13) \quad c = - \frac{g}{\rho_{a0}} \frac{d\rho_a}{dz} \]

The jet was characterized by

Volume flux:

\[ (2.14) \quad Q = w_0 b_0 \]

Kinematic momentum:

\[ (2.15) \quad M = w_0^2 b_0 \]
Kinematic buoyancy:

\[ B = g' Q \]  \hspace{1cm} (2.16)

Tracer:

\[ T = Q c_0 \]  \hspace{1cm} (2.17)

Length scales were defined as

\[ l_Q = Q^2 \frac{M}{g} \]  \hspace{1cm} (2.18)

\[ l_M = M \sqrt[2/3]{B} \]  \hspace{1cm} (2.19)

\[ l_{b'} = B^{1/3} \frac{1}{e^{1/2}} \]  \hspace{1cm} (2.20)

\[ l_{m'} = \left( \frac{M}{e} \right)^{1/3} \]  \hspace{1cm} (2.21)

For a pure plume

\[ \frac{l_M}{l_{b'}} = 0 \]  \hspace{1cm} (2.22)

and for a momentum jet

\[ \frac{l_M}{l_{b'}} \rightarrow \infty \]  \hspace{1cm} (2.23)

2.2.3. ENTRAINMENT

Entrainment was assumed to be proportional to the velocity of the layer multiplied by an empirical function of the overall Richardson number by Ellison and Turner [1959]. The velocity of the inflow into the turbulent region was proportional to the velocity of the scale of the layer. The proportionality constant is called the entrainment constant.
Ellison and Turner [1959] considered entrainment under steady state conditions in surface jets and inclined plumes.

Kantha, Phillips and Azad [1977] examined turbulent entrainment at the density interface of a stable two-layered stratified fluid. They found that the entrainment rate was a function of two variables: the Richardson number and the ratio of the depth of the mixed layer to the tank width. They worked with Richardson number in the range of 30 to 1000.

Christodoulou [1986] examined the phenomenon of turbulent mixing at a density interface. The interaction between layers is of considerable theoretical and practical importance. The interface hydrodynamic forcing was assumed to be transferred by means of interfacial shear. Turbulence within the layer was the dominant factor governing entrainment through the interface. When there was mean flow in at least one layer, the shear stability of the interface was also of primary importance. Vortex entrainment and cusp entrainment were two fundamental types of entrainment from a quiescent layer to a turbulent layer that were distinguished. Vortex entrainment occurred for relatively low stability of the interface and was associated with a small overall Richardson number. Cusp entrainment formed for higher Richardson numbers. Four governing laws, all of power form and applicable in different ranges of overall
Richardson number, $Ri_0$, were identified. These laws are generally valid in flows with mean motion in at least one layer. An intermediate expression for the rate of entrainment for Richardson number in the range of 0.1 to 10 where both entrainment mechanisms seem to coexist was given by

$$\frac{\nu_{ij}}{V_i} = 0.002 Ri_0^{-1}$$

in which

- $\nu_{ij} = \text{interfacial transport rate from layer j to layer i}$
- $V_i = \text{mean velocity of layer i}$
- $Ri_0 = \text{overall Richardson number}$

For the non-buoyant surface jet, the entrainment coefficient is a constant. Arita, Jirka and Tamai (1986) suggested that for the buoyant surface jet, the entrainment coefficient with the increasing influence of buoyancy force along the jet path must be based on experimental data or estimated from a theoretical approach that evaluated the stability of buoyant shear flows. They used an entrainment coefficient, $\alpha_m$, based on mean velocity,

$$\alpha_m = \alpha_{m0} \left[ 1 - \frac{1}{\sqrt{1 + \frac{6.5 Ri_{im}^2}{Ri_{im}^2}}} \right]$$

or an alternative experimental formulation

$$\alpha_m = \alpha_{m0} e^{-3.3 Ri_{im}}$$
in which

\[ \alpha_{\infty} = \text{the entrainment coefficient for neutral (non-buoyant) conditions} \]

\[ R_{im} = \text{the Richardson number based upon mean velocity in the buoyant jet} \]

\[ R_{ic} = \text{the critical value of a shear layer gradient Richardson number} \]

Baddour and Chu [1975] simulated a saline horizontal buoyant surface discharge on a step and sloping bottom. The global turbulent entrainment into the surface layer was determined for the jet and was dependent on the upstream and downstream conditions. Several conditions (a fully entrained jet, a fully developed jet followed by an internal jump, a not fully developed jet followed by an internal jump, a jet semi-flooded by an internal jump and a jet flooded by an internal jump) were examined. The overall entrainment rate was given by

\[
Q_e \frac{Q_0}{Q_0} = \left( \frac{F'}{F_0} \right)^{4/3} \left[ \frac{2}{2 \left( \frac{F'}{F_0} \right)^2 + 1} \right] - 1
\]

in which

\[ Q_e = \text{the overall entrainment rate} \]

\[ Q_0 = \text{the volume flux at the exit} \]

\[ F' = \text{the densimetric Froude number at the downstream section} \]
$F_0'$ = the densimetric Froude number at the upstream section (the exit)

There was good agreement between the theory and experiment for Eq. 2.27, except when the jet was flooded by an internal hydraulic jump. An empirical relation for the overall entrainment rate of the jet under a semi-flooded condition is given by

$$\frac{Q_e^*}{Q_0} \approx 0.029 F_0'$$

in which

$Q_e^*$ = the overall entrainment rate for a semi-flooded condition

2.3. INTERNAL HYDRAULIC JUMPS

The internal hydraulic jump is analogous to the well documented hydraulic jump which occurs in a single-layer flow at a fluid/air interface. An internal hydraulic jump occurs when a heavy fluid flows under a lighter fluid, or when a lighter fluid flows over a heavy fluid at a supercritical velocity [McCorquodale, 1986], if

1. the densimetric Froude number exceeds unity
2. the sequent depth condition is satisfied
3. the jump is stable.

Yih and Guha [1955] considered internal hydraulic jumps in immiscible fluids. Jumps created by underflows and
overflows were analyzed. In experimental studies, three cases were considered (normal hydraulic jump, inverted hydraulic jump, and non-stationary hydraulic jump or surge). They derived two equations analogous to the classical hydraulic jump equation using the principle of momentum balance. The equations may be written as

\[ (2.29) \quad 2 F_2^2 h_2^2 (h_2 - h_2') = h_2' (h_2 + h_2') \left[ r (h_1 - h_1') + (h_2 - h_2') \right] \]

and

\[ (2.30) \quad 2 F_1^2 h_1^2 (h_1 - h_1') = h_1' (h_1 + h_1') \left[ r (h_1 - h_1') + (h_2 - h_2') \right] \]

for the upper layer and lower layer respectively. Four possible real and positive solutions including a trivial solution corresponding to the original state exist. If the densimetric Froude number of either layer is predominantly large, there is only one conjugate state.

Hayakawa [1970] proposed a solution to the problem of finding the region where the momentum equations developed by Yih and Guha [1955] have real and positive solutions and satisfy the energy constraints put upon a hydraulic jump. He suggested that if only one layer is moving, an internal hydraulic jump occurs in the upper layer if

\[ (2.31) \quad 1 < F_{1i}^2 < F_{1c}^2 (K) \]
and occurs in the lower layer if

\begin{align}
(2.32) \quad 1 < F_{21}^2 < F_{ic}^2 \left( \frac{r}{K} \right)
\end{align}

where

\begin{align}
F_{11}^2 = \text{the internal, or densimetric, Froude number of the upper layer}
\end{align}

\begin{align}
F_{21}^2 = \text{the internal, or densimetric, Froude number of the lower layer}
\end{align}

and where \( F_{ic}^2(x) \) is a function of \( x \) and

\begin{align}
(2.33) \quad F_{ic}^2(K) = \frac{1}{8} \left[ 3 - \frac{2}{K} \right]^2 - \frac{1}{8}
\end{align}

and

\begin{align}
(2.34) \quad F_{ic}^2 \left( \frac{r}{K} \right) = \frac{1}{8} \left[ 3 - \frac{2}{r} \right]^2 - \frac{1}{8}
\end{align}

Baddour and Abbink [1982,1987] studied a stable density stratification. Experiments were carried out in a channel of limited depth, with density currents induced by a salt solution with density differences of 0.004 \( \rho_2 \) to 0.03 \( \rho_2 \), where the underflow established a drowned internal jump, a free internal jump or a flow instability, depending on the nature of the interaction between the upstream and downstream conditions. Their densimetric Froude number ranged from 3 to 21, Reynolds numbers from 3100 to 8500 and confinement depth ratio from 15 to 30. The governing equations for the system were summarized as follows:
Momentum:

\[ 2 F_1^2 S \left[ \frac{S^2}{R^2} + \left( \frac{S - 1}{H - R} \right) \left( \frac{H}{R} - R \right) - 1 \right] = S - R^2 \]

Energy:

\[ R + \frac{1}{2} F_1^2 S \left[ \left( \frac{S}{R} \right)^2 - \left( \frac{S - 1}{H - R} \right)^2 \right] = y_c + \frac{F_1^2}{2 \beta^2} \left[ (S y_c)^2 - \left( \frac{S - 1}{H - y_c} \right)^2 \right] \]

Conjugate depth:

\[ 0 \leq R \leq H \]

Energy loss:

\[ \Delta E_j \geq 0 \]

Subcritical region:

\[ F_1^2 S \left[ \frac{S^2}{R^3} + \frac{(S - 1)^2}{(H - R)^3} \right] \leq 1 \]

where

\[ R = \frac{y_2}{y_1}, \]
\[ S = \frac{q_2}{q_1}, \]
\[ H = \frac{h_1}{y_1}, \]
\[ y_c = \frac{y_c}{y_1}, \]
\[ \beta = \text{the contraction ratio at the critical control section}. \]

The turbulent mixing induced by a free internal jump was found to be a maximum when the exit densimetric Froude number was equal to an optimum value for a confinement depth.
The optimum densimetric Froude number was

\[(2.40) \quad F_0 = \frac{U_0}{(g' h_0^{0.5})^{0.5}} \approx \frac{S}{H^3} \]

where

\[ H = \frac{h}{h_0} = \text{the confinement depth ratio} \]

When the densimetric Froude number was less than the optimum value, hydraulic and turbulent mixing properties were found to be essentially unaffected by the limited ambient depth. For densimetric Froude numbers exceeding the optimum value, the limited ambient depth had noticeable effects and turbulent mixing reduced as the Froude number increased. When

\[(2.41) \quad F_0 > \frac{H}{\sqrt{2}} \]

an instability of flow occurred in which the internal jump contacted directly with the confining boundary and turbulent mixing was reduced significantly.

Powley [1987] investigated three rectangular denser internal hydraulic jumps (free, submerged and submerged jump on sloping bed). In the free rectangular jump, with densimetric Froude numbers ranging from 2 to 12, it was found that the maximum positive deviation of the sequent depth ratio from the classical hydraulic jump equation was 20 percent, and that there was hardly any entrainment along the length of the jump. The submerged internal hydraulic
jump looked very similar to the submerged open channel jump. The integral momentum equation predicted the vertical length scale and longitudinal characteristic lengths reasonably well.

On the basis of specific force conservation, Arita, Jirka and Tamai (1986) examined a two-dimensional surface discharge over a stagnant ambient fluid of two miscible fluids. Different transition paths were observed between supercritical upstream conditions and imposed subcritical downstream conditions. The transitions were classified into four regimes: a fully entraining buoyant jet, a jet and jump combination, a direct jump and a flooded, or drowned, jump. With a fully entraining buoyant jet, the jet flow is constantly increased due to turbulent entrainment while the depth grew and ultimately, a critical condition of maximum flow was reached. In the jet and jump combination, the buoyant jet was followed by a hydraulic jump region with a roller formation and elimination of further entrainment. In the direct jump, the starting point of the jump coincided with the discharge outlet and no mixing took place. With the flooded jump, the externally imposed downstream conditions did not satisfy the specific force conservation and the flow at the outlet becomes drowned with no net entrainment. The basic equations engaged were the conservation of buoyancy flux, \( P(x) \), at any position in the
flow

\[(2.42) \quad P(\cdot) = \frac{I_2}{I_1} \frac{\Delta \rho}{\rho_a} g q = \frac{\Delta \rho}{\rho_a} = P_0 \]

and the conservation of specific force, \( \mathbf{KxO} \),

\[(2.43) \quad \mathbf{KxO} = \frac{I_2}{I_2} \frac{q^2}{h^2} + \frac{I_1}{I_4} \frac{P}{Q} h^2 = \frac{q_0^2}{h_0} + \frac{P_0}{d_0} h_0^2 = M_0 \]

in which the constants \( I_1, I_2, I_3 \) and \( I_4 \) are of an integral form. The comparison between the theory and data by Arita, Jirka and Tamai [1986] and by Rajaratnam and Subramanyan [1986a] for the jet and jump combination on a non-dimensional diagram of upper layer depth, \( h_\infty \), and flow rate, \( q_\infty \), scale show excellent agreement with the supercritical initial stage, and the data by Arita, Jirka and Tamai [1986] show a complete approach to the subcritical branch on a \( h_\infty - q_\infty \) diagram.

Rajaratnam and Subramanyan [1986a, 1986b] considered both the case of buoyant surface jets and jumps and denser wall jets and jumps. An experimental study of plane turbulent buoyant surface jets and jumps by Rajaratnam and Subramanyan [1986a] yielded a definition of where the surface jet stopped and the surface jump began. The beginning of the jump was located at the section at which entrainment stopped and reverse flow started. The conjugate depth ratio is related by the classical hydraulic jump equation. A diagram predicted when a surface jet, surface
jet followed by surface jump, surface jump and drowned jump formed as a function of Richardson number and the ratio of the asymptotic value of the thickness of the surface jet, $\overline{b}_\infty$, and the gate opening, $b_0$. The dimensionless surface profile of the surface jump was found to be the same as that of the more familiar open channel hydraulic jump.

A density jump in miscible fluids controlled by a broad crested weir with the upper layer flowing over a lower stationary layer was examined by Wilkinson and Wood [1971]. A density jump is generally accompanied by a change in density of the flowing layer. The fundamental difference between the hydraulic jump and the density jump is that flow conditions on either side of the density jump are not uniquely related. Density jumps with given upstream flow conditions have a range of possible states. The density jump was divided into two distinct zones; the entrainment zone and the roller region. Nearly all entrainment took place in the entrainment zone and the roller region was characterized by flow near the interface in the reverse direction of the main flow. For the density jump, two different values of downstream layer, or densimetric, Froude numbers satisfied the equation of motion. Physical arguments made showed that only the upper value of the densimetric Froude number was a stable flow state. The downstream densimetric Froude number was a single valued
function of the control parameters and the upstream
densimetric Froude number.

Rajaratnam and Subramanyan (1986b) found for a given
discharge with a given thickness of $b_0$ and $R_i_0$, depending
upon the depth of the stratified layer far downstream, either
a wall jet, a wall jet followed by a wall jump, a wall jump,
or a drowned wall jump formed. A diagram to predict the
growth of the wall jet and jump was developed.

2.4. TRAVELLING HYDRAULIC JUMPS IN ONE-PHASE FLOW

In rapidly varied unsteady flow, any change in stage
from subcritical to supercritical flow results in a moving
hydraulic jump according to Chow (1959). The term "moving
hydraulic jump" is used synonymously with "surge" and
"hydraulic bore". The term "surge" refers to a moving
hydraulic jump due to an abrupt decrease or increase in
flow, such as the sudden closing or opening of a gate. The
term "hydraulic bore" refers to a moving hydraulic jump due
to tidal effects.

Moving hydraulic jumps are either positive or negative
surges. In positive surges, the water surface is elevated
and the surge advances with a stable front upstream, such as
in the case of the Johnstown flood of 1889, or downstream,
as in the case of tidal rivers. In negative surges, the
water surface is depressed and the surge retreats with an
unstable front upstream, as in the case of closing the head
gate in a canal, or downstream, as in the case where the
demand is suddenly increased at the lower end of a power
canal.

If the classical hydraulic jump equation based on the
conservation of momentum principle for a stationary
hydraulic jump is reduced to

\[
(2.44) \quad v_1 = \sqrt{\frac{g \cdot y_2}{\frac{1}{2} \cdot y_1}} (y_1 + y_2)
\]

then in terms of the relative velocity, Eq. 2.44 becomes

\[
(2.45) \quad v_1 + v_w = \sqrt{\frac{g \cdot y_2}{\frac{1}{2} \cdot y_1}} (y_1 + y_2)
\]

in which

\[v_w \quad \text{the velocity of the wave}\]

and the velocity of the wave may be represented by

\[
(2.46) \quad v_w = \sqrt{\frac{g \cdot y_2}{\frac{1}{2} \cdot y_1}} (y_1 + y_2) - v_1
\]

2.5. TRAVELLING INTERNAL HYDRAULIC JUMPS IN TWO-PHASE FLOW

Internal hydraulic jumps are associated with the
transition of surface to bottom (or vice versa) density
currents. McCorquodale [1987] examined density currents due
to diurnal heat loading in a radial sedimentation tank. The
models used in the study were a 1:19 scale model of a
centre-fed circular clarifier with a rotating scraper and a sector model with a scale of 1:10.2.

In physical model studies, a steady neutral density condition was established, and under the same flow, the influent temperature was changed rapidly. A travelling radial internal hydraulic jump was induced by both types of density currents.

The centre-fed circular clarifier was used to investigate flow through curves with fluorescent dye for neutral, buoyant and heavy density conditions. Preliminary indications were that the scraper significantly disturbed the bottom density current.

In the sector model, the internal flow structure was observed with dye injected in the influent to permit flow visualization. Both the conditions of warm ambient with cool influent and warm influent with cool ambient were considered. The differences between the surface and bottom density current hydrodynamics were that the buoyant plume resulted in greater short circuiting of the influent to the effluent weir than the bottom density current and that the initial entrainment was higher for the surface current.
3. THEORY

3.1. INTRODUCTION

The phenomenon in the rectangular basin were divided into three parts for the purpose of modelling:

1. the denser wall jet,
2. the moving internal hydraulic jump,
3. the submerged internal hydraulic jump.

Systems of non-linear ordinary differential equations were developed to describe the jet and moving internal hydraulic jump. These equations were solved by the Runge-Kutta method. The submerged internal hydraulic jump equation was solved directly using data predicted from the jet and moving internal hydraulic jump submodels.

3.1.1. ASSUMPTIONS

The following assumptions were made in the development of the equations:

1. the liquid is incompressible,
2. steady state conditions apply for the wall jet,
3. two-dimensional flow applies for the wall jet,
4. unsteady state conditions apply for the moving internal hydraulic jump,
5. kinetic energy correction factor, $\alpha_1$, is unity,
6. momentum coefficient, $\beta$, is unity,
7. thermal correction factor, $\sigma$, is 0.01.

8. entrainment coefficient, $a$, is $\frac{0.002}{\text{RI}}$ [Christodoulou, 1986].

9. the momentum of entrained fluid is negligible.

3.1.2. TEMPERATURE-DENSITY STATE EQUATION

It was necessary to obtain a state equation to describe the relationship between the temperature and the density of water to enable the variable density, $\rho$, to be expressed as a function of temperature, $T$. Tabulated values of the temperature of water and its corresponding density are listed in Table 3.1. A third degree polynomial equation was found using a least-squares curve fitting method [James, Smith and Wolford, 1977] to express density as a function of temperature for the data in Table 3.1. This resulted in the following relationship:

$$\rho = C_0 + C_1 T + C_2 T^2 + C_3 T^3$$

in which

\begin{align*}
C_0 &= +1.00001557 \times 10^3 \\
C_1 &= +1.910871 \times 10^{-2} \\
C_2 &= -5.91523612 \times 10^{-3} \\
C_3 &= +1.58955438 \times 10^{-5}
\end{align*}

and where the units of density are kg/m$^3$ and the units of temperature are °C. By differentiating Eq. 3.1 with respect to temperature, the resulting equation is
\[
\frac{dp}{dT} = c_1 + 2c_2 T + 3c_3 T^2
\]

\[
= c_T
\]

3.2. THE RECTANGULAR DENSER WALL JET SUBMODEL

In deriving a system of equations to describe the denser wall jet, the principles of the conservation of mass, the conservation of momentum and the conservation of energy were applied between two sections of the denser wall jet as shown in Figure 3.1. A system of non-linear ordinary differential equations were developed and were solved by the Runge-Kutta method. The equations developed were the mass balance equation, the momentum equation, the thermal mass balance equation and the energy (modified Bernoulli) equation.

3.2.1. THE MASS BALANCE EQUATION

The mass balance equation was obtained by applying the continuity equation to the element of the jet shown in Figure 3.1. This equation is

\[
(3.3) \quad \rho_1 Q_1 + \rho_0 \Delta Q_e = \rho_2 Q_2
\]

in which

\[
\rho_1 = \text{the density at section 1}
\]

\[
Q_1 = \text{the discharge at section 1}
\]

\[
(3.4) \quad = \gamma_1 V_1 b
\]

\[
\rho_2 = \text{the density at section 2}
\]
\[ Q_2 = \rho_1 \frac{dp}{dx} \, dx \]
\[ Q_2 = \text{the discharge at section 2} \]

\[ Q_0 = y_2 V_2 \, b \]
\[ Q_0 = \text{the density of the ambient fluid} \]
\[ \Delta Q_e = \alpha (V_1 - V_0) \, b \, dx \]
\[ V_0 = \text{the discharge entrained by the jet} \]
\[ V_0 = \text{the velocity of the ambient fluid} \]
\[ \approx 0 \]

The substitution of Eq. 3.4, 3.6 and 3.7 in Eq. 3.3 leads to Eq. 3.8, in which the width of the tank, \( b \), was factored from the equation, i.e.

\[ \rho_1 y_1 V_1 + \alpha \rho_0 V_1 \, dx = \rho_2 y_2 V_2 \]

where

\[ V_2 = \text{the velocity at section 2} \]
\[ y_2 = \text{the depth at section 2} \]

\[ \frac{dy}{dx} \]
\[ \frac{dy}{dx} \]

The substitution and expansion of Eq. 3.5, 3.9 and 3.10 into Eq. 3.8 leads to Eq. 3.11, where the second degree differential terms were neglected since \((du)^2 \ll (du)\).

\[ \alpha \rho_0 V_1 \, dx = \rho_1 y_1 \frac{dy}{dx} \, dx + y_1 V_1 \frac{dp}{dx} \, dx \]

\[ + \rho_1 y_1 \frac{dV}{dx} \, dx \]

Since,

\[ \frac{dp}{dx} = \frac{dp}{dT} \frac{dT}{dx} \]
the substitution of Eq. 3.12 and 3.2 into Eq. 3.11 results
in
\begin{equation}
(3.13) \quad \alpha \rho_0 \ n_1 = \rho_1 \ n_1 \ \frac{dy}{dx} + c_T \ n_1 \ \frac{dT}{dx} + \rho_1 \ n_1 \ \frac{dV}{dx}
\end{equation}

which can be expressed in the form

\begin{equation}
(3.14) \quad A_1 \ \frac{dy}{dx} + c_T \ A_2 \ \frac{dT}{dx} + A_3 \ \frac{dV}{dx} = B_1
\end{equation}

\begin{align*}
A_1 &= \rho_1 \ n_1 \\
A_2 &= y_1 \ n_1 \\
A_3 &= \rho_1 \ n_1 \\
B_1 &= \alpha \rho_0 \ n_1 \\
C_T &= c_1 + 2 \ c_2 \ T + 3 \ c_3 \ T^2 \quad \text{(Eq. 3.2)}
\end{align*}

3.2.2. THE MOMENTUM EQUATION

The momentum equation was obtained by applying the
momentum balance to the element of the jet shown in Figure
3.1, as follows:

\begin{equation}
(3.15) \quad \Sigma F_x = \Delta \left( \beta \rho V Q \right)
\end{equation}

or

\begin{equation}
(3.16) \quad P_1 - P_2 - F_f = \rho_2 V_2 q_2 - \rho_1 V_1 q_1
\end{equation}
in which

\begin{align*}
P_1 &= \text{the hydrostatic pressure force per unit width} \\
&\quad \text{at section 1} \\
(3.17) &= \frac{1}{2} g \Delta \rho_1 y_1^2
\end{align*}
\[ P_2 = \text{the hydrostatic pressure force per unit width at section 2} \]
\[ P_2 = \frac{1}{2} g \Delta \rho_2 y_2^2 \]
\[ = \frac{1}{2} g \left( \rho_1 + \frac{d\rho}{dx} \right) \left( y_1 + \frac{dy}{dx} dx \right)^2 \]

\( F_f \) = the frictional force per unit width on the bed
\[ (3.19) \quad = \tau dx \]

\( q_2 \) = the discharge per unit width of the fluid at section 2
\[ (3.20) \quad = q_1 + \Delta q_e \]
\[ = y_1 V_1 + \alpha V_1 dx \]

\( g \) = the acceleration due to gravity

\( \Delta \rho_1 = (\rho_1 - \rho_0) \)
\[ (3.21) \quad \Delta \rho_2 = (\rho_2 - \rho_0) \]

An equation for shear at the bed was suggested by Schlichting [1958]

\[ (3.22) \quad \tau = 0.0225 \rho U_m 1.75 \left( \frac{\nu}{y} \right) 0.25 \]

in which

\( \tau \) = the shear stress at the bed
\( \rho \) = the density
\( U_m \) = the maximum velocity
\( \nu \) = kinematic viscosity
\( y \) = depth of the boundary layer

The velocity distribution was approximated by a function
such as the $\frac{1}{7}$ th power law, or

$$u = U_m \left[ \frac{y}{\delta} \right]^{\frac{1}{7}}, \quad 0 < y \leq \delta$$

in which

- $u$ = the velocity at depth $y$
- $U_m$ = the maximum velocity
- $\delta$ = the distance from the boundary to the point of maximum velocity
- $y$ = the vertical distance measured from the bed

Using Eq. 3.24 to find the average velocity, $V$, at depth $\frac{y}{\delta}$

$$V = 0.905 U_m$$

and rearranging the terms results in

$$U_m = 1.104 V$$

The substitution of Eq. 3.5, 3.9, 3.10, 3.17, 3.18, 3.19, 3.20, 3.21 and 3.22 into Eq. 3.16 leads to

$$\frac{1}{2} g \left( \rho_1 - \rho_0 \right) y_1^2 - \frac{1}{2} g \left( \rho_1 + \frac{d\rho}{dx} \right) \frac{dy}{dx}^2 - \rho_0 \frac{dy}{dx}^2 = \left( \rho_1 + \frac{d\rho}{dx} \right) \frac{dV}{dx} \frac{dy}{dx}$$

$$+ \left( \rho_1 V_1^2 \right) \frac{dV}{dx} = \tau + \alpha \rho_1 V_1^2$$

Expanding Eq. 3.27 and neglecting second degree derivatives results in

$$g \left( \rho_1 - \rho_0 \right) y_1 \frac{dy}{dx} + \left( -\rho_1 V_1^2 y_1 - \frac{1}{2} g y_1^2 \right) \frac{d\rho}{dx}$$

$$+ \left( -\rho_1 V_1^2 y_1 \right) \frac{dV}{dx} = \tau + \alpha \rho_1 V_1^2$$

And substituting Eq. 3.12 and 3.2 in Eq. 3.28 yields
\[ g \left( \rho_1 - \rho_0 \right) y_1 \frac{dy}{dx} + \left( -\rho_1 V_1^2 y_1 - \frac{1}{2} g y_1^2 \right) c_T \frac{dT}{dx} \]
\[ + \left( -\rho_1 V_1^2 y_1 \right) \frac{dV}{dx} = \tau + \alpha \rho_1 V_1^2 \]
which can be expressed in the form
\[ A4 \frac{dy}{dx} + C_T A5 \frac{dT}{dx} + A8 \frac{dV}{dx} = B2 \]
\[ A4 = g \left( \rho_1 - \rho_0 \right) y_1 \]
\[ A5 = \left( -\rho_1 V_1^2 y_1 - \frac{1}{2} g y_1^2 \right) \]
\[ A8 = \left( -\rho_1 V_1^2 y_1 \right) \]
\[ B2 = \tau + \alpha \rho_1 V_1^2 \]

3.2.3. THE THERMAL BALANCE EQUATION

The heat balance equation was obtained by applying the mass conservation equation while considering density and temperature effects to the element of the jet shown in Figure 3.1. Neglecting heat loss due to conduction and diffusion, the simplified equation is
\[ C_p \rho_1 T_1 Q_1 + C_p \rho_0 T_0 \Delta Q_e + C_p \sigma \rho_0 \Delta Q_e \Delta T \]
\[ = C_p \rho_2 T_2 Q_2 \]
where
\[ T_1 = \text{the temperature at section 1} \]
\[ \Delta T = \text{the difference in temperature between the ambient fluid and the jet} \]
\( (3.32) \quad \Delta T = (T_0 - T_1) \)

\[ T_0 = \text{the temperature of the ambient fluid} \]

\[ T_2 = \text{the temperature at section 2} \]

\( (3.33) \quad C_p = \frac{dT}{dx} \)

\( C_p = \text{specific heat of the fluid} \)

The substitution of Eq. 3.4, 3.6, 3.7, 3.32, in Eq. 3.31, and factoring the width of the tank, \( b \), from the expression yields

\( (3.34) \quad \rho_1 T_1 y_1 V_1 + \alpha \rho_0 T_0 V_1 dx \)

\[ + \sigma \alpha \rho_0 V_1 (T_0 - T_1) = \rho_2 T_2 y_2 V_2 \]

The substitution of Eq. 3.5, 3.9, 3.10 and 3.33 in Eq. 3.34, expanding and neglecting second degree differential terms results in

\( (3.35) \quad \alpha \rho_0 T_0 V_1 dx + \sigma \alpha \rho_0 V_1 (T_0 - T_1) dx \)

\[ = \rho_1 V_1 T_1 \frac{dy}{dx} dx + \rho_1 y_1 V_1 \frac{d\rho}{dx} dx \]

\[ + y_1 V_1 T_1 \frac{dT}{dx} dx + \rho_1 T_1 y_1 \frac{dV}{dx} dx \]

The substitution of Eq. 3.12 and 3.2 in Eq. 3.35 results in

\( (3.36) \quad \alpha \rho_0 T_0 V_1 + \sigma \alpha \rho_0 V_1 (T_0 - T_1) = \)

\[ \rho_1 V_1 T_1 \frac{dy}{dx} + (\rho_1 y_1 V_1 C_T + y_1 V_1 T_1) \frac{dT}{dx} \]

\[ + \rho_1 T_1 y_1 \frac{dV}{dx} \]

which can be expressed in the form
\[ (3.37) \quad A7 \frac{dy}{dx} + (C_A A8 + A9) \frac{dT}{dx} + A10 \frac{dV}{dx} = B3 \]

\[ A7 = \rho_1 V_1 T_1 \]
\[ A8 = \rho_1 y_1 V_1 \]
\[ A9 = y_1 V_1 T_1 \]
\[ A10 = \rho_1 T_1 y_1 \]
\[ B3 = a \rho_0 T_0 V_1 + \sigma a \rho_0 V_1 (T_0 - T_1) \]

3.2.4. THE ENERGY (MODIFIED BERNOULLI) EQUATION

The principle of the conservation of mechanical energy was applied to the element of the jet shown in Figure 3.1.

\[ (3.38) \quad z_1 + a_1 \frac{\rho_1 V_1^2}{\rho_0 g} + \frac{\Delta \rho_1}{\rho_0} y_1 = z_2 + a_1 \frac{\rho_2 V_2^2}{\rho_0 g} + \frac{\Delta \rho_2}{\rho_0} y_2 + h_f + \Delta E \]

in which:

\[ z_1 = \text{the elevation of the bed at section 1} \]
\[ z_2 = \text{the elevation of the bed at section 2} \]
\[ = z_1 \]
\[ h_f = \text{the energy losses due to friction} \]
\[ \Delta E = \text{other energy losses or gains} \]
\[ dx = \text{the difference in the longitudinal position of sections 1 and 2} \]

The energy losses due to bed friction were based on the formula for the tractive force in an open channel, where
\( (3.39) \quad \tau = g \rho \left[ \frac{y b}{2 y + b} \right] \frac{h_f}{dx} \)

and by rearranging Eq. 3.39

\( (3.40) \quad h_f = \left[ \frac{2 y + b}{(y b)^2} \right] \frac{\tau}{g \rho} \frac{dx}{\tau} \)

The eddy losses in the jet were approximated by the energy losses in a hydraulic jump, where

\( (3.41) \quad \Delta E = \frac{\Delta y^3}{4 y_1 (y_1 + \Delta y)} \)

in which

\( \Delta y = \) the difference in the depth of the jet between sections 1 and 2

The substitution of Eq. 3.21, 3.22, 3.40

and 3.41 in Eq. 3.38 yields

\( (3.42) \quad \frac{V_1^2}{2g} + \frac{(\rho_1 - \rho_0)}{\rho_0} y_1 = \frac{V_2^2}{2g} + \frac{(\rho_2 - \rho_0)}{\rho_0} y_2 \)

\[ + \frac{\tau}{g \rho_1 y_1} dx + \frac{\Delta y^3}{4 y_1 (y_1 + \Delta y)} \]

The substitution of Eq. 3.5, 3.9, 3.10 into Eq. 3.42 yields
\[
\frac{v_1^2}{\frac{2}{\rho g}} + \frac{(\rho_1 - \rho_0) \gamma_1}{\rho_1} = \frac{(\frac{dv}{dx})^2}{2 g} + \frac{(\rho_1 + \frac{dp}{dx} dx - \rho_0 \gamma_1)}{(\rho_1 + \frac{dp}{dx} dx)} \gamma_1 \frac{dy}{dx} dx \frac{\Delta y^3}{4 \gamma_1 (\gamma_1 + \Delta y)} + \frac{\tau}{g \rho_1 \gamma_1} dx + \frac{\Delta y^3}{4 \gamma_1 (\gamma_1 + \Delta y)}
\]

Expanding Eq. 3.43 and neglecting second degree differential terms results in:

\[
\frac{(\rho_1 - \rho_0) \gamma_1}{\rho_1} \frac{dy}{dx} + \gamma_1 \frac{\rho_0}{\rho_1^2} \frac{dp}{dx} + \frac{v_1}{g} \frac{dv}{dx} = -\frac{\tau}{g \rho_1 \gamma_1} dx - \frac{\Delta y^3}{4 \gamma_1 (\gamma_1 + \Delta y)}
\]

The substitution of Eq. 3.12 and 3.2 into Eq. 3.44 results in:

\[
\frac{(\rho_1 - \rho_0) \gamma_1}{\rho_1} \frac{dy}{dx} + \gamma_1 \frac{\rho_0}{\rho_1^2} \frac{dT}{dx} + \frac{v_1}{g} \frac{dv}{dx} = -\frac{\tau}{g \rho_1 \gamma_1} dx - \frac{\Delta y^3}{4 \gamma_1 (\gamma_1 + \Delta y)}
\]

which can be expressed in the form
(3.46) \[ A11 \frac{dy}{dx} + C_T A12 \frac{dT}{dx} + A13 \frac{dV}{dx} = B4 \]

\[ A11 = \frac{\rho_1 - \rho_0}{\rho_1} \]

\[ A12 = y_1 \frac{\rho_0}{\rho_1^2} \]

\[ A13 = \frac{\nu_1}{g} \]

\[ B4 = -\frac{\tau}{g \rho_1 y_1} \frac{dx}{y_1^3} - \frac{\Delta y^3}{4 y_1(y_1 + \Delta y)} \]

3.2.5. NUMERICAL SOLUTION

Two sets of ordinary differential equations were expressed in matrix form. The first set of ordinary differential equations involved the mass balance equation, Eq. 3.14, the momentum equation, Eq. 3.30 and the thermal mass balance equation, Eq. 3.37. The matrix form is:

(3.47) \[
\begin{bmatrix}
A1 & C_T & A2 & A3 \\
A4 & C_T & A5 & A5 \\
A7 & C_T & A8 + A9 & A10
\end{bmatrix}
\begin{bmatrix}
dy \\
\frac{dT}{dx} \\
\frac{dV}{dx}
\end{bmatrix}
= \begin{bmatrix}
B1 \\
B2 \\
B3
\end{bmatrix}
\]

The second set of equations involved the mass balance equation, Eq. 3.14, the energy equation, Eq. 3.46, and the thermal mass balance equation, Eq. 3.37. It was used in the solution of the denser wall jet when the first set of
equations did not satisfy the requirements of decreasing energy. The matrix form is:

\[
\begin{bmatrix}
A_1 & C_T A_2 & A_3 \\
A_{11} & C_T A_{12} & A_{13} \\
A_7 & C_T A_8 + A_9 & A_{10}
\end{bmatrix}
\begin{bmatrix}
\frac{dy}{dx} \\
\frac{dT}{dx} \\
\frac{dV}{dx}
\end{bmatrix}
= 
\begin{bmatrix}
B_1 \\
B_4 \\
B_3
\end{bmatrix}
\]

The coefficient matrix A and the vector matrix B are functions of y, V, and T and they can be written as

\[
\begin{bmatrix}
\frac{dy}{dx} \\
\frac{dT}{dx} \\
\frac{dV}{dx}
\end{bmatrix}
= 
\begin{bmatrix}
A_1 & C_T A_2 & A_3 \\
A_{11} & C_T A_{12} & A_{13} \\
A_7 & C_T A_8 + A_9 & A_{10}
\end{bmatrix}^{-1}
\begin{bmatrix}
B_1 \\
B_4 \\
B_3
\end{bmatrix}
\]

and

\[
\begin{bmatrix}
\frac{dy}{dx} \\
\frac{dT}{dx} \\
\frac{dV}{dx}
\end{bmatrix}
= 
\begin{bmatrix}
A_1 & C_T A_2 & A_3 \\
A_{11} & C_T A_{12} & A_{13} \\
A_7 & C_T A_8 + A_9 & A_{10}
\end{bmatrix}^{-1}
\begin{bmatrix}
B_1 \\
B_4 \\
B_3
\end{bmatrix}
\]

The sets of equations are first order non-linear differential equations. These equations are solved using the fourth order Runge-Kutta method with initial values of depth, y, temperature, T, and velocity, V, for the jet used to calculate new values of y, T, and V at longitudinal position step, x = x + Ax.

The new values are used as initial values for the next step. The details of this method are given by James.
Smith and Wolford [1977]. The flow chart and the computer program are listed in Appendix F.

The initial conditions used in the mathematical solution of the denser wall jet submodel were ambient fluid temperature, jet fluid temperature, discharge per unit width, and initial jet depth.

3.3. THE MOVING INTERNAL HYDRAULIC JUMP SUBMODEL.

In deriving a system of equations to describe the moving internal hydraulic jump, the principles of conservation of mass and conservation of momentum are applied. The continuity equation is applied to the control volume of the hydraulic jump as shown in Figure 3.2. The momentum balance is applied to the section between the initial andsequent depths of the internal hydraulic jump, considering the relative velocity of the hydraulic jump as shown in Figure 3.3. A third equation defined the relationship between the surge velocity and the position of the moving internal hydraulic jump. A system of non-linear ordinary differential equations were developed and were solved by the Runge-Kutta method.

3.3.1. THE SURGE VELOCITY EQUATION.

The surge velocity equation was by definition the relationship between the surge velocity, $V_s$, and the
position of the moving internal hydraulic jump, $X_1$, as shown in Figure 3.2. The equation is by definition

$$\frac{dx_1}{dt} = -V_s \tag{3.51}$$

in which

$V_s$ = the surge velocity of the moving hydraulic jump

$x_1$ = the position of the initial depth of the moving internal hydraulic jump.

Equation 3.51 can be expressed in the form

$$A_{14} \frac{dx_1}{dt} + A_{15} \frac{dv_s}{dt} + A_{16} \frac{dy_2}{dt} = BS \tag{3.52}$$

\[
A_{14} = 1.0
\]

\[
A_{15} = 0.0
\]

\[
A_{16} = 0.0
\]

\[
BS = -V_s
\]

3.3.2. THE MOMENTUM EQUATION

The momentum equation was obtained by applying the principle of the momentum balance and the conservation of mass to the control volume shown in Figure 3.3. The reference direction was along the bed.

$$\Sigma F_X = A \left( \beta \rho V Q \right) \tag{3.53}$$

or

$$P_1 - P_2 = \rho_2 V_{2R} q_{2R} - \rho_1 V_{1R} q_{1R} \tag{3.54}$$

in which
\( P_1 \) = the hydrostatic pressure force per unit width at section 1

\[
(3.55) \quad P_1 = \frac{1}{2} g \Delta \rho_1 y_1^2;
\]

\( P_2 \) = the hydrostatic pressure force per unit width at section 2

\[
(3.56) \quad P_2 = \frac{1}{2} g \Delta \rho_2 y_2^2;
\]

\( q_{2R} \) = the discharge per unit width of at section 2

\[
(3.57) \quad q_{2R} = v_{2R} y_2;
\]

\( q_{1R} \) = the relative discharge per unit width at section 1

\[
(3.58) \quad q_{1R} = v_{1R} y_1;
\]

\( V_{1R} \) = the relative velocity at section 1

\[
(3.59) \quad V_{1R} = v_1 + v_s;
\]

\( V_{2R} \) = the relative velocity at section 2

\[
(3.60) \quad V_{2R} = v_2 + v_s;
\]

\( \Delta \rho_1 = (\rho_1 - \rho_0) \); 

\( \Delta \rho_2 = (\rho_2 - \rho_0) \).

The substitution of Eq. 3.55 to 3.62 in Eq. 3.54 yields

\[
(3.63) \quad \frac{1}{2} g (\rho_1 - \rho_0) y_1^2 - \frac{1}{2} g (\rho_2 - \rho_0) y_2^2
\]

\[
= \rho_2 (v_2 + v_s)^2 y_2 - \rho_1 (v_1 + v_s)^2 y_1
\]

The principle of conservation of mass for the control volume yields this equation,

\[
(3.64) \quad \rho_1 q_{1R} + \rho_0 \Delta \rho_{eR} = \rho_2 q_{2R}.
\]
where

\[ \Delta q_{eR} = \text{the relative discharge per unit width} \]

entrained by the moving internal hydraulic jump

(3.65) \[ \Delta q_{eR} = q_{1R} K_e \]

and from Eq. 3.78

(3.66) \[ \rho_2 = \frac{(\rho_1 + \rho_0 K_e)}{(1 + K_e)} \]

The substitution of Eq. 3.57, 3.58, 3.59, 3.60, and 3.65 in Eq. 3.64 yields

(3.67) \[ \rho_1 (V_1 + V_s) y_1 + \rho_0 (V_1 + V_s) y_1 K_e \]

\[ = \rho_2 (V_2 + V_s) y_2 \]

and substituting Eq. 3.66 and rearranging Eq. 3.67 yields

(3.68) \[ (V_2 + V_s) = \frac{(V_1 + V_s) y_1 (1 + K_e)}{y_2} \]

The substitution of Eq. 3.68 and 3.68 in Eq. 3.63 yields

(3.69) \[ \frac{1}{2} g (\rho_1 - \rho_0) y_1^2 - \frac{1}{2} g \left(\frac{(\rho_1 + \rho_0 K_e)}{(1 + K_e)} - \rho_0\right) y_2^2 \]

\[ = \frac{(\rho_1 + \rho_0 K_e)}{(1 + K_e)} \left(\frac{(V_1 + V_s) y_1 (1 + K_e)}{y_2}\right)^2 y_2 \]

\[ - \rho_1 (V_1 + V_s)^2 y_1 \]

Differentiating Eq. 3.69 with respect to time yields
\[(3.70) \quad g \left( \rho_1 - \rho_0 \right) y_1 \frac{dy_1}{dt} + \frac{1}{2} g \ y_1^2 \frac{d\rho_1}{dt}\]

\[- g \left( \frac{\rho_1 - \rho_0}{1 + K_e} \right) y_2 \frac{dy_2}{dt} - \frac{1}{2} g \ y_2^2 \frac{d\rho_1}{dt}\]

\[= \frac{y_1^2}{y_2} (1 + K_e) (\rho_1 + \rho_0 K_e) (V_1 + V_s)^2 \frac{d\rho_1}{dt}\]

\[+ 2 \frac{y_1^2}{y_2} (1 + K_e) (\rho_1 + \rho_0 K_e) (V_1 + V_s)^2 \left( 2 \frac{y_1}{y_2} \frac{dy_1}{dt} - \frac{y_1^2}{y_2} \frac{dy_2}{dt} \right)\]

\[- 2 \rho_1 y_1 (V_1 + V_s) \left( \frac{dV_1}{dt} + \frac{dV_s}{dt} \right) - \rho_1 (V_1 + V_s)^2 \frac{dy_1}{dt}\]

\[- y_1 (V_1 + V_s)^2 \frac{d\rho_1}{dt}\]

Since,

\[(3.71) \quad \frac{dy_1}{dt} = \frac{dy_1}{dx_1} \frac{dx_1}{dt}\]

\[(3.72) \quad \frac{dV_1}{dt} = \frac{dV_1}{dx_1} \frac{dx_1}{dt}\]

\[(3.73) \quad \frac{d\rho_1}{dt} = \frac{d\rho_1}{dT_1} \frac{dT_1}{dx_1} \frac{dx_1}{dt}\]

the substitution of Eq. 3.2, 3.12, 3.71, 3.72, and 3.73 into Eq. 3.70 results in
\begin{equation}
(3.74) \quad g \left( \rho_1 - \rho_0 \right) y_1 \frac{dy_1}{dx_1} + \frac{1}{2} g y_2 \frac{\rho_1}{dT_1} \frac{dx_1}{dt} + \frac{1}{2} \left[ g \left( \frac{\rho_1 - \rho_0}{1 + k_e} \right) \right] \frac{dy_2}{dt} - \frac{1}{2} \left[ g \left( \frac{\rho_1 - \rho_0}{1 + k_e} \right) \right] \frac{\rho_1}{dT_1} \frac{dx_1}{dt} \\
= \frac{y_1^2}{y_2} (1 + k_e) \left( \rho_1 + \rho_0 k_e \right) (V_1 + V_s)^2 \left( \frac{dp_1}{dT_1} \frac{dx_1}{dt} + \frac{dV_s}{dt} \right) \\
+ 2 \frac{y_1^2}{y_2} (1 + k_e) \left( \rho_1 + \rho_0 k_e \right) (V_1 + V_s)^2 \left[ \frac{y_1}{y_2} \frac{dy_1}{dx_1} \frac{dx_1}{dt} - \frac{y_1^2}{y_2^2} \frac{dy_2}{dt} \right] \\
+ (1 + k_e) \left( \rho_1 + \rho_0 k_e \right) (V_1 + V_s)^2 \left( \frac{dV_1}{dx_1} \frac{dx_1}{dt} + \frac{dV_s}{dt} \right). - \rho_1 (V_1 + V_s)^2 \frac{dy_1}{dt} \\
- \frac{y_1}{y_2} (V_1 + V_s)^2 \frac{dp_1}{dT_1} \frac{dT_1}{dx_1} \frac{dx_1}{dt}
\end{equation}

where \( \frac{dy_1}{dx_1} \), \( \frac{dV_1}{dx_1} \), and \( \frac{dT_1}{dx_1} \) were determined from the jet submodel. Eq. 3.74 can be expressed in the form

\begin{equation}
(3.75) \quad A17 \frac{dx_1}{dt} + A18 \frac{dV_s}{dt} + A19 \frac{dy_2}{dt} = 0
\end{equation}

\begin{align*}
A17 &= AA1 \frac{dy_1}{dx_1} + AA2 \frac{dV_1}{dx_1} + AA3 \frac{dp_1}{dT_1} \\
A18 &= AA4 \frac{dy_1}{dx_1} + AA5 \frac{dV_1}{dx_1} + AA6 \frac{dT_1}{dx_1}
\end{align*}
AA1 = \( g(\rho_1 - \rho_0) y_1 + \rho_1 (V_1 + V_s)^2 \)

\[ \begin{align*}
- 2 (1 + K_e) (\rho_1 + \rho_0 K_e) (V_1 + V_s)^2 & \begin{pmatrix} \frac{y_1}{y_2} \end{pmatrix} \\
AA2 &= 2 \rho_1 y_1 (V_1 + V_s) \\
- 2 \frac{y_1^2}{y_2} (1 + K_e) (\rho_1 + \rho_0 K_e) (V_1 + V_s) \\
AA3 &= \frac{1}{2} g y_1^2 + y_1 (V_1 + V_s)^2 \\
- \frac{1}{2} \frac{g y_2^2}{(1 + K_e)} - \frac{y_1^2}{y_2} (1 + K_e) (V_1 + V_s)^2 \\
A18 &= AA2 \\
A18 &= - g \left( \frac{\rho_1 - \rho_0}{1 + K_e} \right) y_2 \\
&+ (1 + K_e) (\rho_1 + \rho_0 K_e) (V_1 + V_s)^2 \begin{pmatrix} \frac{y_1^2}{y_2^2} \end{pmatrix} \\
B0 &= 0.0
\]

3.3.3. THE CONTINUITY EQUATION

The continuity equation was obtained by applying the conservation of mass equation to the control volume shown in Figure 3.2.

(3.76) \( Q_{in} = Q_{out} \)

or

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\( (3.77) \quad \rho_1 q_1 + \rho_0 \Delta q_e = \rho_3 q_1 + \rho_{23} (x_2 - x_3) \frac{dy_2}{dt} \)

\[ + V_s \rho_{12} (y_2 - y_1) + \rho_2 y_2 V_s \]

where

\( \rho_0 \) = the density of the ambient fluid;

\( \rho_{12} \) = the average density between sections 1 and 2

\[ = \frac{1}{2} (\rho_1 + \rho_2); \]

\( \rho_{23} \) = the average density between sections 2 and 3

\[ = \frac{1}{2} (\rho_2 + \rho_3); \]

\( \rho_1 \) = the density at section 1;

\( \rho_2 \) = the density at section 2;

\( \rho_3 \) = the density at section 3, the weir;

\( y_1 \) = the initial depth of the moving internal hydraulic jump;

\( y_2 \) = the sequent depth of the moving internal hydraulic jump;

\( V_1 \) = the velocity at section 1;

\( V_2 \) = the velocity at section 2;

\( x_2 \) = the longitudinal position of section 2;

\( x_3 \) = the longitudinal position of section 3, the weir;

\( q_1 \) = the discharge per unit width at section 1

\[ = y_1 V_1; \]

\( \Delta q_e \) = the discharge per unit width entrained by the moving internal hydraulic jump
(3.81) \[ \Delta q_e = q_1 K_e; \]
- \( q_L \) = the discharge short circuiting at the weir
(3.82) \[ = q_1 K_L; \]
- \( K_e \) = the jump entrainment coefficient;
- \( K_L \) = the weir short circuiting coefficient.

The substitution of Eq. 3.78, 3.79, 3.80, 3.81 and 3.82 in Eq. 3.77 yields

(3.83) \[ \rho_1 y_1 v_1 + \rho_0 y_1 v_1 K_e = \rho_3 y_1 v_1 K_L \]
\[ + \frac{1}{2} (\rho_2 + \rho_3) (x_2 - x_3) \frac{dy_2}{dt} \]
\[ + \frac{1}{2} (\rho_1 + \rho_2) (y_2 - y_1) v_s + \rho_2 y_2 v_s \]

Equation 3.83 can be expressed in the form

(3.84) \[ \frac{dx_2}{dt} + A_{21} \frac{dv_s}{dt} + A_{22} \frac{dy_2}{dt} = B_7 \]

in which

\[ A_{20} = 0.0 \]
\[ A_{21} = 0.0 \]
\[ A_{22} = \frac{1}{2} (\rho_2 + \rho_3) (x_2 - x_3) \]
\[ B_7 = \rho_1 y_1 v_1 + \rho_0 y_1 v_1 K_e - \rho_3 y_1 v_1 K_L \]
\[ + \frac{1}{2} (\rho_1 + \rho_2) (y_2 - y_1) v_s + \rho_2 y_2 v_s \]
3.3.4. NUMERICAL SOLUTION

A set of three first order ordinary differential equations was expressed in matrix form involving the surge velocity equation, Eq. 3.52, and the momentum equation, Eq. 3.75, and the continuity equation, Eq. 3.84. The matrix form is:

\[
\begin{bmatrix}
A14 & A15 & A16 \\
A17 & A18 & A19 \\
A20 & A21 & A22
\end{bmatrix}
\begin{bmatrix}
\frac{dx_1}{dt} \\
\frac{dV_s}{dt} \\
\frac{dy_2}{dt}
\end{bmatrix}
= 
\begin{bmatrix}
B5 \\
B6 \\
B7
\end{bmatrix}
\]

The coefficient matrix \( A \) and the vector matrix \( B \) are functions of \( x_1 \), \( V_s \), and \( y_2 \) and they were rewritten as:

\[
\begin{bmatrix}
\frac{dx_1}{dt} \\
\frac{dV_s}{dt} \\
\frac{dy_2}{dt}
\end{bmatrix}
= 
\begin{bmatrix}
A14 & A15 & A16 \\
A17 & A18 & A19 \\
A20 & A21 & A22
\end{bmatrix}^{-1}
\begin{bmatrix}
B5 \\
B6 \\
B7
\end{bmatrix}
\]

The set of equations was solved using the fourth order Runge-Kutta method with information from the jet submodel and initial values of position, \( x_1 \), surge velocity, \( V_s \), and sequent depth, \( y_2 \), for the moving internal hydraulic jump used to calculate new values of \( x_1 \), \( V_s \), and \( y_2 \) at time step, \( t = t + \Delta t \). The new values are used as initial values for the next time step. A flow chart and the computer submodel are listed in Appendix F.
The initial conditions used for the solution of the moving internal hydraulic jump model were the starting position for the moving internal hydraulic jump, an initial value for the velocity at the sequested depth section and an initial value for the surge velocity. The initial value of the velocity at the sequested depth section was assumed to be small (i.e. 0.1 mm/s). The starting value of the surge velocity was determined by approximating the solution of the classical rectangular hydraulic jump sequested depth relationship.

3.4. THE SUBMERGED INTERNAL HYDRAULIC JUMP

The submerged internal hydraulic jump was described by an equation showing the relationship between the depth, $y_1$, velocity, $V_1$, and density, $\rho_1$, at the gate opening, $y_1$, the submerged depth, $y_s$, the sequested depth of the hydraulic jump, $y_2$, the velocity, $V_2$, and density, $\rho_2$, at the longitudinal section corresponding to the sequested depth, and the density of the ambient fluid, $\rho_0$.

In deriving an equation to describe the submerged internal hydraulic jump, the principle of the conservation of mass and the momentum balance were applied to a submerged internal hydraulic jump control volume, as shown in Figure 3.4. The reference direction was the x-axis, along the bed.

\[ (3.87) \quad \Sigma F_x = \Delta (\beta \rho V Q) \]
\[(3.88) \quad P_1 - P_2 = \rho_2 v_2 q_2 - \rho_1 v_1 q_1\]

in which:

\[P_1 = \text{the hydrostatic pressure force per unit width at section 1}\]

\[(3.89) \quad = \frac{1}{2} g \Delta \rho_1 y_s^2;\]

\[P_2 = \text{the hydrostatic pressure force per unit width at section 2}\]

\[(3.90) \quad = \frac{1}{2} g \Delta \rho_2 y_2^2;\]

\[q_2 = \text{the discharge per unit width at section 2}\]

\[(3.91) \quad = v_2 y_2;\]

\[q_1 = \text{the discharge per unit width at section 1}\]

\[(3.92) \quad = v_1 y_1;\]

\[(3.93) \quad \Delta \rho_1 = (\rho_1 - \rho_0);\]

\[(3.94) \quad \Delta \rho_2 = (\rho_2 - \rho_0).\]

The substitution of Eq. 3.89 to 3.94 in Eq. 3.88 yields

\[(3.95) \quad \frac{1}{2} g (\rho_1 - \rho_0) y_s^2 - \frac{1}{2} g (\rho_2 - \rho_0) y_2^2 = \rho_2 v_2^2 y_2 - \rho_1 v_1^2 y_1\]

and can be rearranged as

\[(3.96) \quad y_s = \left[ \left( \frac{1}{2} g (\rho_2 - \rho_0) y_2^2 + \rho_2 v_2^2 y_2 \right. \right.

\[\left. - \rho_1 v_1^2 y_1 \right] + \left[ \frac{1}{2} g (\rho_1 - \rho_0) \right] \right]^{0.5}

Equation 3.96 allows for a direct solution for the
submerged depth, $y_s$. 
4. EXPERIMENTAL APPARATUS

4.1. INTRODUCTION

The experiments were carried out in a physical model of a rectangular clarifier and equipment measured temperature, and the concentration of a dye in the test section. The tests were also recorded on video tape and by photographs.

4.2. THE TEST SECTION

The tests were carried out in a plexiglass flume, as shown in Figure 4.1. The flume was 1.8 m long, by 0.5 m high and 0.125 ± 0.003 m wide. The flow entered the flume at the end where a fibre filter was installed to damp out inflow macroturbulence. The source of the flow was a hose attached to a hot and cold water supply. The water flowed under a round lip gate into the test section. The test section was 0.74 m long. The weirs used were sharp crested: 0.085 m and 0.170 m high. Effluent from the test section was expelled to the drain through a hose or into a volumetric measuring cylinder.

4.3. THE TEMPERATURE STUDY

A Fluke model 2240B data logger was used to measure temperature in the test section. Copper-Constantan thermocouples were positioned at stationary locations along the flume wall and on the face of the gate and the weir and
in a plexiglass probe which had eleven thermocouple wires at specific elevations and could be moved along the flume centreline as shown in Photos 4.1 to 4.5. The thermocouples sensed temperature. The Analog to Digital converter in the data logger converted the analog signals to digital signals and relayed these signals to an Apple II microcomputer which was used to store the temperature data on diskettes. The set up for the temperature study is shown in Photo 4.6.

4.4. THE PHOTOGRAPHIC DYE STUDY

To record the results of visual dye tests, a 35 mm camera equipped with a wide-angle lens was used to take a series of photographs during the test. A wall clock with a sweep second hand was photographed with the flume test section to give a time reference. Potassium Permanganate, Rhodamin B and Sodium Fluorescein dyes were added to the tests for visualization of the phenomena. Tests were also recorded by a VHS video camera.

4.5. THE FLUORESCENT DYE STUDY

In the fluorescent dye tests, a Turner model III fluorometer was used to measure the concentration of Sodium Fluorescein, a fluorescent dye. Samples were continuously collected by a monostat pump through teflon tubing and pumped to the fluorometer. The fluorometer yielded an output signal in the range of 0 to 5 volts and an AI13
12 bit Analog to Digital Input System converter conveyed the signals to an Apple II microcomputer. These signals were recorded as a plot of dye concentration versus time and the image of the graph was saved on a diskette. The fluorescent dye test equipment is shown in Photo 4.7.

4.6. DYE INJECTION SYSTEM

Dyes were injected upstream of the gate of the test section for the photographic and fluorescent tests. In the photographic dye tests, the dye was mixed in and pumped from a 500 ml container through teflon tubing to a diffuser upstream of the gate opening, as shown in Figure 4.2. In the fluorescent dye test, dye was mixed in a twenty gallon drum. Dye was pumped from the drum to another container to maintain a constant head from which to pump the dye to a diffuser upstream of the gate opening.
5. EXPERIMENTAL PROGRAM

5.1. INTRODUCTION

The experimental program undertaken involved temperature tests, flow visualization dye tests and fluorescent dye tests. These three tests were repeated for similar test conditions. In the experiment the variables were flowrate, gate opening, weir height, ambient fluid temperature and influent temperatures in initial tank.

5.2. EXPERIMENTAL RANGES

The ranges of the experimental data are as follows:

Flume width: \( b = 12.5 \) cm

Flowrate: \( Q = 0.050 \) L/s to \( 0.230 \) L/s

Gate opening: \( G = 3 \) cm and \( 5 \) cm

Weir height: \( h_w = 8.5 \) cm and \( 17 \) cm

Denser Wall jet case, ambient fluid temperature:

\[ T_o = 32 \, ^\circ C \text{ to } 43 \, ^\circ C \]

minimum jet temperature:

\[ T_1 = 13.7 \, ^\circ C \text{ to } 26 \, ^\circ C \]

Buoyant jet case, ambient fluid temperature:

\[ T_o = 15.7 \, ^\circ C \text{ to } 29 \, ^\circ C \]

maximum jet temperature:

\[ T_1 = 34 \, ^\circ C \text{ to } 43 \, ^\circ C \]

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5.3. THE TEMPERATURE STUDY

The temperature experiment was conducted to determine the temperature distribution throughout the tank volume at various time intervals during test. A typical test for the denser wall jet case was carried out as follows:

1. The gate was positioned to a specified opening;
2. The cold water tap was opened to required influent discharge;
3. The temperature probe was positioned at a longitudinal section;
4. The hot water tap was opened to achieve the required ambient fluid temperature in the test section; the stationary thermocouple temperature levels were monitored;
5. The data logger and microcomputer program for the test were set up. The time interval between temperature scans and the number of scans required for the duration of the test was inputted on the computer; the scan time on the data logger was adjusted to correspond with that of the computer program;
6. The hot water tap was closed;
7. The computer data collection sequence was initiated;
8. The collected data was saved on a computer diskette;
9. The effluent flowrate was measured;

10. The test steps were repeated for the next longitudinal section.

For the buoyant jet, the test steps were repeated but the hot water tap was opened for jet discharge and the cold water tap was used to adjust ambient fluid temperature.

5.4. THE PHOTOGRAPHIC DYE STUDY

The photographic dye experiment was conducted to record the movement of the dye through the physical model of the clarifier. The dyes used were Potassium Permanganate, Rhodamin B and Sodium Fluorescein. These tests were used to estimate velocities and density current depths in the test section. A typical test for the denser wall jet case was carried out as follows:

1. The gate was adjusted to a specified opening;

2. The cold water tap was opened to the required influent discharge;

3. The hot water tap was adjusted to achieve the required ambient temperature in the test section; the stationary thermocouple temperature levels were monitored;

4. The camera and clock were set up;

5. The data logger was set up as in the temperature study, except only the stationary point temperatures were recorded; these readings were
saved on print out tape;

6. The dye injection system was prepared;

7. The hot water tap was closed;

8. The thermocouple temperature levels at a section upstream of the gate was monitored; when the temperature at the gate began to decrease, dye was pumped to the diffuser at the gate opening and temperatures were recorded;

9. The test section was photographed at approximately five second intervals as dye spread throughout the test section.

For the buoyant jet case, the procedure was repeated except the hot water tap was adjusted to the desired jet discharge and the cold water tap was used to adjust the ambient temperature. Also, the dye was warmed to approximately the temperature of the jet before it was injected into the system.

5.5. THE FLUORESCENT DYE STUDY

The fluorescent dye study was conducted to record the intensity of a fluorescent dye, Sodium Fluorescein, sampled from the influent at the gate opening and the effluent at the weir. The results were used to estimate entrainment and flow through characteristics. A typical test for the denser wall jet case was carried out as follows:

1. The gate was positioned to the specified opening;
2. The cold water tap was opened to the required influent discharge;

3. The hot water tap was adjusted to achieve the required ambient fluid temperature in the test section; the stationary thermocouple temperatures were monitored;

4. The fluorometer, sampling pumps and computer were set up; the sampling time was inputted on the computer; the sampling tube was adjusted to withdraw the sample from the influent at the gate opening;

5. The data logger was set up as in the photographic dye study;

6. The dye injection system was prepared, continuous sample of the influent was withdrawn;

7. The hot water tap was closed;

8. The thermocouple temperature at section upstream of the gate was monitored; when the temperature at the gate began to decrease, dye was pumped to the diffuser upstream of the gate; the stationary thermocouple temperatures were recorded on print out tape and the dye concentration was recorded on the microcomputer.

The test was repeated for a sample of the effluent withdrawn at weir. The test was also repeated for the buoyant jet case in which the hot water tap was used to
achieve the desired jet discharge and the cold water tap was used to adjust the ambient temperature of the test section.
6. EXPERIMENTAL RESULTS

6.1. INTRODUCTION

The experimental data from 109 experiments under fifteen test conditions are documented in temperature contour plots from the temperature study, in photographs and in influent and effluent dye concentration graphs from the fluorescent dye tests. In Table 6.1, the conditions for the experiments are listed.

6.2. THE TEMPERATURE STUDY

The experimental data from 97 tests conducted under seven conditions are on file at the Department of Civil and Environmental Engineering at the University of Windsor. The data was combined and adjusted to develop contour plots of the distribution of temperature in the test section for each test condition. The contour plots are documented in Figures 6.1 to 6.20 in Appendix A and in Figures H.1 to H.42 in Appendix H. All length dimensions are given in mm, the flowrate in L/s, temperature in °C and time in seconds.

In Table 6.2, the case numbers, type of test, scan intervals and figure numbers are listed for the temperature study tests.

6.3. THE PHOTOGRAPHIC DYE STUDY

Photographs were taken of experiments under four test
conditions at an interval of approximately five seconds. The experiments are documented in Photos 6.1 to 6.24 in Appendix B and in Photos I.1 to I.20 in Appendix I.

In Table 6.3, the case numbers and type of test for the photographic dye study test and the corresponding photo numbers are listed for the denser wall jet case and the buoyant surface jet case. The figure numbers of the temperature influent/effluent plots are also listed.

6.4. THE FLUORESCENT DYE STUDY

In the fluorescent dye study, eight tests were conducted to sample the influent and effluent of the test section and to measure the concentration of dye in the fluid under four test conditions. The graphs of the dye concentration versus time are shown in Figures 6.25, 6.26, 6.28, 6.29, 6.31, 6.32, 6.34 and 6.35.

In Table 6.4, the case numbers and the type of test for the fluorescent dye study test and the corresponding figure numbers are listed for the denser wall jet case and the buoyant surface jet case. The figure numbers of the dye concentration plots of influent and effluent samples and the temperature influent/effluent plots are also listed.
7. DATA REDUCTION AND ANALYSIS

7.1. INTRODUCTION

In the experiments undertaken, an Apple microcomputer data acquisition system was used to record data from the temperature and fluorescent dye tests. Photographs were also used to record dye tests. The raw data collected from these tests were reduced to a more concise and presentable form.

7.2. TEMPERATURE STUDY DATA REDUCTION

The data from the temperature study were collected and recorded using an Apple II microcomputer. These data ultimately are presented in thermal contour plots using the SAS contour plotting on the IBM mainframe computer.

7.2.1. DATA COLLECTION

The Copper-Constantan thermocouples and the Fluke data logger measured and recorded the temperature at various locations in the flume and these temperatures were recorded on an Apple II microcomputer using the data acquisition program, NEWFLUKE, listed in Appendix D. This program stored the results in a column matrix. The elements in the column matrix are the number of scans of temperature to be made during a test, and a matrix consisting of the temperatures recorded at twenty points in the flume, the
time elapsed during the test, and the time expressed as the day, hour, minute and second.

7.2.2. DATA MANIPULATION

Once the temperature data were collected and recorded on the Apple II microcomputer, these data were re-formatted so that they could be used by the SAS program on the mainframe computer for preparing thermal contour plots.

7.2.2.1. DATA TRANSFER FROM THE APPLE II TO IBM MICROCOMPUTER

The first step in re-formating the data was to transfer the column matrix Apple data file to an IBM data file using the QMODEM computer program package, an Apple II microcomputer, an IBM microcomputer and an RS232 card to connect the two computers so that they could communicate.

7.2.2.2. SORTING OF DATA

The data was then inserted in an IBM data file in a column matrix. Before the file could be transferred to the mainframe computer, the data from relevant tests was sorted and merged into one file for each test condition. The sorting program, TEMP4.FOR, is listed in Appendix E. This program reads information from an input file required by the program to combine the data files from separate temperature tests executed under the same test conditions.
and merges the data files into a single file. A sample input file and a portion of the output file from TEMP4.FOR are listed in Appendix E. This single file describes the temperature in the flume under a specific test condition. The new file has counters describing the size of the data saved in the file in the first line. Successive lines are filled with columns of longitudinal position, elevation, temperature, and time for the stationary points in the flume and the points whose temperatures were recorded using the temperature probes. The last line in the file has a counter which indicates the end of the file.

The next step in sorting the data involved the linear shifting of the data to an initial reference temperature for ambient conditions in the flume before the appearance of the jet and the interpolation of the data to a finer rectangular grid. The interpolation program, INTERP4.FOR, is listed in Appendix E. This program reads the results from the sorting program, TEMP4.FOR, calculates the shift in the temperature for each probe location based on the ambient temperature and applies this to the entire set of data, and linearly interpolates the existing temperature data to a finer rectangular grid to be used by the SAS plotting package. The output of this program is in the form of columns of longitudinal position, elevation, temperature, and time for specific times during the test and is listed in Appendix E.
7.2.2.3. DATA TRANSFER FROM MICROCOMPUTER TO MAINFRAME COMPUTER

Now that the data is in a form that the SAS plotting package can read, the data files are transferred from the IBM computer to the IBM mainframe computer. This is achieved using the computer package XTALK.

7.2.3. DATA PRESENTATION

With the temperature data files saved on the mainframe computer, the SAS plotting package can be used to create a two-dimensional thermal contour plot of the flume for specific times from each test. Since these data files are the result of merging the data from separate tests conducted under the same test conditions, the resulting contour plots have irregularities and require some additional smoothing.

7.2.3.1. SMOOTHING OF DATA

The data files on the mainframe computer that required smoothing to adjust inconsistent contour lines were edited by hand. This was necessary because of the method of generating the thermal data. The data for each test condition was collected through a series of up to fourteen separate tests. These tests were conducted under similar, but not identical, conditions of discharge and temperature.
The data was sorted and merged into a single data file for each test condition using TEMP4.FOR, which is listed in Appendix E. An interpolation program, INTERP4.FOR, which is listed in Appendix E, was used to linearly shift the temperatures from each test to the same average starting temperature and linearly interpolate the temperature data into a finer rectangular grid. This resulted in contour plots that were not smooth. Examples of the contour plots without smoothing are shown in Figures 7.1 and 7.2. The corresponding contour plots with smoothing are shown in Figures 6.2 and 6.14. The thermal contour plots for each test condition and time were inspected for irregular contour lines and the desired contour lines were sketched on the plots.

A computer program, TABLE.FOR, listed in Appendix E, was used to tabulate the data files using a microcomputer. The print out of the tabulated data files were used in conjunction with the sketched contour plots. A sample tabulated data file is listed in Appendix E. Changes to the tabulated data files were made to correspond with the contour lines that were marked by hand and these changes were made to the mainframe data file. The new contour lines eliminated anomalies resulting from the merging of the individual experimental data sets, while maintaining the representative trends of the original contour lines. The SAS plotting package was used to create a two-dimensional
thermal contour plot of the edited data files.

7.2.4. DATA REDUCTION

During the temperature study experiments, temperature profiles were recorded at fourteen longitudinal positions along the centre line of the flume. Contour plots were made of the temperatures throughout the flume for specific test times for each test condition. The temperature tests were conducted for four denser wall jet conditions and for three buoyant surface jet conditions.

7.2.4.1. DENSER WALL JET CASE DATA REDUCTION

During the denser wall jet case experiments, six phases were seen. The six phases were:

1. denser wall jet
2. splash at weir
3. moving internal hydraulic jump
4. submerged hydraulic jump
5. splash at baffle
6. stratification.

From the thermal contour plots, information describing four phases (denser wall jet, splash at weir, moving internal hydraulic jump and submerged hydraulic jump) was determined. The reduced data for the two denser wall jet cases are listed in Tables 7.1 to 7.12.

From the thermal contour plots of the denser wall
jet phase, the average jet depth, $y_1$, and the average jet temperature, $T_1$, with respect to longitudinal position, $x_1$, were determined. The velocity of the jet, $V_1$, the densimetric Froude number, $F'_1$, the entrainment coefficient, $\alpha$, and the thermal entrainment correction factor, $\sigma$, were calculated with respect to longitudinal position and are listed in Tables 7.1 to 7.4. Figures 6.1 and 6.2 correspond with Table 7.1. Figures H.1 and H.2 correspond with Table 7.2. Figures H.21 to H.23 correspond with Table 7.3. Figures H.37 and H.38 correspond with Table 7.4.

From the thermal contour plots of the splash at the weir, the longitudinal extent, height and temperature of the splash were determined. The average rate of rise of the splash was calculated and is listed in Tables 7.5 to 7.8. Figures 6.2 and 6.3 correspond with Table 7.5. Figures H.3 and H.4 correspond with Table 7.6. Figures H.24 to H.26 correspond with Table 7.7. Figures H.37 to H.40 correspond with Table 7.8.

From the thermal contour plots of the moving internal hydraulic jump, the initial depth, $y_1$, and its corresponding temperature, $T_1$, and the sequent depth, $y_2$, and their respective longitudinal positions, $x_1$ and $x_2$, were established. The velocity, $V_1$, corresponding to the initial depth was estimated from the thermal contour plots of the jet. The length of the hydraulic jump, $L_3$, the surge velocity, $V_s$, and the relative densimetric Froude number,
were calculated with respect to longitudinal position of the initial depth and with respect to time. The maximum and minimum range of the discharge entrained by the moving internal hydraulic jump were calculated and expressed as a fraction of the discharge flowing through the tank, \( C_{1\text{max}} \) and \( C_{1\text{min}} \). The results are listed in Tables 7.9 to 7.10. Figures 6.3 to 6.6 correspond with Table 7.9. Figures H.5 and H.6 correspond with Table 7.10.

The submerged hydraulic jump developed in both of the tests conducted with weir heights of 17 cm. From the thermal contour plots of the submerged hydraulic jump, the sequent depth, \( y_z \), the submerged depth, \( y_{s} \), and the length of the jump, \( L_{j} \), were established. The temperature at the longitudinal position corresponding to the sequent depth and the temperature of the influent were established. The velocity, \( V_{z} \), corresponding to the sequent depth, and the densimetric Froude number, \( F'_{z} \), were calculated. The maximum and minimum factors of the discharge entrained by the submerged hydraulic jump are \( C_{z\text{max}} \) and \( C_{z\text{min}} \). The calculation of \( C_{z\text{max}} \) was made by determining the area of the advance of a thermal contour line between two successive plots. The volume of the advance was calculated by multiplying the area by the width of the tank. The discharge was calculated by dividing that volume by the time interval between the plots. This was expressed as a fraction of the flowrate, \( Q \), through the tank. It was
assumed that the flow through the tank had no effect on the rate of the advance of the contour lines. The calculation of $C_{z_{\text{min}}}$ was made by assuming that the flow through the tank was included in the advance of the contour lines. Therefore, the factor $C_{z_{\text{min}}}$ is the factor $C_{z_{\text{max}}}$ minus unity, the flowrate through the tank. The results are listed in Tables 7.11 and 7.12. Figures 6.7 to 6.10 correspond with Table 7.11. Figures H.6 to H.9 correspond with Table 7.12.

7.2.4.2. BUOYANT SURFACE JET CASE DATA REDUCTION

During the buoyant surface jet case experiments, four phases were observed. The four phases were:

1. rising plume with entrainment
2. buoyant surface jet
3. moving internal hydraulic jump
4. stratification.

From the thermal contour plots, information describing the four phases was determined. The reduced data for the two buoyant surface jet cases are listed in Tables 7.13 to 7.23.

From the thermal contour plots of the rising plume phase, the gross dilution, $Q_{\text{dil}}$, and the gross dilution factor expressed as a fraction of the discharge flowing through the tank, $D_{\text{dil}}$, from the rising jet were calculated from the tests conducted with weir heights of 17 cm. The results are listed in Tables 7.13 and 7.14. Figures 6.12 to 6.13 correspond with Table 7.13. Figures H.10 to H.12
correspond with Table 7.14.

From the thermal contour plots of the buoyant surface jet phase, the average jet depth, \( y_1 \), and temperature, \( T_1 \), with respect to longitudinal position, \( x_1 \), were determined. The velocity of the jet, \( V_1 \), the densimetric Froude number, \( F'_1 \), and the entrainment coefficient, \( \alpha \) were calculated with respect to longitudinal position and are listed in Tables 7.15 to 7.17. Figures 6.13 to 6.15 correspond with Table 7.15. Figures H.10 to H.12 correspond with Table 7.16. Figures H.27 to H.29 correspond with Table 7.17.

From the thermal contour plots of the moving internal hydraulic jump, the initial depth, \( y_1 \), and sequent depth, \( y_2 \), and their longitudinal positions, \( x_1 \) and \( x_2 \), were established. The temperatures at the longitudinal positions of the initial depths were established. The velocity, \( V_1 \), corresponding to the initial depth was estimated from the jet data. The length of the hydraulic jump, \( L_2 \), the surge velocity, \( V_s \), and the relative densimetric Froude number, \( F'_{x_1} \), were calculated with respect to longitudinal position of the initial depth and with respect to time and are listed in Tables 7.18 to 7.20. Figures 6.17 and 6.18 correspond with Table 7.18. Figures H.14 to H.16 correspond with Table 7.19. Figures H.31 to H.33 correspond with Table 7.20.

From the thermal contour plots of the stratification, an estimate of the rate at which the wedge
of cold water at the bottom of the tank was entrained, \( Q_{\text{en}} \), and the dilution factor, \( D_a \), expressed as a fraction of the discharge flowing through the tank are listed in Tables 7.21 to 7.23. Figures 6.18 to 6.20 correspond with Table 7.21. Figures H.16 to H.20 correspond with Table 7.22. Figures H.34 to H.36 correspond with Table 7.23.

7.3. PHOTOGRAPHIC DYE STUDY DATA REDUCTION

Photographs were taken during experiments to record the movement of the dye through the test section. The temperature at several stationary points was also recorded during these tests. Flow visualization dye tests were conducted for both the denser wall jet case and the buoyant surface jet case at a weir height of 17 cm and for gate openings of 3 cm and 5 cm.

7.3.1. DENSER WALL JET CASE DATA REDUCTION

During the denser wall jet case experiments, six phases were seen. The six phases were:

1. denser wall jet
2. splash at weir
3. moving internal hydraulic jump
4. submerged hydraulic jump
5. splash at baffle
6. stratification.

From the photographs, information describing four phases
(denser wall jet, splash at weir, moving internal hydraulic jump and submerged hydraulic jump) was determined.

Additional thermal information about the regimes was estimated from the influent/effluent temperature curves and from the thermal contour plots from the temperature study. The reduced data for the two denser wall jet cases are listed in Tables 7.24 to 7.31.

From the photographs of the denser wall jet, the average jet depth, $y_1$, with respect to longitudinal position, $x_1$, was determined. The temperatures at the longitudinal sections were estimated from the thermal data. The velocity of the jet, $V_1$, the densimetric Froude number, $F'_1$, and the entrainment coefficient, $a$, were calculated with respect to longitudinal position and are listed in Tables 7.24 and 7.25. Photos 6.1 and 6.2 correspond with Table 7.24. Photos I.1 and I.2 correspond with Table 7.25.

From the photographs of the splash at the weir, the longitudinal extent and height of the splash were determined. The average rate of rise of the splash was also calculated and is listed in Tables 7.26 and 7.27. Photos 6.3 and 6.4 correspond with Table 7.26. Photo I.3 corresponds with Table 7.27.

From the photographs of the moving internal hydraulic jump, the initial depth, $y_1$, and sequent depth, $y_2$, and their respective longitudinal positions, $x_1$ and $x_2$, were established. The temperatures at the longitudinal positions
of the initial depths were estimated from the thermal data. The velocity, \( V_1 \), corresponding to the initial depth was estimated from the photographs of the jet. The length of the hydraulic jump, \( L_j \), the surge velocity, \( V_s \), and the relative densimetric Froude number, \( F'_{m1} \), were calculated with respect to longitudinal position of the initial depth and with respect to time and are listed in Tables 7.28 and 7.29. Photos 6.5 to 6.10 correspond with Table 7.28. Photos I.4 to I.9 correspond with Table 7.29.

From the photographs of the submerged hydraulic jump, the sequent depth, \( y_z \), the submerged depth, \( y_m \), and the length of the jump, \( L_j \), were established. The temperature at the longitudinal position corresponding to the sequent depth and the temperature of the influent were estimated from the thermal data. The velocity, \( V_2 \), corresponding to the sequent depth, and the densimetric Froude number, \( F'_{m2} \), were calculated and are listed in Tables 7.30 and 7.31. Table 7.30 corresponds with Photo 6.11. Table 7.31 corresponds with Photo I.10.

The splash at the baffle is pictured in Photos 6.12 and 6.13 and I.11. The stratification is pictured in Photos 6.14 and I.12.

7.3.2. BUOYANT SURFACE JET CASE DATA REDUCTION

During the buoyant surface jet case experiments, four phases were observed. The four phases were:
1. rising plume with entrainment
2. buoyant surface jet
3. moving internal hydraulic jump
4. stratification.

From the photographs, information describing three phases (rising plume with entrainment, buoyant surface jet, and moving internal hydraulic jump) was determined.

Additional thermal information was estimated from the influent/effluent temperature curves and from the thermal contour plots from the temperature study. The reduced data for the two buoyant surface jet cases are listed in Tables 7.32 to 7.37.

From the photographs of the rising plume phase, the trajectory and velocity of the rising jet were calculated and are shown in Figures 7.3 and 7.4. The gross dilution from the rising jet, \( Q_{\text{d1}} \) and the gross dilution factor, \( D_1 \) were calculated and are listed in Tables 7.32 and 7.33. Photos 6.15 to 6.17 correspond with Figure 7.3 and Table 7.32. Photos I.13 to I.15 correspond with Figures 7.4 and Table 7.33.

From the photographs of the buoyant surface jet phase, the average jet depth, \( y_1 \), with respect to longitudinal position, \( x_1 \), was determined. The temperatures at the longitudinal sections were estimated from the thermal data. The velocity of the jet, \( V_1 \), the densimetric Froude number, \( F'_{1} \), and the entrainment coefficient, \( \alpha \) were
calculated with respect to longitudinal position and are listed in Tables 7.34 and 7.35. Photos 6.18 to 6.21 correspond with Table 7.34. Photos I.15 to I.17 correspond with Table 7.35.

From the photographs of the moving internal hydraulic jump, the initial depth, \( y_1 \), and sequent depth, \( y_2 \), and their longitudinal positions, \( x_1 \) and \( x_2 \), were established. The temperatures at the longitudinal positions of the initial depths were estimated from the thermal data. The velocity, \( V_1 \), corresponding to the initial depth was estimated from the jet data. The length of the hydraulic jump, \( L_1 \), the surge velocity, \( V_s \), and the relative densimetric Froude number, \( F'_{x1} \), were calculated with respect to longitudinal position of the initial depth and with respect to time and are listed in Tables 7.36 and 7.37. Photos 6.22 and 6.23 correspond with Table 7.36. Photos I.18 and I.19 correspond with Table 7.37.

The stratification is pictured in Photos 6.24 and I.20.

7.4. FLUORESCENT DYE STUDY DATA REDUCTION

During the fluorescent dye study experiments, the influent and effluent of the test section were sampled for the concentration of a dye, Sodium Fluorescein. The tests were conducted with the continuous injection of the dye. Two denser wall jet cases and two buoyant surface jet cases
were conducted with a weir height of 17 cm and for gate openings of 3 cm and 5 cm. The time at which the test section was fully mixed was the time of equilibrium. Computer plots of the dye concentration versus time were made. The temperatures at several stationary points within the tank were also recorded during the tests.

From the dye concentration plots and the corresponding thermal data, the time of occurrence for several characteristic events of the dye concentration levels in the influent and effluent samples were determined. These factors were:

1. the time of the initial appearance of the dye in the effluent, $T_i$
2. the time of rises in the level of the concentration of the dye
3. peak levels of the dye concentration
4. the time between successive peak levels
5. the time at which equilibrium conditions were achieved, $T_e$

In Table 7.30, the results of the fluorescent dye study data reduction are shown. All plots were based on a dimensionless parameter, time/detention time. The plots present the pattern of the influent dye concentration. The plots underpredicted the average concentration of the influent dye due to the drawdown of clean water by the sampling pump which created a local depression in the
density current.

From the temperature influent/effluent plots in Figures 6.27, 6.30, 6.33 and 6.36, the time of the delay in the appearance of a temperature difference between the influent and the effluent was estimated. This corresponded to the lag time between the appearance of the dye in the influent and the effluent samples found during the experiments.

7.4.1. DENSER WALL JET CASE DATA REDUCTION

From the dye concentration plots of influent and effluent samples from the denser wall jet cases in Figures 6.25, 6.26, 6.31 and 6.32, additional information was obtained. The influent dye concentration peaked and then leveled off to its equilibrium concentration. The effluent dye concentration rose and peaked four times. The first rise in the effluent dye concentration was the time of the initial appearance of the dye.

7.4.2. BUOYANT SURFACE JET CASE DATA REDUCTION

From the dye concentration plots of influent and effluent samples from the buoyant surface jet cases in Figures 6.28, 6.29, 6.34 and 6.35, additional information was obtained. The influent dye concentration peaked once and maintained its equilibrium concentration. The effluent dye concentration rose and peaked twice. The tests were conducted with the continuous injection of the dye. The
time at which the test section was fully mixed was the time of equilibrium.

7.5. TEMPERATURE STUDY DATA ANALYSIS

Thermal contour plots were made from the temperature study data for seven test conditions. The results of the data reduction from the four denser wall jet cases and the three buoyant surface jet cases are listed in Tables 7.1 to 7.25.

7.5.1. DENSER WALL JET CASE DATA ANALYSIS

In the case of the denser wall jet, the phenomena progressed through six phases that were visible in the thermal contour plots. The data reduced from the denser wall jet cases are listed in Tables 7.1 to 7.12.

Figures 7.5 to 7.9 are dimensionless plots representing the denser wall jet. The depth, velocity, temperature, densimetric Froude number, entrainment coefficient, and thermal entrainment correction factor of the jet are plotted versus longitudinal distance. For a weir height of 17 cm and a gate opening of 3 cm the dimensionless jet depth increased with respect to longitudinal distance from 1.0 to 1.5; the dimensionless jet velocity decreased from 1.0 to 0.76; the densimetric Froude number decreased from 2.55 to 2.34; the entrainment coefficient ranged from 0.0044 to 0.0030; the thermal
entrainment correction factor ranged from 0.21 to 0.48. For a weir height of 17 cm and a gate opening of 5 cm the dimensionless jet depth increased with respect to longitudinal distance from 1.0 to 1.18; the dimensionless jet velocity decreased from 1.0 to 0.93; the densimetric Froude number remained constant at 1.26; the entrainment coefficient ranged from 0.0048 to 0.0056; the thermal entrainment correction factor ranged from 0.08 to 0.13. For a weir height of 8.5 cm and a gate opening of 3 cm the dimensionless jet depth increased with respect to longitudinal distance from 1.0 to 1.57; the dimensionless jet velocity decreased from 1.0 to 0.88; the densimetric Froude number decreased from 1.15 to 1.01; the entrainment coefficient ranged from 0.0182 to 0.0103; the thermal entrainment correction factor ranged from 0.027 to 0.037. For a weir height of 8.5 cm and a gate opening of 5 cm the dimensionless jet depth increased with respect to longitudinal distance from 1.0 to 1.17; the dimensionless jet velocity decreased from 1.0 to 0.96; the densimetric Froude number increased from 0.74 to 0.87; the entrainment coefficient ranged from 0.0047 to 0.0100; the thermal entrainment correction factor ranged from 0.07 to 0.01.

The splash at the weir is detailed in Tables 7.5 to 7.8. For a weir height of 17 cm and a gate opening of 3 cm the longitudinal extent of the splash averaged 11.8 cm above the jet surface and the average rate of rise of the splash.
was 1.3 cm/s. For a weir height of 17 cm and a gate opening of 5 cm the longitudinal extent of the splash averaged 9.4 cm above the jet surface and the average rate of rise of the splash was 0.4 cm/s. For a weir height of 8.5 cm and a gate opening of 3 cm the longitudinal extent of the splash averaged 9.1 cm above the jet surface and the average rate of rise of the splash was 0.1 cm/s. For a weir height of 8.5 cm and a gate opening of 5 cm the longitudinal extent of the splash averaged 10.8 cm above the jet surface and the average rate of rise of the splash was 0.2 cm/s.

The moving internal hydraulic jump is characterized by the length of jump, surge velocity, sequent depth, relative densimetric Froude number, and jump entrainment for each test condition. The reduced data is listed in Tables 7.9 and 7.10. For a weir height of 17 cm and a gate opening of 3 cm length of the jump increased from 9.2 cm to 20.5 cm; the surge velocity ranged from 0.1 cm/s to 1.4 cm/s and the sequent depth averaged 13.3 cm; the relative densimetric Froude number averaged 1.57; the maximum moving internal hydraulic jump entrainment factor averaged 0.31. For a weir height of 17 cm and a gate opening of 5 cm length of the jump decreased from 23.1 cm to 14.8 cm; the surge velocity was 1.4 cm/s and the sequent depth was 12.6 cm; the relative densimetric Froude number was 1.30; the maximum moving internal hydraulic jump entrainment factor was 0.42. The minimum moving internal hydraulic jump entrainment factor
was 0.00 for both cases. The dimensionless ratios of sequent depth to initial depth and length of jump to sequent depth are plotted with respect to relative densimetric Froude number in Figures 7.10 and 7.11. The ratio of the sequent depth to the initial depth ranged from 1.26 to 2.08 for relative densimetric Froude numbers from 1.02 to 1.62. The ratio of the length of the jump to the sequent depth ranged from 0.72 to 2.34 for relative densimetric Froude number from 1.02 to 1.62.

The submerged internal hydraulic jumps formed for both cases with weir height of 17 cm and they are sketched in Figures 7.12 and 7.13. The submerged depth, \( y_s \), the length of the jump, \( L_s \), and the sequent depth, \( y_s \), are indicated on the figures. The relative densimetric Froude numbers at the sequent depth section are approximately 0.26 for the 3 cm gate opening case and 0.19 for the 5 cm gate opening case. The maximum submerged hydraulic jump entrainment factor was 0.38 for the 3 cm gate opening case and 0.60 for the 5 cm gate opening case. The minimum submerged hydraulic jump entrainment factor was 0.00 for both cases.

7.5.2. BUOYANT SURFACE JET CASE DATA ANALYSIS

In the case of the buoyant surface jet, the phenomena progressed through four phases that were visible in the thermal contour plots. The data reduced from the denser
wall jet cases are listed in Tables 7.15 to 7.25.

Tables 7.13 and 7.14 list the gross dilution factor of the rising plume with entrainment for the test conditions with weir height of 17 cm. For the case with gate opening of 3 cm, the gross dilution factor averaged 1.45. For the case with gate opening of 5 cm, the gross dilution factor was 0.70.

Tables 7.15 to 7.17 characterize the buoyant surface jet. The depth, velocity, temperature, densimetric Froude number, and entrainment coefficient of the jet are listed. For a weir height of 17 cm and a gate opening of 3 cm the dimensionless jet depth increased from 0.53 to 1.33; the dimensionless jet velocity was 0.72; the densimetric Froude number decreased from 2.25 at the gate opening to 0.82 at the surface; the entrainment coefficient was 0.13. For a weir height of 17 cm and a gate opening of 5 cm the dimensionless jet depth increased from 0.42 to 0.72; the dimensionless jet velocity was 0.53; the densimetric Froude number decreased from 2.61 at the gate opening to 0.84 at the surface; the entrainment coefficient was 0.04. For a weir height of 8.5 cm and a gate opening of 3 cm the dimensionless jet depth increased from 0.33 to 1.40; the dimensionless jet velocity decreased from 1.50 to 0.90; the densimetric Froude number decreased from 1.61 at the gate opening to 0.89 at the surface; the entrainment coefficient was 0.03.
The moving internal hydraulic jump is characterized by the length of jump, surge velocity, sequent depth, and relative densimetric Froude number for each test condition. The reduced data is listed in Tables 7.18 to 7.20. For a weir height of 17 cm and a gate opening of 3 cm length of the jump averaged 11.9 cm; the surge velocity ranged was 0.6 cm/s and the sequent depth averaged 13.4 cm; the relative densimetric Froude number was 1.04. For a weir height of 17 cm and a gate opening of 5 cm length of the jump averaged 21.2 cm; the surge velocity ranged was 0.8 cm/s and the sequent depth averaged 13.4 cm; the relative densimetric Froude number decreased from 1.20 to 1.05. For a weir height of 8.5 cm and a gate opening of 3 cm length of the jump increased from 8.0 cm to 19.3 cm; the surge velocity decreased from 1.1 cm/s to 0.5 cm/s and the sequent depth averaged 7.4 cm; the relative densimetric Froude number decreased from 1.24 to 1.01.

In the stratification phase, an estimate of the dilution of the wedge of cold water at the bottom of the tank is listed in Tables 7.21 to 7.23. For the case with gate opening of 3 cm and weir height of 17 cm, the wedge dilution coefficient varied from 0.123 to 0.435. For the case with gate opening of 5 cm and weir height of 17 cm, the wedge dilution coefficient varied from 0.047 to 0.095. For the case with gate opening of 3 cm and weir height of 8.5 cm, the wedge dilution coefficient varied from 0.133 to
0.138.

7.6. PHOTOGRAPHIC DYE STUDY DATA ANALYSIS

Photographs were taken during the flow visualization dye tests under four test conditions. The results of the data reduction from the two denser wall jet cases and the two buoyant surface jet cases are listed in Tables 7.24 to 7.37.

7.6.1. DENSER WALL JET CASE DATA ANALYSIS

In the case of the denser wall jet, the phenomena progressed through six phases that were visible in the photographs. The data reduced from the denser wall jet cases are listed in Tables 7.24 to 7.31.

Figures 7.14 to 7.15 are dimensionless plots representing the denser wall jet. The depth, velocity, temperature, densimetric Froude number, and entrainment coefficient of the jet are plotted versus longitudinal distance. For a weir height of 17 cm and a gate opening of 3 cm the dimensionless jet depth increased with respect to longitudinal distance from 1.0 to 1.6; the dimensionless jet velocity decreased from 1.0 to 0.94; the densimetric Froude number increased from 3.06 to 3.42; the entrainment coefficient ranged from 0.040 to 0.004. For a weir height of 17 cm and a gate opening of 5 cm the dimensionless jet depth increased with respect to longitudinal distance from
1.0 to 1.24; the dimensionless jet velocity increased from 1.0 to 1.03; the densimetric Froude number increased from 1.24 to 1.60; the entrainment coefficient ranged from 0.051 to 0.005.

The splash at the weir is detailed in Tables 7.26 and 7.27. In both cases, the longitudinal extent of the splash is 10 cm above the jet surface. For the 3 cm gate opening, the average rate of rise of the splash was 2.3 cm/s. For the 5 cm gate opening, the average rate of rise of the splash averaged 1.1 cm/s.

The moving internal hydraulic jump is characterized by the length of jump, surge velocity, sequent depth, relative densimetric Froude number, and jump entrainment for each test condition. The reduced data is listed in Tables 7.28 and 7.29 and plotted in Figures 7.17 to 7.22. For a weir height of 17 cm and a gate opening of 3 cm length of the jump averaged 10.5 cm; the surge velocity ranged from 0.5 cm/s to 2.3 cm/s and the sequent depth averaged 13.4 cm; the relative densimetric Froude number ranged from 1.44 to 2.01; the maximum moving internal hydraulic jump entrainment factor ranged from 1.51 to 0.28 and the minimum moving internal hydraulic jump entrainment factor ranged from 0.00 to 0.51. For a weir height of 17 cm and a gate opening of 5 cm length of the jump increased from 9.0 cm to 22.0 cm; the surge velocity ranged from 0.1 cm/s to 1.4 cm/s and the sequent depth averaged 14.7 cm; the relative densimetric
Froude number decreased from 1.62 to 1.01; the maximum moving internal hydraulic jump entrainment factor ranged from 0.09 to 0.74 and the minimum moving internal jump entrainment factor was 0.00. The dimensionless ratios of sequent to initial depth and length of jump to sequent depth are plotted with respect to relative densimetric Froude number in Figures 7.23 and 7.24. The ratio of sequent depth to initial depth ranged from 1.50 to 3.00; the ratio of the length of the jump to the sequent depth ranged from 0.47 to 1.47; the relative densimetric Froude numbers ranged from 1.01 to 2.01.

The submerged internal hydraulic jumps are sketched in Figures 7.25 and 7.26. The submerged depth, $y_s$, the length of the jump, $L_s$, and the sequent depth, $y_z$, are indicated on the figures. The relative densimetric Froude numbers at the sequent depth section are approximately 0.20 for the 3 cm gate opening case and 0.16 for the 5 cm gate opening case. The maximum submerged hydraulic jump entrainment factor ranged from 0.40 to 1.30 for the 3 cm gate opening case and from 0.34 to 0.44 for the 5 cm gate opening case. The minimum submerged hydraulic jump entrainment factor ranged from 0.00 to 0.30 for the 3 cm gate opening case and was 0.00 for the 5 cm gate opening case.
7.6.2. BUOYANT SURFACE JET CASE DATA ANALYSIS

In the case of the buoyant surface jet, the phenomena progressed through four phases that were visible in the photographs. The data reduced from the buoyant surface jet cases are listed in Tables 7.32 to 7.37.

Figures 7.3 and 7.4 and Tables 7.32 and 7.33 describe the rising plume with entrainment phase. Figures 7.3 and 7.4 plot the trajectory and velocity of the rising plume. Tables 7.32 and 7.33 list the gross dilution factor of the rising plume with entrainment. For the case with gate opening of 3 cm, the gross dilution factor ranged from 0.72 to 1.45. For the case with gate opening of 5 cm, the gross dilution factor was 1.13.

Tables 7.34 and 7.35 characterize the buoyant surface jet. The depth, velocity, temperature, densimetric Froude number, and entrainment coefficient of the jet are listed. For a weir height of 17 cm and a gate opening of 3 cm the dimensionless jet depth increased from 2.3 to 4.2; the dimensionless jet velocity increased from 0.40 to 0.75; the densimetric Froude number decreased from 2.18 at the gate opening to 0.04 at the surface; the entrainment coefficient ranged from 0.013 to 0.035. For a weir height of 17 cm and a gate opening of 5 cm the dimensionless jet depth increased from 0.4 to 2.0; the dimensionless jet velocity decreased from 0.90 to 0.19; the densimetric Froude number decreased from 2.64 at the gate opening to 0.39 at the surface; the
entrainment coefficient was 0.30.

The moving internal hydraulic jump is characterized by the length of jump, surge velocity, sequent depth, and relative densimetric Froude number for each test condition. The reduced data is listed in Tables 7.36 to 7.37. For a weir height of 17 cm and a gate opening of 3 cm length of the jump was 6.0 cm; the surge velocity ranged was 2.6 cm/s and the sequent depth averaged 17.0 cm; the relative densimetric Froude number was 1.15. For a weir height of 17 cm and a gate opening of 5 cm length of the jump was 11.0 cm; the surge velocity ranged was 1.0 cm/s and the sequent depth averaged 14.3 cm; the relative densimetric Froude number was 1.16.

7.7. FLUORESCENT DYE STUDY DATA ANALYSIS

The fluorescent dye study involved four test conditions. The results of the data reduction from two denser wall jet cases and two buoyant surface jet cases are in Table 7.38.

7.7.1. DENSER WALL JET CASE DATA ANALYSIS

From Table 7.38, a comparison between the characteristics of the denser wall jet cases at gate openings of 3 cm and 5 cm were made. The dimensionless time of the initial appearance of the dye in the effluent was similar at 0.39 and 0.37 respectively. The time of the peak
in the influent dye concentration was not similar. The sampling pump produced a local depression of the density current and was withdrawing clear water which resulted in underprediction in the level of the concentration of the dye of the influent, especially in the 5 cm gate opening case. The time between the peak concentrations of the effluent indicated a resonance time for the tank. For the 3 cm gate opening, the time between peak concentrations was 0.52, 0.56 and 0.51. For the 5 cm gate opening, the time between peak concentration was 1.03, 0.61 and 1.05. The time at which equilibrium was achieved was not similar, which was due to the influence of the sampling pump.

7.7.2. BUOYANT SURFACE JET CASE DATA ANALYSIS

From Table 7.38, a comparison between the characteristics of the buoyant surface jet cases at gate openings of 3 cm and 5 cm were made. The dimensionless time of the initial appearance of the dye in the effluent was similar, at 0.46 and 0.52 respectively. The time of the peak in the influent dye concentration was similar, at 0.57 and 0.55 respectively. The time at which equilibrium was achieved was similar at 2.30 and 2.63 respectively.
8. DISCUSSION

8.1. INTRODUCTION

The thermal, photographic and fluorescent experiments were conducted under several conditions of geometry, momentum and buoyancy; the characteristic depths, velocity and temperature of the jet and moving hydraulic jump were determined. The characteristic depths, velocity and temperature of the jet and moving hydraulic jump can be compared for experiments executed under similar conditions.

8.2. DENSER WALL JET CASE

The following six phases were observed during the denser wall jet experiments:

1. denser wall jet,
2. splash at weir,
3. moving internal hydraulic jump,
4. submerged hydraulic jump,
5. splash at baffle,
6. stratification.

Phases 3 and 4 were similar to the drowned internal jump and the free internal jump studied by Baddour and Abbink (1982, 1987) which were established by an underflow of a stable density stratification. From the thermal contour plots and the photographs, information describing four phases (denser wall jet, splash at weir, moving internal hydraulic jump and
submerged hydraulic jump) was determined. From the fluorescent dye plots, information describing the denser wall jet was determined.

8.2.1. DENSER WALL JET

From the denser wall jet phase, the average jet depth, \( y_1 \), and the average jet temperature, \( T_1 \), with respect to longitudinal position, \( x_1 \), were determined. The velocity of the jet, \( V_1 \), the densimetric Froude number, \( F'_1 \), the entrainment coefficient, \( \alpha \), and the thermal entrainment correction factor, \( \sigma \), were calculated with respect to longitudinal position.

Figure 8.1 plots the dimensionless depth term, \( y_1/y_0 \), with respect to dimensionless longitudinal position, \( x_1/y_0 \), for the thermal data and the photographic data. The depth increased as longitudinal position increased. The depth determined from the photographic data was slightly higher than that of the thermal data. For the cases with gate opening of 3 cm, the maximum \( y_1/y_0 \) was approximately 1.5. For the cases with gate opening of 5 cm, the maximum \( y_1/y_0 \) was approximately 1.2. This increase is caused by frictional resistance and the entrainment of the ambient fluid.

Figure 8.2 plots the dimensionless velocity term, \( V_1/V_0 \), with respect to dimensionless longitudinal position, \( x_1/y_0 \), for the thermal data and the photographic data. The
velocity decreased as longitudinal position increased. The velocity determined from the photographic data was higher than that of the thermal data; however this may have been due to the longitudinal diffusion of the dye in the photographic experiment. In case 6, a photographic test, the velocity appeared to increase; again this may have been due to the longitudinal diffusion of the dye in the photographic experiment.

Figure 8.3 plots the dimensionless temperature term, \((T-T_\infty)/(T_\infty-T_0)\), with respect to dimensionless longitudinal position, \(x_1/Y_\infty\), for the thermal data and the photographic data. The temperature term increased as longitudinal position increased. The maximum value of \((T-T_\infty)/(T_\infty-T_0)\) was between 0.3 and 0.6. The increase in temperature is the result of the entrainment of the higher temperature ambient fluid.

Figure 8.4 plots the densimetric Froude number, \(F'_{1}\), with respect to dimensionless longitudinal position, \(x_1/Y_\infty\), for the thermal data and the photographic data. The densimetric Froude number decreased as longitudinal position increased. In case 6, the densimetric Froude number appeared to increase since the velocity increased due to the diffusion of the dye in the photographic experiment.

Figure 8.5 plots the entrainment coefficient, \(\alpha\), with respect to dimensionless longitudinal position, \(x_1/Y_\infty\), for the thermal data and the photographic data. The
The entrainment coefficient, $\alpha$, fell within the range of 0.003 to 0.05. The entrainment coefficient decreased as longitudinal position increased. Figure 8.6 plots the entrainment coefficient, $\alpha$, with respect to local densimetric Richardson number, $R_i$, and a relationship governing the entrainment coefficient as a function of Richardson number developed by Christodoulou [1986]

$$\alpha = 0.002 / R_i. \tag{8.1}$$

There was good agreement between the data and Eq. 8.1 for cases 2 and 5. In cases 1, 3 and 4 the value of $\alpha$ estimated from the experiments was greater than that of the values predicted from Eq. 8.1. In case 5, there was better agreement with the points corresponding to values far from the gate opening.

Figure 7.9 plots the thermal entrainment correction factor, $\sigma$, with respect to longitudinal position, $x_1$, for the thermal data. The thermal entrainment correction factor, $\sigma$, fell within the range of 0.00 to 0.50; the range for case 1 was 0.2 to 0.5 and the range for cases 2, 3 and 4 was 0.00 to 0.15.

From the fluorometric experiments, the dimensionless time of the initial appearance of the dye in the effluent, $T_1$, was determined. The corresponding term in the thermal tests and the photographic tests is the time at which the splash at the weir reaches the top of the weir. Table 8.1 lists the detention time, $t_a$, and the dimensionless time
term, $T_i$, for the thermal data, photographic data and the fluorometric data. It should be noted that the temperature tests, photographic dye tests and the fluorometric dye tests were independent tests. The conditions of the tests, for the same geometry, were similar, but not identical, in terms of momentum and buoyancy (discharge, ambient temperature and the temperature in the initial tank). Thus the resulting data from the tests are not identical. The photographic data has the smallest $T_i$ values, due to the apparent dispersion and diffusion of the dye. The thermal data and the fluorometric data have good agreement for similar cases. The range of the values of $T_i$ is between 0.17 and 0.39.

8.2.2. SPLASH AT WEIR

From the thermal data and the photographic data of the splash at the weir, the longitudinal extent above the jet surface, and height of the splash were determined. The longitudinal extent, height, height above the jet surface, average rate of rise of the splash, and average rate of rise of splash in terms of the velocity of the jet at the weir are listed in Table 8.2. The longitudinal extent of the splash is approximately 10 cm for all six cases. The splash height approached the height of the weir for the temperature tests and the photographic tests with a weir height of 17 cm. The splash height remained below the weir height in the temperature tests with a weir height of 8.5 cm. The initial
height of the splash above the jet surface in terms of the densimetric momentum of the jet at a section before the weir varies between 0.08 and 0.59 for the six cases. The average rate of rise of the splash is higher in the photographic tests than in the thermal tests. This is partially due to the large time increment between contour plots, yielding an actual average rate of rise greater than the calculated value. The 17 cm weir has an average rate of rise of the splash between 0.4 and 2.3 cm/s; the 8.5 cm weir has an average rate of rise of the splash at 0.1 and 0.2 cm/s. The 17 cm weir has an average rate of rise of the splash in terms of the jet velocity between 0.13 and 0.48; the 8.5 cm weir has an average rate of rise of the splash in terms of the jet velocity between 0.04 and 0.10.

8.2.3. MOVING INTERNAL HYDRAULIC JUMP

Table 8.3 lists the sequent depth, $y_z$, the surge velocity, $V_s$, the relative densimetric Froude number, $F'_{z1}$, and the maximum discharge entrained by the moving internal hydraulic jump factor, $C_{i\text{max}}$. For the 17 cm weir, the sequent depth, $y_z$, ranged from 12 to 15 cm; the surge velocity, $V_s$, ranged from 0.1 to 2.0 cm/s; the relative densimetric Froude number, $F'_{z1}$, ranged from 1.3 to 2.5; $C_{i\text{max}}$ ranged from 0.09 to 1.51. For the 8.5 cm weir, the sequent depth, $y_z$, was approximately 7.5 cm; the surge velocity, $V_s$, ranged from 0.3 to 1.3 cm/s; the relative
densimetric Froude number, \( F' \), was approximately 1.05; \( C_{\text{max}} \) was approximately 0.3. Figure 8.7 plots \( y_2/y_1 \) versus relative densimetric Froude number, \( F' \), for the experimental data and for the neutral case rectangular hydraulic jump. Cases 1 and 2 have good agreement with the neutral rectangular hydraulic jump. Cases 5 and 6 have values of \( y_2/y_1 \) greater than that of the neutral rectangular hydraulic jump. Figure 8.8 plots \( L_2/y_2 \) versus relative densimetric Froude number, \( F' \), for the experimental data. The ratio \( L_2/y_2 \) decreased slightly with increasing relative densimetric Froude number. The low values of \( L_2/y_2 \) show that the internal hydraulic jumps are steep with jump lengths shorter than those of the classical hydraulic jumps.

8.2.4. SUBMERGED HYDRAULIC JUMP

The submerged hydraulic jump developed in all four of the tests conducted with weir heights of 17 cm. The submerged hydraulic jumps are plotted in Figures 7.13, 7.14, 7.27, 7.28. The submerged hydraulic jumps appear to form sooner in the photographic tests than in the thermal tests. The length of the jumps are longer in the thermal tests than in the photographic tests; the secent depths are lower in the thermal tests than in the photographic tests. These inconsistencies in test results may be the result of the differences in the test conditions. The temperature tests
and the photographic tests were run independently and under similar conditions of momentum and buoyancy. The temperature tests had lower surge velocities and relative densimetric Froude numbers, mainly due to the differences in the thermal conditions from the photographic tests. Table 8.4 lists the densimetric Froude number, $F'_{\infty}$ and the maximum discharge entrained by the submerged hydraulic jump factor, $C_{z_{\text{max}}}$. The densimetric Froude number was approximately 0.2 for all four cases. The values of $C_{z_{\text{max}}}$ ranged from 0.26 to 1.30 and was greater in the photographic tests than in the thermal tests.

8.3. BUOYANT SURFACE JET CASE

During the buoyant surface jet experiments, four phases were observed:

1. rising plume with entrainment,
2. buoyant surface jet,
3. moving internal hydraulic jump,
4. stratification.

Phases 2 and 3 were similar to the surface jet, surface jet followed by a surface jump, and surface jump studied by Rajaratnam and Subramanyan [1986a] which were established by a plane surface jet of warm water entering a rectangular channel into a large depth of stagnant cold water. From the thermal contour plots and the photographs, information describing the four phases was determined. From the
fluorescent dye plots, information describing the buoyant surface jet was determined.

8.3.1. RISING PLUME WITH ENTRAINMENT

From the rising plume with entrainment phase, the trajectory, velocity, the gross dilution, $Q_{d1}$, and the gross dilution factor, $D_1$, of the rising plume were calculated. The trajectory and the velocity of the rising plume from the photographic tests are shown in Figures 7.3 and 7.4. The velocity of the rising plume decreases as it reaches the surface. The trajectory of the rising plume from the temperature tests can be seen in the contour plots in Figures 6.12 to 6.14, H.10 to H.12, and H.27. The gross dilution factor ranged from 0.70 to 2.38. The gross dilution factor indicated the bulk effect of the entrainment through the plume on both the side of the baffle and the side of the weir.

8.3.2. SURFACE JET

From the buoyant surface jet phase, the average jet depth, $y_1$, and the average jet temperature, $T_1$, with respect to longitudinal position, $x_1$, were determined. The velocity of the jet, $V_1$, the densimetric Froude number, $F'1$, and the entrainment coefficient, $\alpha$, were calculated with respect to longitudinal position.

Tables 7.15, 7.16, 7.34 and 7.36 list the
characteristics of the surface jet. The average jet depth increased as the jet expanded with time. The rate of advance of the leading edge of the jet remained approximately constant for each case and in the range of 1.0 to 2.5 cm/s. The temperature decreased as the longitudinal position increased due to the entrainment of the cooler ambient fluid below. The densimetric Froude number decreased, and became subcritical, as the jet depth increased. The entrainment coefficient remained small, between 0.013 and 0.519.

A surface effect is clearly visible in Photos 6.19 to 6.21, I.15 and I.16 and slightly apparent in Figures 6.13, 6.14, H.11, H.12, H.28 and H.29. This surface effect is a gravity effect due to the nap on the weir and results in a thin layer extending from the advancing edge of the jet to the weir.

From the fluorometric experiments, the time of the initial appearance of the dye in the effluent, $T_1$, was determined. The corresponding term in the thermal tests and the photographic tests was the time at which the surface jet reached the weir. Table 8.5 lists the detention time, $t_d$, and the $T_1$, for the thermal data, photographic data and the fluorometric data. The dispersion and diffusion of the dyes used and the difference in the momentum and buoyancy conditions for tests with the same geometry resulted in values in the same range but numerically different. The
range of the values of $T_1$ is between 0.20 and 0.52.

8.3.3. MOVING INTERNAL HYDRAULIC JUMP

Table 8.6 lists the sequent depth, $y_1$, the surge velocity, $V_m$, and the relative densimetric Froude number, $F'_{e1}$ of the inverted moving internal hydraulic jump phase of the buoyant surface jet case. For the 17 cm weir, the sequent depth, $y_1$, ranged from 11.8 to 18 cm; the surge velocity, $V_m$, ranged from 0.6 to 2.6 cm/s; the relative densimetric Froude number, $F'_{e1}$, ranged from 1.01 to 1.20. The very low relative densimetric Froude numbers indicate that the moving internal hydraulic jumps were very weak. The jumps formed did not travel the entire length of the flume, but they joined the rising plume approximately half way between the gate and the weir. Figure 8.9 plots $y_2/y_1$ versus relative densimetric Froude number, $F'_{e1}$, for the experimental data and for the classical rectangular hydraulic jump. The disagreement in Figure 8.9 could be due to the effect of entrainment, the influence of the withdrawal point, or because the jump was limited by the tank depth. Figure 8.10 plots $L_3/y_2$ versus relative densimetric Froude number, $F'_{e1}$, for the experimental data. The ratio $L_3/y_2$ ranges from 0.3 to 2.7. The low values of $L_3/y_2$ show that the internal hydraulic jumps are steep with jump lengths shorter than that of the classical hydraulic jumps.
8.3.4. STRATIFICATION

In the stratification phase, mixing of the warm and cool layers occurs at the gate and the bottom of the tank. The rate at which the cold water wedge was diluted by the upper, warm layer, was expressed in terms of a wedge dilution factor, $D_2$. The wedge dilution factor was calculated from the temperature data and is listed in Tables 7.21 to 7.23. The wedge dilution factor ranged from 0.047 to 0.435. The cases with smaller gate opening (3 cm) had higher values of $D_2$. 

9. MODEL EVALUATION

9.1. INTRODUCTION

In this chapter, the evaluation of the mathematical jet submodel and moving internal hydraulic jump submodel is presented. The sensitivity and stability of the mathematical jet submodel and moving internal hydraulic jump submodel are presented. A verification of both submodels and the submerged hydraulic jump equation is presented and discussed.

9.2. STABILITY

To study the convergence and stability of the mathematical models, several runs were made using various space increments, \( \delta x \), and time increments, \( \delta t \). It was found that a space increment \( \delta x \leq 0.01 \text{ m} \), or \( \delta x \leq 5 \times 10^{-3}/y_{\infty} \), satisfied convergence and stability requirements in the jet submodel. It was also found that a time increment \( \delta t \leq 0.02 \text{ seconds} \), or \( \delta t \leq 3 \times 10^{-2} x y_{\infty}/V_{\infty} \), gave stable moving hydraulic jumps.

9.3. SENSITIVITY ANALYSIS

The mathematical model was run under varying conditions to check the sensitivity of the model to various factors. The sensitivity of the solution was studied with respect to:

1. the entrainment coefficient of the jet,
2. the bed shear,
3. the Reynolds number of the jet,
4. the densimetric Froude number of the jet,
5. the relative submergence of the gate,
6. the jump storage loss coefficient,
7. the jump entrainment coefficient.

A typical model run was carried out under the following conditions:

1. \( q = 1.58 \times 10^{-3} \text{ m}^3/\text{s/m} \),
2. \( y_\alpha = 0.05 \text{ m} \),
3. \( T_\alpha = 28.5 \text{ °C} \),
4. \( T_\theta = 32.5 \text{ °C} \),
5. \( \alpha = 0.002 / \text{Ri} \),
6. \( h_\omega = 0.17 \text{ m} \).

For a typical jet submodel run, the predicted values at the weir relative to values at the gate were an increase in the depth of the jet of 60 percent, a decrease in the velocity of the jet of 29 percent and a decrease in the densimetric Froude number of 39 percent. The temperature at the weir section was 0.5 °C higher than the temperature at the gate section.

For a typical moving internal hydraulic jump submodel run, the sequent depth increased 0.2 percent, the surge velocity decreased 26 percent and the relative densimetric Froude number increased 39 percent as the jump traveled from the weir to the gate in 84 seconds.
9.3.1. JET SUBMODEL

The sensitivity of the jet submodel was evaluated with respect to the effect of the entrainment coefficient, the bed shear, and the Reynolds number on the depth, velocity, temperature and densimetric Froude number of the jet.

9.3.1.1. ENTRAINMENT COEFFICIENT

The mathematical model was run for different values of the entrainment coefficient of the jet. The results are listed in Table 9.1. A decrease in the entrainment coefficient results in a decrease in the rate of change in the jet depth, velocity, temperature and densimetric Froude number. An increase in the entrainment coefficient results in an increase in the rate of change in the jet depth, velocity, temperature and densimetric Froude number.

9.3.1.2. BED SHEAR

The mathematical model was run for different values of the bed shear. The results are listed in Table 9.2. A decrease in the bed shear results in a decrease in the rate of change in the jet depth, velocity and densimetric Froude number and an increase in the rate of change in the temperature. An increase in the bed shear results in an increase in the rate of change in the jet depth, velocity
and densimetric Froude number and a decrease in the rate of change in the temperature.

9.3.1.3. REYNOLDS NUMBER

The mathematical model was run for different values of the Reynolds number and consequently discharge and the initial temperature of the jet while maintaining the same initial densimetric Froude number. The results are listed in Table 9.3. An increase in the Reynolds number, discharge and difference in the ambient fluid and the jet temperatures results in no change in the rate of change in the jet depth or velocity. The change in the temperature of the jet increased in magnitude, although the fraction of the temperature difference between the ambient fluid and jet remains constant. An increase in the Reynolds number results in an increase in the rate of change in the jet densimetric Froude number.

9.3.2. MOVING INTERNAL HYDRAULIC JUMP SUBMODEL

The sensitivity of the moving internal hydraulic jump submodel was evaluated with respect to the effect of the densimetric Froude number of the jet, the relative submergence of the gate, the jump storage loss coefficient and the jump entrainment coefficient on the sequent depth, the surge velocity, the relative densimetric Froude number and the time it took the jump to travel from the weir to the
9.3.2.1. DENSIMETRIC FROUDE NUMBER OF JET

The mathematical model was run for different rates of change in the Froude number of the jet by changing the entrainment coefficient of the jet. The results are listed in Table 9.4. In all cases, the relative densimetric Froude number changed in proportion to the jet densimetric Froude number. As the jet densimetric Froude number increased, the surge velocity decreased 18 to 35 percent as the jump travelled toward the gate. The time for the jump to travel to the gate was between 70 and 93.5 seconds. The sequent depth increased between 0.2 and 3.1 percent.

9.3.2.2. RELATIVE SUBMERGENCE OF THE GATE

The mathematical model was run gate submergence of 0.088, 0.176 and 0.353. For the case with submergence of the gate at 0.088, there was no convergence for the moving hydraulic jump submodel, as the initial sequent depth exceeded the depth of the tank. For the case with submergence of the gate at 0.353, there was no change in the data from the standard case (submergence equal to 0.176).

9.3.2.3. JUMP STORAGE LOSS AND ENTRAINMENT COEFFICIENTS

The mathematical model was run with and without storage loss and entrainment in the jump. The results are
listed in Table 9.5. In all cases, the relative densimetric Froude number increased 39 to 40 percent and the surge velocity decreased 17 to 26 percent as the jump travelled toward the gate. The time for the jump to travel to the gate was between 70 and 84 seconds. The sequent depth decreased approximately 3 percent without entrainment and remained constant or increased slightly with 10 percent jump entrainment.

9.4. DENSER WALL JET

The experimental data and corresponding model predictions for the denser wall jet are illustrated in Figures 9.1 to 9.10. The variations in the depth of the jet, velocity, temperature, densimetric Froude number and temperature factor, \((T-T_w)/(T_0-T_w)\), are plotted against distance for two cases (case 1 temperature data and case 5 photographic data).

The model's prediction of jet depth and velocity variation in Figures 9.1, 9.2, 9.6, and 9.7 show good agreement with the corresponding experimental data. In the model, steady state conditions were assumed, however this was not achieved in the experiments. The temperature predicted in Figures 9.3 and 9.8 show similar trends although the actual values are not identical; therefore, the densimetric Froude number predicted in Figures 9.4 and 9.9 show similar trends and the values predicted were in the
same range as in the experiments. Figures 9.5 and 9.10, which illustrate the variation in the temperature factor, show the same trend in the variation in the temperature factor, although the model underpredicts this factor since steady state conditions were assumed in the model but not achieved in the experiments.

9.5. INTERNAL HYDRAULIC JUMPS

Two internal hydraulic jumps formed. The first jump, a moving internal hydraulic jump, traveled from the weir to the gate. A mathematical submodel predicted the longitudinal position of the initial depth of the jump, the sequent depth and the surge velocity with respect to time. The second jump which formed was a nearly steady internal submerged hydraulic jump at the gate.

9.5.1. MOVING INTERNAL HYDRAULIC JUMP

The experimental data and corresponding model predictions for the moving internal hydraulic jump are illustrated in Figures 9.11 to 9.18. The variations in the sequent depth, surge velocity, and relative densimetric Froude number are plotted against longitudinal distance corresponding to the initial depth of the hydraulic jump and the ratio of the sequent depth to the initial depth is plotted versus the relative densimetric Froude number for two cases (case 1 temperature data and case 5 photographic
The model's prediction of sequent depth variation in Figures 9.11 and 9.15 show that the model underpredicts the value of the sequent depth by about 15 percent. The surge velocity predicted in Figures 9.12 show similar average values to those observed in the experiments and in Figure 9.16 the surge velocity is in the same range as in the experiments. Figures 9.13 and 9.17, which illustrate the variation in the relative densimetric Froude number, show the same trend in the variation, although the model overpredicts the values since in the model, steady state conditions were assumed for the wall jet. Figures 9.14 and 9.18 are plots of the ratio of sequent depth to initial depth versus relative densimetric Froude number. Figure 9.14 shows close agreement between the experimental and theoretical cases and with the classical hydraulic jump equation. Figure 9.18 shows close agreement between the theoretical data and the classical hydraulic jump equation, although the experimental data is mostly above the classical hydraulic equation line. This may be due to errors in velocity measurements because of dye dispersion as observed in the photographic tests.

9.5.2. INTERNAL SUBMERGED HYDRAULIC JUMP

The experimental data and corresponding model predictions for the submerged internal hydraulic jump are
listed in Table 9.6. The ratios of the sequent depth to the initial depth, the ratios of submerged depth to sequent depth and densimetric Froude numbers at the sequent depth section are listed. The model's prediction of ratio of the submerged depth to the sequent depth is in the same range as in the experiments. The densimetric Froude numbers predicted are in the same range as those calculated from the experiments, although the values of the densimetric Froude numbers in the model are overpredicted since in the model, steady state conditions were assumed for the wall jet.

9.6. DISCUSSION

In evaluating the mathematical submodels, the predicted and measured values for six cases of experimental conditions were plotted in Figures 9.19 to 9.25.

For the denser wall jet submodel, the depth of the jet, velocity, temperature, and densimetric Froude number were plotted for predicted and measured values. Figure 9.19 shows that the prediction of the depth of the jet showed good agreement for cases 1, 5 and 6, and fair agreement for cases 3 and 4. Figure 9.20 shows that the prediction of the velocity of the jet was close to the calculated velocity from the experiments. Figure 9.21 shows that the predicted values of the jet temperature are close to the experimental values for cases 1, 2, 3, 4 and 6. Case 5 has predicted values lower than the measured values. Figure 9.22 shows
that the predicted values for densimetric Froude number of
the jet agree closely for the temperature data (cases 1, 2, 3 and 4) and case 6. Case 5 has predicted values lower than
the measured values.

For the moving internal hydraulic jump submodel, the
sequent depth of the jump, the surge velocity, and relative
densimetric Froude number were plotted for predicted and
measured values for cases 1, 2, 5 and 6. In cases 3 and 4,
the phenomena did not develop due to the restriction of the
tank depth. Figure 9.23 shows that the sequent depth of the
jump was underpredicted by approximately twenty percent.
This is probably the result of neglecting the volume loss,
or neglecting the jump entrainment, or due to unsteady
wall jet. Figure 9.24 shows that the prediction of the
surge velocity was scattered. Figure 9.25 shows that the
predicted values of the relative densimetric Froude number
are higher than the measured values and this is because they
are dependent on the surge velocity. The cases with a
smaller gate opening show more scatter.
10. CONCLUSIONS

The conclusions of this thesis are considered in two parts:

1. those related to the denser wall jet, moving internal hydraulic jump and submerged hydraulic jump;

2. those related to the experimental studies of the buoyant surface jet and inverted moving internal hydraulic jump.

10.1. DENSER WALL JET

Six phases were observed in the experiments of the denser wall jet phenomena (denser wall jet, splash at weir, moving internal hydraulic jump, submerged hydraulic jump, splash at baffle and stratification). The jet submodel accurately described variation in the depth of the jet and velocity with respect to longitudinal position. The prediction of the temperature of the jet was in the same range as the experimental values, although the model assumed steady state which was not achieved in the experiments. The moving internal hydraulic jump submodel described the longitudinal position of the initial depth, the sequent depth and the surge velocity with respect to time. The plot of the ratio of the sequent depth to the initial depth of the jump versus relative densimetric Froude number was
scattered above the plot for the classical hydraulic jump. The moving internal hydraulic jumps were steeper and shorter than the classical hydraulic jumps. The maximum factor of the discharged entrained by the moving internal hydraulic jump was found to be between 0.09 and 1.51. This indicates the importance of entrainment in the moving internal hydraulic jump.

10.2. BUOYANT SURFACE JET

Four phases were observed in the experiments of the buoyant surface jet phenomena (rising plume with entrainment, buoyant surface jet, moving internal hydraulic jump and stratification). The rising plume entrained ambient fluid on both the side of the baffle and the side of the weir. The surface jet increased in depth. The moving internal hydraulic jump travelled backwards from the weir until it joined with the rising plume. The plot of the ratio of the sequest depth to the initial depth of the jump versus relative densimetric Froude number was scattered on the plot for the classical hydraulic jump. The internal hydraulic jumps were steeper and shorter than the classical hydraulic jumps. In the stratification phase, the wedge of cold water at the tank bottom was diluted at a very slow rate. The wedge dilution factor was between 0.047 and 0.435.
10.3. RECOMMENDATIONS

The study has given rise to several points for further research. The following investigations are recommended:

1. experimental study of the density currents in rectangular sedimentation tank including a velocity study;
2. an unsteady state numerical model for the denser wall jet;
3. a numerical model for the buoyant surface jet and moving inverted internal hydraulic jump.
Appendix A. FIGURES
Figure 2.1 Definition Sketch of Buoyant Surface Jets and Jumps
Figure 3.1 Definition Sketch for the Jet
Figure 3.2 Definition Sketch for the Travelling Hydraulic Jump
Figure 3.3 Definition Sketch of Relative Control Volume of Moving Internal Hydraulic Jump
Figure 3.4 Definition Sketch of the Submerged Hydraulic Jump
Figure 4.1 The Test Section

Figure 4.2 The Dye Injection System
Figure 6.1 Denser Wall Jet Case Thermal Contour Plot
G=3 cm, hw=17 cm, Q=0.184 L/s at t=12 s

Depth (mm)

Longitudinal Position (mm)

Temperature (Degrees Celsius)

17 18 19 20
21 22 23 24
25 26 27 28
29 30 31 32
Figure 6.2  Denser Wall Jet Case Thermal Contour Plot
G = 3 cm, hw = 17 cm, Q = 0.184 L/s at t = 30 s

Temperature (Degrees Celsius)

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Figure 6.3  Denser Wall Jet Case Thermal Contour Plot
G=3 cm, hw=17 cm, Q=0.184 L/s at t=42 s

Temperature (Degrees Celsius)

17  18  19  20
21  22  23  24
25  26  27  28
29  30  31  32
Figure 6.4  Denser Wall Jet Case Thermal Contour Plot
Q=3 cm, hw=17 cm, Q=0.184 L/s at t=30 s

Temperature (Degrees Celsius)

T  17  18  19  20
--- 21  22  23  24
--- 25  26  27  28
--- 29  30  31  32
Figure 6.5 Denser Wall Jet Case Thermal Contour Plot
G=3 cm, hw=17 cm, Q=0.184 L/s at t=72 s
Figure 6.6 Denser Wall Jet Case Thermal Contour Plot
G=3 cm, hw=17 cm, Q=0.184 L/s at t=90 s
Figure 6.7  Denser Wall Jet Case Thermal Contour Plot
G=3 cm, hw=17 cm, Q=0.184 L/s at t=120 s
Figure 6.8  Denser Wall Jet Case Thermal Contour Plot
G=3 cm, hw=17 cm, Q=0.184 L/s at t=150 s
Figure 6.9 Denser Wall Jet Case Thermal Contour Plot
G=3 cm, hw=17 cm, Q=0.184 L/s at t=180 s
Figure 6.10  Denser Wall Jet Case Thermal Contour Plot
G=3 cm, hw=17 cm, Q=0.184 L/s at t=210 s

Temperature (Degrees Celsius)

1  17  18  19  20
21  22  23  24
25  26  27  28
29  30  31  22
Figure 6.11 Denser Wall Jet Case Thermal Contour Plot
G=3 cm, hw=17 cm, Q=0.184 L/s at t=240 s
Figure 6.12  Buoyant Surface Jet Case Thermal Contour Plot  
G=3 cm, hw=17 cm, Q=0.078 L/s at t=12 s

[Diagram showing temperature contours with depth and longitudinal position]
Figure 6.13  Buoyant Surface Jet Case Thermal Contour Plot
Q=3 cm, hw=17 cm, Q=0.078 L/s at t=30 s
Figure 6.14 Buoyant Surface Jet Case Thermal Contour Plot
G=3 cm, hw=17 cm, Q=0.078 L/s at t=42 s

Temperature (Degrees Celsius)

Depth (mm)

Longitudinal Position (mm)
Figure 6.15 Buoyant Surface Jet Case Thermal Contour Plot

$G = 3$ cm, $hw = 17$ cm, $Q = 0.078$ L/s at $t = 60$ s
Figure 6.16 Buoyant Surface Jet Case Thermal Contour Plot
G=3 cm, hw=17 cm, Q=0.078 L/s at t=72 s
Figure 6.17  Buoyant Surface Jet Case Thermal Contour Plot
G=3 cm, hw=17 cm, Q=0.078 L/s at t=90 s
Figure 6.18 Buoyant Surface Jet Case Thermal Contour Plot
G=3 cm, hw=17 cm, Q=0.078 L/s at t=120 s
Figure 6.19  Buoyant Surface Jet Case Thermal Contour Plot
$G=3$ cm, $hw=17$ cm, $Q=0.078$ L/s at $t=150$ s

Temperature (Degrees Celsius):

1  30  31  32  33
34  35  36

Depth (mm)

Longitudinal Position (mm)
Figure 6.20 Buoyant Surface Jet Case Thermal Contour Plot
G=3 cm, hw=17 cm, Q=0.078 L/s at t=174 s

Temperature (Degrees Celsius)

1  30  31  32  33  34  35  36
Figure 6.21 Denser Wall Jet Temperature Plot
of Influent/Effluent for
$G = 3 \text{ cm}$, $h_w = 17 \text{ cm}$, $Q = 0.171 \text{ L/s}$
Figure 6.22 Buoyant Surface Jet Temperature Plot of Influent/Effluent for
$G = 3 \text{ cm}$, $h_w = 17 \text{ cm}$, $Q = 0.072 \text{ L/s}$
Figure 6.23  Denser Wall Jet Temperature Plot of Influent/Effluent for $G = 5 \text{ cm}, h_w = 17 \text{ cm}, Q = 0.189 \text{ L/s}$
Figure 6.24 Buoyant Surface Jet Temperature Plot of Influent/Effluent for $G = 5$ cm, $h_w = 17$ cm, $Q = 0.191$ L/s
Figure 6.25 Denser Wall Jet Dye Concentration Plot for $D = 5 \text{ cm}$, $h_w = 17 \text{ cm}$, $Q = 0.190 \text{ L/s}$ at Influent

Figure 6.26 Denser Wall Jet Dye Concentration Plot for $D = 5 \text{ cm}$, $h_w = 17 \text{ cm}$, $Q = 0.190 \text{ L/s}$ at Effluent
Figure 6.29 Buoyant Surface Jet Dye Concentration Plot for
G = 5 cm, h_w = 17 cm, Q = 0.230 L/s at Influent

Figure 6.29 Buoyant Surface Jet Dye Concentration Plot for
G = 5 cm, h_w = 17 cm, Q = 0.230 L/s at Effluent
Figure 8.30 Buoyant Surface Jet Temperature Plot of Influent/Effluent for
$G = 5 \text{ cm}, \ h_w = 17 \text{ cm}, \ Q = 0.230 \text{ L/s}$
Figure 6.31 Denser Wall Jet Dye Concentration Plot for
\[ G = 3 \text{ cm}, \ h_w = 17 \text{ cm}, \ Q = 0.197 \text{ L/s at Influenent} \]

Figure 6.32 Denser Wall Jet Dye Concentration Plot for
\[ G = 3 \text{ cm}, \ h_w = 17 \text{ cm}, \ Q = 0.197 \text{ L/s at Effluent} \]
Figure 6.33 Denser Nalit Jet Temperature Plot of Influent/Effluent for $G = 3 \text{ cm}, h_w = 0.17 \text{ cm}, Q = 0.105 \text{ L/s}$
Figure 6.34 Buoyant Surface Jet Dye Concentration Plot for
$G = 3 \text{ cm}$, $h_w = 17 \text{ cm}$, $Q = 0.110 \text{ L/s at Influent}$

Figure 6.35 Buoyant Surface Jet Dye Concentration Plot for
$G = 3 \text{ cm}$, $h_w = 17 \text{ cm}$, $Q = 0.110 \text{ L/s at Effluent}$
Figure 6.36 Buoyant Surface Jet Temperature Plot of Influent/Effluent for

\[ G = 3 \text{ cm}, \ h_w = 17 \text{ cm}, \ Q = 0.110 \text{ L/s} \]
Figure 7.1 Denser Wall Jet Case Thermal Contour Plot
Without Smoothing for
G=3 cm, hw=17 cm, Q=0.184 L/s at t=30 s
Figure 7.2 Buoyant Surface Jet Case Thermal Contour Plot Without Smoothing for $G=3$ cm, $hw=17$ cm, $Q=0.079$ L/s at $t=42$ s
Figure 7.3 Trajectory and Velocity of Rising Plume for $G = 3$ cm, $h_w = 17$ cm, $Q = 0.072$ K/s

Figure 7.4 Trajectory and Velocity of Rising Plume for $G = 5$ cm, $h_w = 17$ cm, $Q = 0.191$ K/s
Figure 7.5 Denser Wall Jet Case Thermal Data
Depth and Velocity versus Distance

Case 1: $G=3$ cm, $hw=17$ cm, $Q=0.184$ L/s, $Y_g=3.0$ cm, $V_g=4.9$ cm/s
Case 2: $G=5$ cm, $hw=17$ cm, $Q=0.189$ L/s, $Y_g=5.0$ cm, $V_g=3.0$ cm/s
Case 3: $G=3$ cm, $hw=8.5$ cm, $Q=0.057$ L/s, $Y_g=2.0$ cm, $V_g=2.3$ cm/s
Case 4: $G=5$ cm, $hw=8.5$ cm, $Q=0.072$ L/s, $Y_g=2.9$ cm, $V_g=2.0$ cm/s

LEGEND
- - - Case 1: $Y/Y_g$
- - - Case 2: $Y/Y_g$
- - - Case 3: $Y/Y_g$
- - - Case 4: $Y/Y_g$
- - - Case 1: $V/V_g$
- - - Case 2: $V/V_g$
- - - Case 3: $V/V_g$
- - - Case 4: $V/V_g$
Figure 7.6 Denser Wall Jet Case Thermal Data
Temperature versus Distance

Case 1: \( G=3 \text{ cm}, \ h_w=17 \text{ cm}, \ Q=0.184 \text{ L/s}, \ Y_g=3.0 \text{ cm}, \ V_g=4.9 \text{ cm/s} \)
Case 2: \( G=5 \text{ cm}, \ h_w=17 \text{ cm}, \ Q=0.189 \text{ L/s}, \ Y_g=5.0 \text{ cm}, \ V_g=3.0 \text{ cm/s} \)
Case 3: \( G=3 \text{ cm}, \ h_w=8.5 \text{ cm}, \ Q=0.057 \text{ L/s}, \ Y_g=2.0 \text{ cm}, \ V_g=2.3 \text{ cm/s} \)
Case 4: \( G=5 \text{ cm}, \ h_w=8.5 \text{ cm}, \ Q=0.072 \text{ L/s}, \ Y_g=2.9 \text{ cm}, \ V_g=2.0 \text{ cm/s} \)
Figure 7.7 Denser Wall Jet Case Thermal Data
Densimetric Froude Number versus Distance

Case 1: \( G=3 \text{ cm}, \ h_w=17 \text{ cm}, \ Q=0.184 \text{ L/s}, \ Y_g=3.0 \text{ cm}, \ V_g=4.9 \text{ cm/s} \)
Case 2: \( G=5 \text{ cm}, \ h_w=17 \text{ cm}, \ Q=0.189 \text{ L/s}, \ Y_g=5.0 \text{ cm}, \ V_g=3.0 \text{ cm/s} \)
Case 3: \( G=3 \text{ cm}, \ h_w=8.5 \text{ cm}, \ Q=0.057 \text{ L/s}, \ Y_g=2.0 \text{ cm}, \ V_g=2.3 \text{ cm/s} \)
Case 4: \( G=5 \text{ cm}, \ h_w=8.5 \text{ cm}, \ Q=0.072 \text{ L/s}, \ Y_g=2.9 \text{ cm}, \ V_g=2.0 \text{ cm/s} \)
Figure 7.8  Denser Wall Jet Case Thermal Data
Entrainment Coefficient, $\alpha$, versus Distance

Case 1: $G=3$ cm, $hw=17$ cm, $Q=0.184$ L/s, $Yg=3.0$ cm, $Vg=4.9$ cm/s
Case 2: $G=5$ cm, $hw=17$ cm, $Q=0.189$ L/s, $Yg=5.0$ cm, $Vg=3.0$ cm/s
Case 3: $G=3$ cm, $hw=8.5$ cm, $Q=0.057$ L/s, $Yg=2.0$ cm, $Vg=2.3$ cm/s
Case 4: $G=5$ cm, $hw=8.5$ cm, $Q=0.072$ L/s, $Yg=2.9$ cm, $Vg=2.0$ cm/s
Figure 7.9 Denser Wall Jet Case Thermal Data
Thermal Entrainment Correction Factor, $\sigma$, versus Distance

Case 1: $G=3$ cm, $h_w=17$ cm, $Q=0.184$ L/s, $Y_g=3.0$ cm, $V_g=4.9$ cm/s
Case 2: $G=5$ cm, $h_w=17$ cm, $Q=0.189$ L/s, $Y_g=5.0$ cm, $V_g=3.0$ cm/s
Case 3: $G=3$ cm, $h_w=8.5$ cm, $Q=0.057$ L/s, $Y_g=2.0$ cm, $V_g=2.3$ cm/s
Case 4: $G=5$ cm, $h_w=8.5$ cm, $Q=0.072$ L/s, $Y_g=2.9$ cm, $V_g=2.0$ cm/s
Figure 7.10  Denser Wall Jet Case Thermal Data

Y2 / Y1 versus Fr1

Case 1: G=3 cm, hw=17 cm, Q=0.184 L/s, Yg=3.0 cm, Vg=4.9 cm/s
Case 2: G=5 cm, hw=17 cm, Q=0.189 L/s, Yg=5.0 cm, Vg=3.0 cm/s
Case 3: G=3 cm, hw=8.5 cm, Q=0.057 L/s, Yg=2.0 cm, Vg=2.3 cm/s
Case 4: G=5 cm, hw=8.5 cm, Q=0.072 L/s, Yg=2.9 cm, Vg=2.0 cm/s
Figure 7.11 Denser Wall Jet Case Thermal Data
Lj / Y2 versus Fr1

Case 1: G=3 cm, hw=17 cm, Q=0.184 L/s, Yg=3.0 cm, Vg=4.9 cm/s
Case 2: G=5 cm, hw=17 cm, Q=0.189 L/s, Yg=5.0 cm, Vg=3.0 cm/s
Case 3: G=3 cm, hw=8.5 cm, Q=0.057 L/s, Yg=2.0 cm, Vg=2.3 cm/s
Case 4: G=5 cm, hw=8.5 cm, Q=0.072 L/s, Yg=2.9 cm, Vg=2.0 cm/s
Figure 7.12 Denser Wall Jet Case Thermal Data
Submerged Internal Hydraulic Jump
for \( G=3 \text{ cm}, h_w=17 \text{ cm}, Q=0.184 \text{ L/s} \)
Figure 7.13 Denser Wall Jet Case Thermal Data
Submerged Internal Hydraulic Jump
for G=5 cm, hw=17 cm, Q=0.188 L/s

LEGEND
- - - Time = 90 s
△ △ △ Time = 120 s
- - - - Time = 150 s
- - - - Time = 210 s
Figure 7.14 Denser Wall Jet Case
Photographic Data
Depth and Velocity versus Distance

Case 5: \( G=3 \) cm, \( h_w=17 \) cm, \( Q=0.171 \) L/s, \( Y_g=3.0 \) cm, \( V_g=4.6 \) cm/s
Case 6: \( G=5 \) cm, \( h_w=17 \) cm, \( Q=0.189 \) L/s, \( Y_g=5.0 \) cm, \( V_g=3.0 \) cm/s
Figure 7.15  Denser Wall Jet Case
Photographic Data
Densimetric Froude Number versus Distance

Case 5:  G=3 cm, hw=17 cm, Q=0.171 L/s, Yg=3.0 cm, Vg=4.6 cm/s
Case 6:  G=5 cm, hw=17 cm, Q=0.189 L/s, Yg=5.0 cm, Vg=3.0 cm/s
Figure 7.16 Denser Wall Jet Case
Photographic Data
Entrainment Coefficient, $\alpha$, versus Distance

Case 5: $G=3$ cm, $h_w=17$ cm, $Q=0.171$ L/s, $Y_g=3.0$ cm, $V_g=4.6$ cm/s
Case 6: $G=5$ cm, $h_w=17$ cm, $Q=0.189$ L/s, $Y_g=5.0$ cm, $V_g=3.0$ cm/s
Figure 7.17 Denser Wall Jet Case 5 Photographic Data

$Y_2, L_j, V_s, F'r_1$ versus $X_1$
for $G=3$ cm, $h_w=17$ cm, $Q=0.171$ L/s
Figure 7.18  Denser Wall Jet Case 5
Photographic Data
Y2, Lj versus Time
for G=3 cm, hw=17 cm, Q=0.171 L/s
Figure 7.19  Denser Wall Jet Case 5
Photographic Data
Vs, Fr1 versus Time
for G=3 cm, hw=17 cm, Q=0.171 L/s
Figure 7.20 Denser Wall Jet Case 6
Photographic Data

\[ Y_2, L_j, V_s, F'r_1 \] versus \( X_1 \)
for \( G=5 \text{ cm}, h_w=17 \text{ cm}, Q=0.189 \text{ L/s} \)

![Graph showing data points for different variables vs. distance](image-url)
Figure 7.21 Denser Wall Jet Case 6
Photographic Data
$Y_2$, $L_j$ versus Time
for $G=5$ cm, $hw=17$ cm, $Q=0.189$ L/s

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LEGEND
- $Y_2$
- $L_j$
Figure 7.22  Denser Wall Jet Case 6
Photographic Data

$V_s, Fr_1$ versus Time
for $G=5$ cm, $h_w=17$ cm, $Q=0.189$ L/s
Figure 7.23 Denser Wall Jet Case
Photographic Data

Y2 / Y1 versus Fr1

Case 5: G=3 cm, hw=17 cm, Q=0.171 L/s
Case 6: G=5 cm, hw=17 cm, Q=0.189 L/s
Figure 7.24 Denser Wall Jet Case
Photographic Data
Lj / Y2 versus Fr1

Case 5: G=3 cm, hw=17 cm, Q=0.171 L/s
Case 6: G=5 cm, hw=17 cm, Q=0.189 L/s

Legend:
- □ □ □ Case 5
- △ △ △ Case 6
Figure 7.25  Denser Wall Jet Case 5
Photographic Data
Submerged Internal Hydraulic Jump
for G=3 cm, hw=17 cm, Q=0.171 L/s

LEGEND  
- - - - Time = 66.5 s  
△ △ △ Time = 69.0 s  
● ● ● Time = 71.3 s  
● ● ● Time = 73.3 s
Figure 7.26 Denser Wall Jet Case 6
Photographic Data
Submerged Internal Hydraulic Jump for G=5 cm, hw=17 cm, Q=0.189 L/s

![Diagram of hydraulic jump with key points L, y1, y2, and y_s indicating depth at different longitudinal positions. The legend shows the time for the jet at 68.6 s and 90.8 s.](image-url)
Figure 8.1 Denser Wall Jet Experimental Data
Depth versus Distance

Case 1: $G=3$ cm, $h=17$ cm, $Q=0.184$ L/s, $Y_g=3.0$ cm, $V_g=4.9$ cm/s
Case 2: $G=5$ cm, $h=17$ cm, $Q=0.189$ L/s, $Y_g=5.0$ cm, $V_g=3.0$ cm/s
Case 3: $G=3$ cm, $h=8.5$ cm, $Q=0.057$ L/s, $Y_g=2.0$ cm, $V_g=2.3$ cm/s
Case 4: $G=5$ cm, $h=8.5$ cm, $Q=0.072$ L/s, $Y_g=2.9$ cm, $V_g=2.0$ cm/s
Case 5: $G=3$ cm, $h=17$ cm, $Q=0.171$ L/s, $Y_g=3.0$ cm, $V_g=4.6$ cm/s
Case 6: $G=5$ cm, $h=17$ cm, $Q=0.189$ L/s, $Y_g=5.0$ cm, $V_g=3.0$ cm/s
Figure 8.2 Denser Wall Jet Experimental Data
Velocity versus Distance

Case 1: \( G = 3 \) cm, \( hw = 17 \) cm, \( Q = 0.184 \) L/s, \( Yg = 3.0 \) cm, \( Vg = 4.9 \) cm/s
Case 2: \( G = 5 \) cm, \( hw = 17 \) cm, \( Q = 0.189 \) L/s, \( Yg = 5.0 \) cm, \( Vg = 3.0 \) cm/s
Case 3: \( G = 3 \) cm, \( hw = 8.5 \) cm, \( Q = 0.057 \) L/s, \( Yg = 2.0 \) cm, \( Vg = 2.3 \) cm/s
Case 4: \( G = 5 \) cm, \( hw = 8.5 \) cm, \( Q = 0.072 \) L/s, \( Yg = 2.9 \) cm, \( Vg = 2.0 \) cm/s
Case 5: \( G = 3 \) cm, \( hw = 17 \) cm, \( Q = 0.171 \) L/s, \( Yg = 3.0 \) cm, \( Vg = 4.6 \) cm/s
Case 6: \( G = 5 \) cm, \( hw = 17 \) cm, \( Q = 0.189 \) L/s, \( Yg = 5.0 \) cm, \( Vg = 3.0 \) cm/s
Figure 8.3 Denser Wall Jet Experimental Data
\((T - T_g) / (T_0 - T_g)\) versus \(X / Y_g\)

Case 1: \(G = 3\) cm, \(h_w = 17\) cm, \(Q = 0.184\) L/s, \(Y_g = 3.0\) cm, \(V_g = 4.9\) cm/s
Case 2: \(G = 5\) cm, \(h_w = 17\) cm, \(Q = 0.189\) L/s, \(Y_g = 5.0\) cm, \(V_g = 3.0\) cm/s
Case 3: \(G = 3\) cm, \(h_w = 8.5\) cm, \(Q = 0.057\) L/s, \(Y_g = 2.0\) cm, \(V_g = 2.3\) cm/s
Case 4: \(G = 5\) cm, \(h_w = 8.5\) cm, \(Q = 0.072\) L/s, \(Y_g = 2.9\) cm, \(V_g = 2.0\) cm/s
Case 5: \(G = 3\) cm, \(h_w = 17\) cm, \(Q = 0.171\) L/s, \(Y_g = 3.0\) cm, \(V_g = 4.6\) cm/s
Case 6: \(G = 5\) cm, \(h_w = 17\) cm, \(Q = 0.189\) L/s, \(Y_g = 5.0\) cm, \(V_g = 3.0\) cm/s

LEGEND
- - - - Case 1
- - - - Case 2
- - - - Case 3
- - - - Case 4
- - - - Case 5
- - - - Case 6
Figure 8.4 Denser Wall Jet Experimental Data
Densimetric Froude Number versus Distance

Case 1: G=3 cm, hw=17 cm, Q=0.184 L/s, Yg=3.0 cm, Vg=4.9 cm/s
Case 2: G=5 cm, hw=17 cm, Q=0.189 L/s, Yg=5.0 cm, Vg=3.0 cm/s
Case 3: G=3 cm, hw=8.5 cm, Q=0.057 L/s, Yg=2.0 cm, Vg=2.3 cm/s
Case 4: G=5 cm, hw=8.5 cm, Q=0.072 L/s, Yg=2.9 cm, Vg=2.0 cm/s
Case 5: G=3 cm, hw=17 cm, Q=0.171 L/s, Yg=3.0 cm, Vg=4.6 cm/s
Case 6: G=5 cm, hw=17 cm, Q=0.189 L/s, Yg=5.0 cm, Vg=3.0 cm/s

LEGEND
- - - - Case 1
- - - - Case 2
- - Case 3
- - - - Case 4
- - - - Case 5
- - - - Case 6

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Figure 8.5 Denser Wall Jet Experimental Data

Entrainment Coefficient, $\alpha$ versus Distance

Case 1: $G=3$ cm, $hw=17$ cm, $Q=0.184$ L/s, $Yg=3.0$ cm, $Vg=4.9$ cm/s
Case 2: $G=5$ cm, $hw=17$ cm, $Q=0.189$ L/s, $Yg=5.0$ cm, $Vg=3.0$ cm/s
Case 3: $G=3$ cm, $hw=8.5$ cm, $Q=0.057$ L/s, $Yg=2.0$ cm, $Vg=2.3$ cm/s
Case 4: $G=5$ cm, $hw=8.5$ cm, $Q=0.072$ L/s, $Yg=2.9$ cm, $Vg=2.0$ cm/s
Case 5: $G=3$ cm, $hw=17$ cm, $Q=0.171$ L/s, $Yg=3.0$ cm, $Vg=4.6$ cm/s
Case 6: $G=5$ cm, $hw=17$ cm, $Q=0.189$ L/s, $Yg=5.0$ cm, $Vg=3.0$ cm/s
Figure 8.6  Denser Wall Jet Experimental Data  
\( \alpha \) versus Ri

Case 1:  G=3 cm, hw=17 cm, Q=0.184 L/s, Yg=3.0 cm, Vg=4.9 cm/s  
Case 2:  G=5 cm, hw=17 cm, Q=0.188 L/s, Yg=5.0 cm, Vg=3.0 cm/s  
Case 3:  G=3 cm, hw=4.5 cm, Q=0.057 L/s, Yg=2.0 cm, Vg=2.3 cm/s  
Case 4:  G=5 cm, hw=4.5 cm, Q=0.072 L/s, Yg=2.9 cm, Vg=2.0 cm/s  
Case 5:  G=3 cm, hw=17 cm, Q=0.171 L/s, Yg=3.0 cm, Vg=4.6 cm/s  
Case 6:  G=5 cm, hw=17 cm, Q=0.169 L/s, Yg=5.0 cm, Vg=3.0 cm/s

![Graphical representation of the data showing Entrainment Coefficient, \( \alpha \) versus Richardson Number, Ri. The graph includes markers for each case as described in the list above. The legend indicates the symbols used for each case:  
+ + + Case 1  
○ ○ ○ Case 3  
△ △ △ Case 4  
◇ ◇ ◇ Case 5  
* * * Case 6  
--- Eq. 8.1]
Figure 8.7 Denser Wall Jet Experimental Data

\[ \frac{Y_2}{Y_1} \text{ versus } \text{Fr1} \]

Case 1: G=3 cm, hw=17 cm, Q=0.184 L/s, Yg=3.0 cm, Vg=4.9 cm/s
Case 2: G=5 cm, hw=17 cm, Q=0.189 L/s, Yg=5.0 cm, Vg=3.0 cm/s
Case 3: G=3 cm, hw=8.5 cm, Q=0.087 L/s, Yg=2.0 cm, Vg=2.3 cm/s
Case 4: G=5 cm, hw=8.5 cm, Q=0.072 L/s, Yg=2.9 cm, Vg=2.0 cm/s
Case 5: G=3 cm, hw=17 cm, Q=0.171 L/s, Yg=3.0 cm, Vg=4.6 cm/s
Case 6: G=5 cm, hw=17 cm, Q=0.189 L/s, Yg=5.0 cm, Vg=3.0 cm/s
Figure 8.8  Denser Wall Jet Experimental Data

$Lj / Y2$ versus $Fr1$

Case 1:  $G=3$ cm, $hw=17$ cm, $Q=0.184$ L/s, $Yg=3.0$ cm, $Vg=4.9$ cm/s
Case 2:  $G=5$ cm, $hw=17$ cm, $Q=0.139$ L/s, $Yg=5.0$ cm, $Vg=3.0$ cm/s
Case 3:  $G=3$ cm, $hw=8.5$ cm, $Q=0.057$ L/s, $Yg=2.0$ cm, $Vg=2.3$ cm/s
Case 4:  $G=5$ cm, $hw=8.5$ cm, $Q=0.072$ L/s, $Yg=2.9$ cm, $Vg=2.0$ cm/s
Case 5:  $G=3$ cm, $hw=17$ cm, $Q=0.171$ L/s, $Yg=3.0$ cm, $Vg=4.6$ cm/s
Case 6:  $G=5$ cm, $hw=17$ cm, $Q=0.189$ L/s, $Yg=5.0$ cm, $Vg=3.0$ cm/s
Figure 8.9 Bouyant Surface Jet Experimental Data
Y2 / Y1 versus Fr1

Case 9: G=3 cm, hw=17 cm, Q=0.076 L/s
Case 10: G=5 cm, hw=17 cm, Q=0.179 L/s
Case 11: G=3 cm, hw=8.5 cm, Q=0.050 L/s
Case 12: G=3 cm, hw=17 cm, Q=0.074 L/s
Case 13: G=5 cm, hw=17 cm, Q=0.194 L/s

LEGEND

Case 9  Case 10  Case 11  Case 12  Case 13  Classical Jump
Figure 8.10 Bouyant Surface Jet Experimental Data

Lj / Y2 versus Fr1

Case 9: G=3 cm, hw=17 cm, Q=0.078 L/s
Case 10: G=5 cm, hw=17 cm, Q=0.179 L/s
Case 11: G=3 cm, hw=8.5 cm, Q=0.050 L/s
Case 12: G=3 cm, hw=17 cm, Q=0.074 L/s
Case 13: G=5 cm, hw=17 cm, Q=0.194 L/s

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**LEGEND**

+ + + Case 9
○ ○ ○ Case 11
△ △ △ Case 12
◇ ◇ ◇ Case 13
Figure 9.1 Denser Wall Jet Case 1
Depth versus Distance

Case 1: \( d = 3 \text{ cm}, \ h_w = 17 \text{ cm}, \ Q = 0.184 \text{ L/s}, \ Y_g = 3.0 \text{ cm}, \ V_g = 4.9 \text{ cm/s} \)
Figure 9.2 Denser Wall Jet Case 1
Velocity versus Distance

Case 1: G=3 cm, hw=17 cm, Q=0.184 L/s, Yg=3.0 cm, Vg=4.9 cm/s
Figure 9.3 Denser Wall Jet Case 1
Temperature versus Distance

Case 1: G=3 cm, hw=17 cm, Q=0.184 L/s, Yg=3.0 cm, Vg=4.9 cm/s
Figure 9.4 Denser Wall Jet Case 1
Densimetric Froude Number versus Distance

Case 1: \( G = 3 \) cm, \( h_w = 17 \) cm, \( Q = 0.184 \) L/s, \( Y_g = 3.0 \) cm, \( V_g = 4.9 \) cm/s

![Graph showing Densimetric Froude Number versus Distance with experimental and theoretical data points.](image-url)
Figure 9.5 Denser Wall Jet Case 1

\( \frac{T - T_g}{T_0 - T_g} \) versus \( \frac{X}{Y_g} \)

Case 1: \( G=3 \text{ cm}, h_w=17 \text{ cm}, Q=0.184 \text{ L/s}, Y_g=3.0 \text{ cm}, V_g=4.9 \text{ cm/s} \)

![Graph showing the relationship between \( \frac{T - T_g}{T_0 - T_g} \) and \( \frac{X}{Y_g} \)](image)

Legend:
- ▲▲ Experimental
- ■■ Theoretical
Figure 9.6 Denser Wall Jet Case 5
Depth versus Distance

Case 5: \( G=3 \text{ cm}, \ h_w=17 \text{ cm}, \ Q=0.171 \text{ L/s}, \ Y_g=3.0 \text{ cm}, \ V_g=4.6 \text{ cm/s} \)
Figure 9.7 Denser Wall Jet Case 5
Velocity versus Distance

Case 5: \( G=3 \text{ cm}, \ h_w=17 \text{ cm}, \ Q=0.171 \text{ L/s}, \ Y_g=3.0 \text{ cm}, \ V_g=4.6 \text{ cm/s} \)

![Graph showing velocity versus distance](imageURL)
Figure 9.8 Denser Wall Jet Case 5
Temperature versus Distance

Case 5: \( G=3 \text{ cm}, \, h_w=17 \text{ cm}, \, Q=0.171 \text{ L/s}, \, Y_g=3.0 \text{ cm}, \, V_g=4.6 \text{ cm/s} \)
Figure 9.9 Denser Wall Jet Case 5
Densimetric Froude Number versus Distance

Case 5: \( d = 3 \) cm, \( h \ell = 17 \) cm, \( Q = 0.171 \) L/s, \( Y_g = 3.0 \) cm, \( V_g = 4.6 \) cm/s

![Graph showing densimetric Froude number versus distance with legend indicating experimental and theoretical data.]
Figure 9.10 Denser Wall Jet Case 5
(T - Tg) / (T0 - Tg) versus X / Yg

Case 5: G=3 cm, hw=17 cm, Q=0.171 L/s, Yg=3.0 cm, Vg=4.6 cm/s
Figure 9.11 Denser Wall Jet Case 1
Sequent Depth versus Distance

Case 1: G=3 cm, hw=17 cm, Q=0.184 L/s, Yg=3.0 cm, Vg=4.9 cm/s
Figure 9.12 Denser Wall Jet Case 1
Surge Velocity versus Distance

Case 1: \( h = 3 \text{ cm}, h_w = 17 \text{ cm}, Q = 0.184 \text{ L/s}, Y_g = 3.0 \text{ cm}, V_g = 4.9 \text{ cm/s} \)
Figure 9.13 Denser Wall Jet Case 1
Fr1 versus X1

Case 1: G=3 cm, hw=17 cm, Q=0.184 L/s, Yg=3.0 cm, Vg=4.9 cm/s

LEGEND
△ △ Experimental
■ ■ Theoretical
Figure 9.14 Denser Wall Jet Case 1
Y2 / Y1 versus Fr1

Case 1: G=3 cm, hw=17 cm, Q=0.184 L/s, Yg=3.0 cm, Vg=4.9 cm/s

LEGEND

△ △ △ Experimental

□ □ Classical Jump

Theoretical
Figure 9.15 Denser Wall Jet Case 5
Sequent Depth versus Distance

Case 5: G=3 cm, hw=17 cm, Q=0.171 L/s, Yg=3.0 cm, Vg=4.6 cm/s
Figure 9.16 Denser Wall Jet Case 5
Surge Velocity versus Distance

Case 5: \( G=3 \text{ cm}, h_w=17 \text{ cm}, Q=0.171 \text{ L/s}, Y_g=3.0 \text{ cm}, V_g=4.6 \text{ cm/s} \)
Figure 9.17 Denser Wall Jet Case 5
Fr1 versus X1

Case 5: G=3 cm, hw=17 cm, Q=0.171 L/s, Yg=3.0 cm, Vg=4.6 cm/s
Figure 9.18 Denser Wall Jet Case 5
Y2 / Y1 versus Fr1

Case 5: G=3 cm, hw=17 cm, Q=0.171 L/s, Yg=3.0 cm, Vg=4.6 cm/s

LEGEND
△ △ △ Experimental
□ □ □ Model (case)
--- Classical Jump

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Figure 9.19  Denser Wall Jet Depth Data
Y/Yg Predicted versus Measured

Case 1: G=3 cm, hw=17 cm, Q=0.184 L/s, Yg=3.0 cm, Vg=4.9 cm/s
Case 2: G=5 cm, hw=17 cm, Q=0.189 L/s, Yg=5.0 cm, Vg=3.0 cm/s
Case 3: G=3 cm, hw=8.5 cm, Q=0.057 L/s, Yg=2.0 cm, Vg=2.3 cm/s
Case 4: G=5 cm, hw=8.5 cm, Q=0.072 L/s, Yg=2.9 cm, Vg=2.0 cm/s
Case 5: G=3 cm, hw=17 cm, Q=0.171 L/s, Yg=3.0 cm, Vg=4.6 cm/s
Case 6: G=5 cm, hw=17 cm, Q=0.189 L/s, Yg=5.0 cm, Vg=3.0 cm/s
Figure 9.20  Denser Wall Jet Velocity Data
V/Vg Predicted versus Measured

Case 1:  G=3 cm, hw=17 cm, Q=0.184 L/s, Yg=3.0 cm, Vg=4.9 cm/s
Case 2:  G=5 cm, hw=17 cm, Q=0.189 L/s, Yg=5.0 cm, Vg=3.0 cm/s
Case 3:  G=3 cm, hw=8.5 cm, Q=0.057 L/s, Yg=2.0 cm, Vg=2.3 cm/s
Case 4:  G=5 cm, hw=8.5 cm, Q=0.072 L/s, Yg=2.9 cm, Vg=2.0 cm/s
Case 5:  G=3 cm, hw=17 cm, Q=0.171 L/s, Yg=3.0 cm, Vg=4.6 cm/s
Case 6:  G=5 cm, hw=17 cm, Q=0.189 L/s, Yg=5.0 cm, Vg=3.0 cm/s
Figure 9.21 Denser Wall Jet Temperature Data Predicted versus Measured

Case 1: G=3 cm, hw=17 cm, Q=0.184 L/s, Yg=3.0 cm, Vg=4.9 cm/s
Case 2: G=5 cm, hw=17 cm, Q=0.189 L/s, Yg=5.0 cm, Vg=3.0 cm/s
Case 3: G=3 cm, hw=8.5 cm, Q=0.057 L/s, Yg=2.0 cm, Vg=2.3 cm/s
Case 4: G=5 cm, hw=8.5 cm, Q=0.072 L/s, Yg=2.9 cm, Vg=2.0 cm/s
Case 5: G=3 cm, hw=17 cm, Q=0.171 L/s, Yg=3.0 cm, Vg=4.6 cm/s
Case 6: G=5 cm, hw=17 cm, Q=0.189 L/s, Yg=5.0 cm, Vg=3.0 cm/s
Figure 9.22 Denser Wall Jet
F' Predicted versus Measured

Case 1: G=3 cm, hw=17 cm, Q=0.184 L/s, Yg=3.0 cm, Vg=4.9 cm/s
Case 2: G=5 cm, hw=17 cm, Q=0.189 L/s, Yg=5.0 cm, Vg=3.0 cm/s
Case 3: G=3 cm, hw=8.5 cm, Q=0.057 L/s, Yg=2.0 cm, Vg=2.3 cm/s
Case 4: G=5 cm, hw=8.5 cm, Q=0.072 L/s, Yg=2.9 cm, Vg=2.0 cm/s
Case 5: G=3 cm, hw=17 cm, Q=0.171 L/s, Yg=3.0 cm, Vg=4.6 cm/s
Case 6: G=5 cm, hw=17 cm, Q=0.189 L/s, Yg=5.0 cm, Vg=3.0 cm/s
Figure 9.23  Denser Wall Jet Sequent Depth Data
Predicted versus Measured

Case 1:  G=3 cm, hw=17 cm, Q=0.184 L/s, Yg=3.0 cm, Vg=4.9 cm/s
Case 2:  G=5 cm, hw=17 cm, Q=0.189 L/s, Yg=5.0 cm, Vg=3.0 cm/s
Case 5:  G=3 cm, hw=17 cm, Q=0.171 L/s, Yg=3.0 cm, Vg=4.6 cm/s
Case 6:  G=5 cm, hw=17 cm, Q=0.189 L/s, Yg=5.0 cm, Vg=3.0 cm/s
Figure 9.24  Denser Wall Jet Surge Velocity Data
Predicted versus Measured

Case 1:  G=3 cm, hw=17 cm, Q=0.184 L/s, Yg=3.0 cm, Vg=4.9 cm/s
Case 2:  G=5 cm, hw=17 cm, Q=0.189 L/s, Yg=5.0 cm, Vg=3.0 cm/s
Case 5:  G=3 cm, hw=17 cm, Q=0.171 L/s, Yg=3.0 cm, Vg=4.6 cm/s
Case 6:  G=5 cm, hw=17 cm, Q=0.189 L/s, Yg=5.0 cm, Vg=3.0 cm/s

Legend

+ + + Case 1    □ □ □ Case 2
○ ○ ○ Case 5    * * * Case 6
--- P = M
Figure 9.25  Denser Wall Jet
Fr1 Predicted versus Measured

Case 1:  G=3 cm, hw=17 cm, Q=0.184 L/s, Yg=3.0 cm, Vg=4.9 cm/s
Case 2:  G=5 cm, hw=17 cm, Q=0.189 L/s, Yg=5.0 cm, Vg=3.0 cm/s
Case 5:  G=3 cm, hw=17 cm, Q=0.171 L/s, Yg=3.0 cm, Vg=4.6 cm/s
Case 6:  G=5 cm, hw=17 cm, Q=0.189 L/s, Yg=5.0 cm, Vg=3.0 cm/s

Legend:
+ + + Case 1
◊ ◊ ◊ Case 5
* * * Case 6
P = M
Appendix B. PHOTOGRAPHS
Photo 4.1 Layout of Thermocouples in Test Section

Photo 4.2 Thermocouple at Gate Opening
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Photo 4.5 Thermocouples in Temperature Probe

Photo 4.6 Temperature Test Equipment
Photo 4.7 Fluorescent Dye Test Equipment
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G = 3 cm, hω = 17 cm, Q = 0.171 L/s

Photo 6.2  Denser Wall Jet Case at time = 11.4 s for
G = 3 cm, hω = 17 cm, Q = 0.171 L/s
Photo 6.3  Denser Wall Jet Case at time = 16.1 s for
G = 3 cm, h_w = 17 cm, Q = 0.171 L/s

Photo 6.4  Denser Wall Jet Case at time = 19.1 s for
G = 3 cm, h_w = 17 cm, Q = 0.171 L/s
Photo 6.5  Denser Wall Jet Case at time = 24.6 s for 
\[ G = 3 \text{ cm}, \ h_w = 17 \text{ cm}, \ Q = 0.171 \text{ L/s} \]

Photo 6.6  Denser Wall Jet Case at time = 27.3 s for 
\[ G = 3 \text{ cm}, \ h_w = 17 \text{ cm}, \ Q = 0.171 \text{ L/s} \]
Photo 6.7  Denser Wall Jet Case at time = 36.2 s for
G = 3 cm, h_w = 17 cm, Q = 0.171 L/s

Photo 6.8  Denser Wall Jet Case at time = 44.3 s for
G = 3 cm, h_w = 17 cm, Q = 0.171 L/s
Photo 6.9  Denser Wall Jet Case at time = 52.2 s for

\[ G = 3 \text{ cm}, \ h_w = 17 \text{ cm}, \ Q = 0.171 \text{ L/s} \]

Photo 6.10  Denser Wall Jet Case at time = 63.0 s for

\[ G = 3 \text{ cm}, \ h_w = 17 \text{ cm}, \ Q = 0.171 \text{ L/s} \]
Photo 6.11  Denser Wall Jet Case at time = 69.0 s for
\[ G = 3 \text{ cm}, \ h_w = 17 \text{ cm}, \ Q = 0.171 \text{ L/s} \]

Photo 6.12  Denser Wall Jet Case at time = 77.8 s for
\[ G = 3 \text{ cm}, \ h_w = 17 \text{ cm}, \ Q = 0.171 \text{ L/s} \]
Photo 6.13  Denser Wall Jet Case at time = 84.6 s for

\[ G = 3 \text{ cm}, \; h_w = 17 \text{ cm}, \; Q = 0.171 \text{ L/s} \]

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\[ G = 3 \text{ cm}, \; h_w = 17 \text{ cm}, \; Q = 0.171 \text{ L/s} \]
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for G = 3 cm, h_w = 17 cm, Q = 0.072 L/s

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for \( G = 3 \text{ cm} \), \( h_w = 17 \text{ cm} \), \( Q = 0.072 \text{ L/s} \)

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for \( G = 3 \text{ cm} \), \( h_w = 17 \text{ cm} \), \( Q = 0.072 \text{ L/s} \)
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for G = 3 cm, h_w = 17 cm, Q = 0.072 L/s

Photo 6.20  Buoyant Surface Jet Case at time = 55.2 seconds
for G = 3 cm, h_w = 17 cm, Q = 0.072 L/s
Photo 6.21 Buoyant Surface Jet Case at time \(= 61.2\) seconds

for \(G = 3\) cm, \(h_w = 17\) cm, \(Q = 0.072\) L/s

Photo 6.22 Buoyant Surface Jet Case at time \(= 79.4\) seconds

for \(G = 3\) cm, \(h_w = 17\) cm, \(Q = 0.072\) L/s
Photo 6.23 Buoyant Surface Jet Case at time = 100.3 seconds
for $G = 3 \text{ cm}$, $h = 17 \text{ cm}$, $Q = 0.072 \text{ L/s}$

Photo 6.24 Buoyant Surface Jet Case at time = 109.3 seconds
for $G = 3 \text{ cm}$, $h = 17 \text{ cm}$, $Q = 0.072 \text{ L/s}$
Appendix C. TABLES
<table>
<thead>
<tr>
<th>Temperature (°C)</th>
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</tr>
<tr>
<td>5</td>
<td>1000.0</td>
</tr>
<tr>
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<td>70</td>
<td>977.8</td>
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<td>80</td>
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<th>h_w (cm)</th>
<th>Q (L/s)</th>
<th>T_0 (°C)</th>
<th>T_1 (°C)</th>
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<td>t.t.</td>
</tr>
<tr>
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<td>0.189</td>
<td>32.0</td>
<td>17.0</td>
<td>d.w.j.</td>
<td>t.t.</td>
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<td>26.0</td>
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<td>8.5</td>
<td>0.072</td>
<td>43.0</td>
<td>26.0</td>
<td>d.w.j.</td>
<td>t.t.</td>
</tr>
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<td>17</td>
<td>0.171</td>
<td>37.0</td>
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<td>p.d.t.</td>
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<td>5</td>
<td>17</td>
<td>0.189</td>
<td>32.0</td>
<td>22.0</td>
<td>d.w.j.</td>
<td>p.d.t.</td>
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<td>5</td>
<td>17</td>
<td>0.190</td>
<td>37.0</td>
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<td>d.w.j.</td>
<td>f.d.t.</td>
</tr>
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<td>17</td>
<td>0.078</td>
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<td>38.0</td>
<td>b.s.j.</td>
<td>t.t.</td>
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<td>24.0</td>
<td>43.0</td>
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<td>t.t.</td>
</tr>
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<td>8.5</td>
<td>0.050</td>
<td>22.0</td>
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<td>t.t.</td>
</tr>
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<td>17</td>
<td>0.072</td>
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<td>32.0</td>
<td>b.s.j.</td>
<td>p.d.t.</td>
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<td>17</td>
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<td>40.8</td>
<td>b.s.j.</td>
<td>f.d.t.</td>
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*Extreme values

†Type of Experiments are Denser Wall Jet (d.w.j.) and Buoyant Surface Jet (b.s.j.)

‡Source of Data are Temperature Tests (t.t.), Photographic Dye Tests (p.d.t.) and Fluorescent Dye Tests (f.d.t.).
### Table 6.2 Temperature Experiments

<table>
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<th>Scan Interval (seconds)</th>
<th>Figure No.</th>
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<td>6.1-6.11</td>
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<td>d.w.j.</td>
<td>6</td>
<td>H.1-H.9</td>
</tr>
<tr>
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<td>d.w.j.</td>
<td>7</td>
<td>H.21-H.26</td>
</tr>
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<td>7</td>
<td>H.37-H.42</td>
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<td>6</td>
<td>6.12-6.20</td>
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<td>H.10-H.20</td>
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<td>b.s.j.</td>
<td>7</td>
<td>H.27-H.36</td>
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†Type of Experiments are Denser Wall Jet (d.w.j.) and Buoyant Surface Jet (b.s.j.)

### Table 6.3 Photographic Dye Experiments

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<th>Case No.</th>
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<th>Photo No.</th>
<th>Figure No.‡</th>
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<td>d.w.j.</td>
<td>5.1-5.14</td>
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†Type of Experiments are Denser Wall Jet (d.w.j.) and Buoyant Surface Jet (b.s.j.)

‡Temperature Influent/Effluent Plots

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<table>
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<th>Case No.</th>
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<th>Figure No.*</th>
<th>Figure No.‡</th>
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†Type of Experiments are Denser Wall Jet (d.w.j.) and Buoyant Surface Jet (b.s.j.)

* Dye Concentration Influent and Effluent Plots

‡ Temperature Influent/Effluent Plots
### Table 7.1 Temperature Study Data Reduction for Denser Wall Jet Case 1
for $G = 3 \text{ cm}$, $h_w = 17 \text{ cm}$, $Q_w = 0.184 \text{ L/s}$

<table>
<thead>
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<th>Time (seconds)</th>
<th>X (cm)</th>
<th>Y (cm)</th>
<th>T (°C)</th>
<th>V (cm/s)</th>
<th>F'</th>
<th>$\alpha$</th>
<th>$\sigma$</th>
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<td>3.7</td>
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### Table 7.2 Temperature Study Data Reduction for Denser Wall Jet Case 2
for $G = 5 \text{ cm}$, $h_w = 17 \text{ cm}$, $Q_w = 0.189 \text{ L/s}$

<table>
<thead>
<tr>
<th>Time (seconds)</th>
<th>X (cm)</th>
<th>Y (cm)</th>
<th>T (°C)</th>
<th>V (cm/s)</th>
<th>F'</th>
<th>$\alpha$</th>
<th>$\sigma$</th>
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<td>1.25</td>
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<td>2.8</td>
<td>1.25</td>
<td>0.0055</td>
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Table 7.3 Temperature Study Data Reduction for Denser Wall Jet Case 3 for $G = 3 \text{ cm}$, $h_w = 8.5 \text{ cm}$, $Q = 0.057 \text{ L/s}$, $Y_g = 2.0 \text{ cm}$ of Denser Wall Jet

<table>
<thead>
<tr>
<th>Time (Seconds)</th>
<th>X (cm)</th>
<th>Y (cm)</th>
<th>T (°C)</th>
<th>V (cm/s)</th>
<th>F'</th>
<th>α</th>
<th>σ</th>
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<td>42</td>
<td>73.4</td>
<td>3.3</td>
<td>38.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 7.4 Temperature Study Data Reduction for Denser Wall Jet Case 4 for $G = 5 \text{ cm}$, $h_w = 8.5 \text{ cm}$, $Q = 0.072 \text{ L/s}$, $Y_g = 2.0 \text{ cm}$ of Denser Wall Jet

<table>
<thead>
<tr>
<th>Time (Seconds)</th>
<th>X (cm)</th>
<th>Y (cm)</th>
<th>T (°C)</th>
<th>V (cm/s)</th>
<th>F'</th>
<th>α</th>
<th>σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.0</td>
<td>2.0</td>
<td>37.5</td>
<td>2.0</td>
<td>0.77</td>
<td>0.0047</td>
<td>0.070</td>
</tr>
<tr>
<td>14</td>
<td>58.5</td>
<td>3.1</td>
<td>39.4</td>
<td>1.9</td>
<td>0.87</td>
<td>0.0100</td>
<td>0.010</td>
</tr>
<tr>
<td>28</td>
<td>88.4</td>
<td>3.4</td>
<td>41.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 7.5 Temperature Study Data Reduction for Denser Wall Jet Case 1
for G= 3 cm, h_w = 17 cm, Q= 0.184 L/s
of Splash at Weir

<table>
<thead>
<tr>
<th>Time</th>
<th>Splash Length</th>
<th>Splash Height</th>
<th>T</th>
<th>Rate of Rise</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>cm</td>
<td>cm</td>
<td>ºC</td>
<td>cm/s</td>
</tr>
<tr>
<td>30</td>
<td>17.0</td>
<td>16.0</td>
<td>32</td>
<td></td>
</tr>
<tr>
<td>42</td>
<td>8.5</td>
<td>16.0</td>
<td>31</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Table 7.6 Temperature Study Data Reduction for Denser Wall Jet Case 2
for G= 5 cm, h_w = 17 cm, Q= 0.180 L/s
of Splash at Weir

<table>
<thead>
<tr>
<th>Time</th>
<th>Splash Length</th>
<th>Splash Height</th>
<th>T</th>
<th>Rate of Rise</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>cm</td>
<td>cm</td>
<td>ºC</td>
<td>cm/s</td>
</tr>
<tr>
<td>42</td>
<td>6.9</td>
<td>6.9</td>
<td>31</td>
<td>0.4</td>
</tr>
<tr>
<td>60</td>
<td>8.9</td>
<td>14.0</td>
<td>31</td>
<td></td>
</tr>
</tbody>
</table>
Table 7.7 Temperature Study Data Reduction for Denser Wall Jet Case 3
for G = 3 cm, h_w = 8.5 cm, Q = 0.057 L/s, Y_g = 2.0 cm
of Splash at Weir

<table>
<thead>
<tr>
<th>Time (seconds)</th>
<th>Splash Length (cm)</th>
<th>Splash Height (cm)</th>
<th>T (°C)</th>
<th>Rate of Rise (cm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>56</td>
<td>8.2</td>
<td>5.1</td>
<td>40</td>
<td>0.1</td>
</tr>
<tr>
<td>70</td>
<td>10.4</td>
<td>7.1</td>
<td>40</td>
<td>0.0</td>
</tr>
<tr>
<td>91</td>
<td>10.8</td>
<td>7.9</td>
<td>40</td>
<td></td>
</tr>
</tbody>
</table>

Table 7.8 Temperature Study Data Reduction for Denser Wall Jet Case 4
for G = 5 cm, h_w = 8.5 cm, Q = 0.072 L/s, Y_g = 2.9 cm
of Splash at Weir

<table>
<thead>
<tr>
<th>Time (seconds)</th>
<th>Splash Length (cm)</th>
<th>Splash Height (cm)</th>
<th>T (°C)</th>
<th>Rate of Rise (cm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>10.8</td>
<td>5.8</td>
<td>43</td>
<td>0.2</td>
</tr>
<tr>
<td>28</td>
<td>12.3</td>
<td>8.5</td>
<td>43</td>
<td>0.3</td>
</tr>
<tr>
<td>42</td>
<td>10.8</td>
<td>4.6</td>
<td>42</td>
<td>0.2</td>
</tr>
<tr>
<td>56</td>
<td>9.4</td>
<td>7.4</td>
<td>42</td>
<td></td>
</tr>
</tbody>
</table>

244
### Table 7.9 Temperature Study Data Reduction for Denser Wall Jet Case 1
for $G = 3 \text{ cm}$, $h_w = 17 \text{ cm}$, $Q = 0.184 \text{ L/s}$
of Moving Internal Hydraulic Jump

<table>
<thead>
<tr>
<th>Time (sec)</th>
<th>$X_1$ (cm)</th>
<th>$X_2$ (cm)</th>
<th>$Y_1$ (cm)</th>
<th>$Y_2$ (cm)</th>
<th>$L_j$ (cm)</th>
<th>$V_s$ (cm/s)</th>
<th>$F'_{ri}$</th>
<th>$C_{imax}$</th>
<th>$C_{imin}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>42</td>
<td>55.5</td>
<td>54.7</td>
<td>6.2</td>
<td>12.8</td>
<td>9.2</td>
<td>0.1</td>
<td>1.60</td>
<td>0.322</td>
<td>0.0</td>
</tr>
<tr>
<td>60</td>
<td>51.7</td>
<td>63.2</td>
<td>8.0</td>
<td>14.0</td>
<td>11.6</td>
<td>0.4</td>
<td>1.48</td>
<td>0.258</td>
<td>0.0</td>
</tr>
<tr>
<td>72</td>
<td>45.5</td>
<td>58.6</td>
<td>8.2</td>
<td>13.6</td>
<td>13.0</td>
<td>1.4</td>
<td>1.62</td>
<td>0.344</td>
<td>0.0</td>
</tr>
<tr>
<td>90</td>
<td>17.0</td>
<td>37.4</td>
<td>8.0</td>
<td>12.8</td>
<td>20.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 7.10 Temperature Study Data Reduction for Denser Wall Jet Case 2
for $G = 5 \text{ cm}$, $h_w = 17 \text{ cm}$, $Q = 0.189 \text{ L/s}$
of Moving Internal Hydraulic Jump

<table>
<thead>
<tr>
<th>Time (sec)</th>
<th>$X_1$ (cm)</th>
<th>$X_2$ (cm)</th>
<th>$Y_1$ (cm)</th>
<th>$Y_2$ (cm)</th>
<th>$L_j$ (cm)</th>
<th>$V_s$ (cm/s)</th>
<th>$F'_{ri}$</th>
<th>$C_{imax}$</th>
<th>$C_{imin}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>72.72</td>
<td>35.4</td>
<td>58.6</td>
<td>9.2</td>
<td>12.6</td>
<td>23.1</td>
<td>1.4</td>
<td>1.30</td>
<td>0.420</td>
<td>0.0</td>
</tr>
<tr>
<td>90</td>
<td>14.5</td>
<td>29.3</td>
<td>10.0</td>
<td>12.8</td>
<td>14.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

245
### Table 7.11 Temperature Study Data Reduction for Denser Wall Jet Case 1
for \( G = 3 \text{ cm}, h_w = 17 \text{ cm}, Q = 0.184 \text{ L/s} \)
of Submerged Hydraulic Jump

<table>
<thead>
<tr>
<th>Time (sec)</th>
<th>( L_j ) (cm)</th>
<th>( Y_s ) (cm)</th>
<th>( Y_2 ) (cm)</th>
<th>( T ) (°C)</th>
<th>( F' )</th>
<th>( C_{2\text{max}} )</th>
<th>( C_{2\text{min}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>120</td>
<td>12.1</td>
<td>6.2</td>
<td>9.0</td>
<td>25</td>
<td>0.30</td>
<td>0.377</td>
<td>0.0</td>
</tr>
<tr>
<td>150</td>
<td>25.2</td>
<td>6.4</td>
<td>10.4</td>
<td>24</td>
<td>0.26</td>
<td>0.311</td>
<td>0.0</td>
</tr>
<tr>
<td>180</td>
<td>29.9</td>
<td>5.8</td>
<td>10.8</td>
<td>22</td>
<td>0.24</td>
<td>0.258</td>
<td>0.0</td>
</tr>
<tr>
<td>210</td>
<td>28.2</td>
<td>6.0</td>
<td>11.2</td>
<td>21</td>
<td>0.23</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 7.12 Temperature Study Data Reduction for Denser Wall Jet Case 2
for \( G = 5 \text{ cm}, h_w = 17 \text{ cm}, Q = 0.189 \text{ L/s} \)
of Submerged Hydraulic Jump

<table>
<thead>
<tr>
<th>Time (sec)</th>
<th>( L_j ) (cm)</th>
<th>( Y_s ) (cm)</th>
<th>( Y_2 ) (cm)</th>
<th>( T ) (°C)</th>
<th>( F' )</th>
<th>( C_{2\text{max}} )</th>
<th>( C_{2\text{min}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>8.3</td>
<td>7.6</td>
<td>8.8</td>
<td>32</td>
<td>0.21</td>
<td>0.601</td>
<td>0.0</td>
</tr>
<tr>
<td>120</td>
<td>26.3</td>
<td>8.2</td>
<td>12.2</td>
<td>27</td>
<td>0.22</td>
<td>0.388</td>
<td>0.0</td>
</tr>
<tr>
<td>150</td>
<td>34.5</td>
<td>7.6</td>
<td>12.8</td>
<td>25</td>
<td>0.18</td>
<td>0.367</td>
<td>0.0</td>
</tr>
<tr>
<td>210</td>
<td>29.9</td>
<td>9.0</td>
<td>12.2</td>
<td>21</td>
<td>0.15</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 7.13 Temperature Study Data Reduction for Buoyant Surface Jet Case 9
for $G = 3 \text{ cm}$, $h_w = 17 \text{ cm}$, $Q = 0.078 \text{ L/s}$
of Rising Plume with Entrainment

<table>
<thead>
<tr>
<th>Time (seconds)</th>
<th>Gross Dilution $Q_{D1} \text{ L/s}$</th>
<th>Gross Dilution Factor $D_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>0.103</td>
<td>1.3</td>
</tr>
<tr>
<td>30</td>
<td>0.123</td>
<td>1.6</td>
</tr>
<tr>
<td>42</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 7.14 Temperature Study Data Reduction for Buoyant Surface Jet Case 10
for $G = 5 \text{ cm}$, $h_w = 17 \text{ cm}$, $Q = 0.179 \text{ L/s}$
of Rising Plume with Entrainment

<table>
<thead>
<tr>
<th>Time (seconds)</th>
<th>Gross Dilution $Q_{D1} \text{ L/s}$</th>
<th>Gross Dilution Factor $D_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>0.121</td>
<td>0.7</td>
</tr>
<tr>
<td>42</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Table 7.15 Temperature Study Data Reduction for Buoyant Surface Jet Case 9
for G= 3 cm, h_w = 17 cm, Q= 0.072 L/s
of Buoyant Surface Jet

<table>
<thead>
<tr>
<th>Time (seconds)</th>
<th>X (cm)</th>
<th>Y (cm)</th>
<th>T (°C)</th>
<th>V (cm/s)</th>
<th>F'</th>
<th>α</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>58.6</td>
<td>1.6</td>
<td>31.2</td>
<td>1.5</td>
<td>1.18</td>
<td>0.13</td>
</tr>
<tr>
<td>42</td>
<td>65.7</td>
<td>4.0</td>
<td>31.0</td>
<td>1.5</td>
<td>0.82</td>
<td>0.17</td>
</tr>
<tr>
<td>60</td>
<td>74.0</td>
<td>9.0</td>
<td>30.8</td>
<td>1.5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 7.16 Temperature Study Data Reduction for Buoyant Surface Jet Case 10
for G= 5 cm, h_w = 17 cm, Q= 0.179 L/s
of Buoyant Surface Jet

<table>
<thead>
<tr>
<th>Time (seconds)</th>
<th>X (cm)</th>
<th>Y (cm)</th>
<th>T (°C)</th>
<th>V (cm/s)</th>
<th>F'</th>
<th>α</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>37.3</td>
<td>2.1</td>
<td>29.4</td>
<td>1.5</td>
<td>0.89</td>
<td>0.042</td>
</tr>
<tr>
<td>30</td>
<td>55.5</td>
<td>3.2</td>
<td>28.0</td>
<td>1.5</td>
<td>0.84</td>
<td>0.018</td>
</tr>
<tr>
<td>42</td>
<td>74.0</td>
<td>3.6</td>
<td>27.8</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Table 7.17 Temperature Study Data Reduction for Buoyant Surface Jet Case 11
for $G=3$ cm, $h_w=8.5$ cm, $Q=0.050$ L/s of Buoyant Surface Jet

<table>
<thead>
<tr>
<th>Time (seconds)</th>
<th>X  (cm)</th>
<th>Y  (cm)</th>
<th>T  (°C)</th>
<th>V  (cm/s)</th>
<th>$F'$</th>
<th>$\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>30.8</td>
<td>1.0</td>
<td>25.0</td>
<td></td>
<td>2.0</td>
<td>1.74</td>
</tr>
<tr>
<td>28</td>
<td>58.6</td>
<td>2.2</td>
<td>25.0</td>
<td></td>
<td>1.2</td>
<td>0.89</td>
</tr>
<tr>
<td>42</td>
<td>74.0</td>
<td>4.2</td>
<td>24.0</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 7.18 Temperature Study Data Reduction for Buoyant Surface Jet Case 9
for $G=3$ cm, $h_w=17$ cm, $Q=0.078$ L/s of Moving Internal Hydraulic Jump

<table>
<thead>
<tr>
<th>Time (sec)</th>
<th>$X_1$ (cm)</th>
<th>$X_2$ (cm)</th>
<th>$Y_1$ (cm)</th>
<th>$Y_2$ (cm)</th>
<th>$L_j$ (cm)</th>
<th>$V_s$ (cm/s)</th>
<th>$F'_{ri}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>57.3</td>
<td>70.0</td>
<td>9.7</td>
<td>13.8</td>
<td>12.7</td>
<td></td>
<td>0.8</td>
</tr>
<tr>
<td>120</td>
<td>59.6</td>
<td>65.8</td>
<td>10.2</td>
<td>13.0</td>
<td>11.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Table 7.10 Temperature Study Data Reduction for Buoyant Surface Jet Case 10
for $G = 5 \text{ cm, } h_w = 17 \text{ cm, } Q = 0.179 \text{ L/s}$
of Moving Internal Hydraulic Jump

<table>
<thead>
<tr>
<th>Time (sec)</th>
<th>$X_1$ (cm)</th>
<th>$X_2$ (cm)</th>
<th>$Y_1$ (cm)</th>
<th>$Y_2$ (cm)</th>
<th>$L_j$ (cm)</th>
<th>$V_s$ (cm/s)</th>
<th>$F_{ri}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>72</td>
<td>44.7</td>
<td>33.2</td>
<td>12.1</td>
<td>14.3</td>
<td>18.5</td>
<td>0.8</td>
<td>1.20</td>
</tr>
<tr>
<td>90</td>
<td>33.6</td>
<td>52.1</td>
<td>11.8</td>
<td>14.2</td>
<td>18.5</td>
<td>0.8</td>
<td>1.05</td>
</tr>
<tr>
<td>120</td>
<td>33.9</td>
<td>60.6</td>
<td>8.6</td>
<td>11.8</td>
<td>28.7</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 7.20 Temperature Study Data Reduction for Buoyant Surface Jet Case 11
for $G = 3 \text{ cm, } h_w = 8.5 \text{ cm, } Q = 0.050 \text{ L/s}$
of Moving Internal Hydraulic Jump

<table>
<thead>
<tr>
<th>Time (sec)</th>
<th>$X_1$ (cm)</th>
<th>$X_2$ (cm)</th>
<th>$Y_1$ (cm)</th>
<th>$Y_2$ (cm)</th>
<th>$L_j$ (cm)</th>
<th>$V_s$ (cm/s)</th>
<th>$F_{ri}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>70</td>
<td>56.6</td>
<td>68.6</td>
<td>4.8</td>
<td>7.3</td>
<td>8.0</td>
<td>1.1</td>
<td>1.24</td>
</tr>
<tr>
<td>90</td>
<td>30.8</td>
<td>47.8</td>
<td>4.5</td>
<td>7.4</td>
<td>17.0</td>
<td>0.5</td>
<td>1.01</td>
</tr>
<tr>
<td>110</td>
<td>16.3</td>
<td>38.6</td>
<td>5.0</td>
<td>7.4</td>
<td>19.3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

250
### Table 7.21 Temperature Study Data Reduction for Buoyant Surface Jet Case 9
for \( G=3 \text{ cm}, \ h_w=17 \text{ cm}, \ Q=0.078 \text{ L/s} \)

<table>
<thead>
<tr>
<th>Time (seconds)</th>
<th>Gross Dilution ( Q_{D_2}, \text{ L/s} )</th>
<th>Wedge Dilution Factor ( D_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>120</td>
<td>0.034</td>
<td>0.435</td>
</tr>
<tr>
<td>150</td>
<td>0.010</td>
<td>0.123</td>
</tr>
<tr>
<td>174</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 7.22 Temperature Study Data Reduction for Buoyant Surface Jet Case 10
for \( G=5 \text{ cm}, \ h_w=17 \text{ cm}, \ Q=0.179 \text{ L/s} \)

<table>
<thead>
<tr>
<th>Time (seconds)</th>
<th>Gross Dilution ( Q_{D_2}, \text{ L/s} )</th>
<th>Wedge Dilution Factor ( D_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>120</td>
<td>0.017</td>
<td>0.005</td>
</tr>
<tr>
<td>150</td>
<td>0.008</td>
<td>0.047</td>
</tr>
<tr>
<td>180</td>
<td>0.014</td>
<td>0.081</td>
</tr>
<tr>
<td>210</td>
<td>0.009</td>
<td>0.049</td>
</tr>
<tr>
<td>240</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 7.23 Temperature Study Data Reduction for Buoyant Surface Jet Case 11
for $G = 3 \text{ cm}$, $h_w = 8.5 \text{ cm}$, $Q = 0.050 \text{ L/s}$

<table>
<thead>
<tr>
<th>Time seconds</th>
<th>Gross Dilution $Q_{D_2}$, L/s</th>
<th>Wedge Dilution Factor $D_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>147</td>
<td>0.007</td>
<td>0.133</td>
</tr>
<tr>
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Table 7.25 Photographic Dye Study Data Reduction for Denser Wall Jet Case 6 for Denser Wall Jet

<table>
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<th>Time (seconds)</th>
<th>X (cm)</th>
<th>Y (cm)</th>
<th>V (cm/s)</th>
<th>F'</th>
<th>α</th>
</tr>
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<td>0.005</td>
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</table>
### Table 7.26 Photographic Dye Study Data Reduction for Denser Wall Jet Case 5
for \( G = 3 \text{ cm}, h_w = 17 \text{ cm}, Q = 0.171 \text{ L/s} \)
of Splash at Weir

<table>
<thead>
<tr>
<th>Time (seconds)</th>
<th>Splash Length (cm)</th>
<th>Splash Height (cm)</th>
<th>Rate of Rise (cm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.7</td>
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<tr>
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<td>15.0</td>
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</tr>
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</table>

### Table 7.27 Photographic Dye Study Data Reduction for Denser Wall Jet Case 6
for \( G = 5 \text{ cm}, h_w = 17 \text{ cm}, Q = 0.189 \text{ L/s} \)
of Splash at Weir

<table>
<thead>
<tr>
<th>Time (seconds)</th>
<th>Splash Length (cm)</th>
<th>Splash Height (cm)</th>
<th>Rate of Rise (cm/s)</th>
</tr>
</thead>
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<tr>
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</table>
### Table 7.28 Photographic Dye Study Data Reduction for Denser Wall Jet Case 5

for $G = 3$ cm, $h_w = 17$ cm, $Q = 0.171$ L/s

of Moving Internal Hydraulic Jump

<table>
<thead>
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<th>Time (sec)</th>
<th>$x_1$ (cm)</th>
<th>$x_2$ (cm)</th>
<th>$y_1$ (cm)</th>
<th>$y_2$ (cm)</th>
<th>$L_j$ (cm)</th>
<th>$V_s$ (cm/s)</th>
<th>$F'ri$</th>
<th>$C_{imax}$</th>
<th>$C_{imin}$</th>
</tr>
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<td>$Y_1$ (cm)</td>
<td>$Y_2$ (cm)</td>
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<td>$V_s$ (cm/s)</td>
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<td>$C_{max}$</td>
<td>$C_{min}$</td>
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<td>(Y_2) (cm)</td>
<td>(L_j) (cm)</td>
<td>(V_s) (cm/s)</td>
<td>(F^*)</td>
<td>(C_{imax})</td>
<td>(C_{imin})</td>
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### Table 7.30: Photographic Dye Study Data Reduction for Denser Wall Jet Case 5
for \( G = 3 \, \text{cm}, \ h_w = 17 \, \text{cm}, \ Q = 0.171 \, \text{L/s} \)
of Submerged Hydraulic Jump

<table>
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<tr>
<th>Time (sec)</th>
<th>(L_j) (cm)</th>
<th>(Y_s) (cm)</th>
<th>(Y_2) (cm)</th>
<th>(F')</th>
<th>(C_{2\max})</th>
<th>(C_{2\min})</th>
</tr>
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<td>11.5</td>
<td>0.21</td>
<td>1.30</td>
<td>0.3</td>
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<tr>
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<td>7.0</td>
<td>12.0</td>
<td>0.19</td>
<td>0.71</td>
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<td>12.0</td>
<td>0.19</td>
<td>0.40</td>
<td>0.0</td>
</tr>
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<td>12.0</td>
<td>0.19</td>
<td>0.80</td>
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</tbody>
</table>

### Table 7.31: Photographic Dye Study Data Reduction for Denser Wall Jet Case 6
for \( G = 5 \, \text{cm}, \ h_w = 17 \, \text{cm}, \ Q = 0.189 \, \text{L/s} \)
of Submerged Hydraulic Jump

<table>
<thead>
<tr>
<th>Time (sec)</th>
<th>(L_j) (cm)</th>
<th>(Y_s) (cm)</th>
<th>(Y_2) (cm)</th>
<th>(F')</th>
<th>(C_{2\max})</th>
<th>(C_{2\min})</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0.15</td>
<td>0.44</td>
<td>0.0</td>
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<td>12.0</td>
<td>14.0</td>
<td>0.16</td>
<td>0.34</td>
<td>0.0</td>
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</table>
### Table 7.32: Photographic Dye Study Data Reduction

for Buoyant Surface Jet Case 12
for $G = 3 \text{ cm}, h_w = 17 \text{ cm}, Q = 0.072 \text{ L/s}

* Rising Plume with Entrainment *

<table>
<thead>
<tr>
<th>Time (seconds)</th>
<th>Gross Dilution $Q_{DL}$, L/s</th>
<th>Gross Dilution Factor $D_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>21.9</td>
<td>0.053</td>
<td>0.72</td>
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<td>42.3</td>
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</tbody>
</table>

### Table 7.33: Photographic Dye Study Data Reduction

for Buoyant Surface Jet Case 13
for $G = 5 \text{ cm}, h_w = 17 \text{ cm}, Q = 0.121 \text{ L/s}

* Rising Plume with Entrainment *

<table>
<thead>
<tr>
<th>Time (seconds)</th>
<th>Gross Dilution $Q_{DL}$, L/s</th>
<th>Gross Dilution Factor $D_1$</th>
</tr>
</thead>
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</tbody>
</table>
Table 7.3d. Photographic Dye Study Data Reduction
for Buoyant Surface Jet Case 12
for \( G = 3 \text{ cm}, h_v = 17 \text{ cm}, Q = 0.072 \text{ L/s} \)
of Buoyant Surface Jet

<table>
<thead>
<tr>
<th>Time (seconds)</th>
<th>X (cm)</th>
<th>Y (cm)</th>
<th>V (cm/s)</th>
<th>F'</th>
<th>α</th>
</tr>
</thead>
<tbody>
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<td>0.47</td>
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<td>1.5</td>
<td>0.64</td>
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<td></td>
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</table>
Table 7.36 Photographic Dye Study Data Reduction for Buoyant Surface Jet Case 13
for $G = 5$ cm, $h_w = 17$ cm, $Q = 0.161$ L/s
of Buoyant Surface Jet

<table>
<thead>
<tr>
<th>Time seconds</th>
<th>X cm</th>
<th>Y cm</th>
<th>$V$ cm/s</th>
<th>$F'$</th>
<th>$\alpha$</th>
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</tr>
</tbody>
</table>
### Table 7.36 Photographic Dye Study Data Reduction

for Buoyant Surface Jet Case 12
for $G=3$ cm, $h_w=17$ cm, $Q=0.072$ L/s
of Moving Internal Hydraulic Jump

<table>
<thead>
<tr>
<th>Time (sec)</th>
<th>$X_1$ (cm)</th>
<th>$X_2$ (cm)</th>
<th>$Y_1$ (cm)</th>
<th>$Y_2$ (cm)</th>
<th>$L_j$ (cm)</th>
<th>$V_s$ (cm/s)</th>
<th>$F_{r1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>79.4</td>
<td>60</td>
<td>65</td>
<td>13.0</td>
<td>16.0</td>
<td>6.0</td>
<td></td>
<td>2.8 1.15</td>
</tr>
<tr>
<td>100.3</td>
<td>44</td>
<td>50</td>
<td>16.0</td>
<td>18.0</td>
<td>6.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 7.37 Photographic Dye Study Data Reduction

for Buoyant Surface Jet Case 13
for $G=5$ cm, $h_w=17$ cm, $Q=0.121$ L/s
of Moving Internal Hydraulic Jump

<table>
<thead>
<tr>
<th>Time (sec)</th>
<th>$X_1$ (cm)</th>
<th>$X_2$ (cm)</th>
<th>$Y_1$ (cm)</th>
<th>$Y_2$ (cm)</th>
<th>$L_j$ (cm)</th>
<th>$V_s$ (cm/s)</th>
<th>$F_{r1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>32.9</td>
<td>54</td>
<td>65</td>
<td>12.0</td>
<td>14.0</td>
<td>11.0</td>
<td></td>
<td>1.0 1.15</td>
</tr>
<tr>
<td>37.1</td>
<td>50</td>
<td>61</td>
<td>13.0</td>
<td>14.5</td>
<td>11.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case No.</td>
<td>7</td>
<td>8</td>
<td>14</td>
<td>15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>---------</td>
<td>-------</td>
<td>-------</td>
<td>-------</td>
<td>-------</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type</td>
<td>d.w.j.</td>
<td>d.w.j.</td>
<td>b.s.j.</td>
<td>b.s.j.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>G (cm)</td>
<td>3</td>
<td>5</td>
<td>3</td>
<td>8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>h_w (cm)</td>
<td>17</td>
<td>17</td>
<td>17</td>
<td>17</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Q (L/s)</td>
<td>0.197</td>
<td>0.190</td>
<td>0.110</td>
<td>0.230</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T_0 (°C)</td>
<td>37.2</td>
<td>37.0</td>
<td>15.7</td>
<td>18.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T_1 (°C)</td>
<td>13.7</td>
<td>14.1</td>
<td>36.3</td>
<td>40.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F'</td>
<td>2.82</td>
<td>1.18</td>
<td>2.04</td>
<td>1.83</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>t_d (sec)</td>
<td>83</td>
<td>86</td>
<td>148</td>
<td>71</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T_1</td>
<td>0.39</td>
<td>0.37</td>
<td>0.46</td>
<td>0.52</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T_e</td>
<td>2.88</td>
<td>5.01</td>
<td>2.30</td>
<td>2.63</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T_{1e}</td>
<td>0.79</td>
<td>1.54</td>
<td>0.57</td>
<td>0.53</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T_{1e}</td>
<td>0.47</td>
<td>0.61</td>
<td>0.77</td>
<td>1.24</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T_2</td>
<td>0.99</td>
<td>1.54</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T_3</td>
<td>1.55</td>
<td>2.15</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T_4</td>
<td>2.00</td>
<td>3.20</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T_{12}</td>
<td>0.52</td>
<td>1.03</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T_{23}</td>
<td>0.58</td>
<td>0.61</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T_{34}</td>
<td>0.51</td>
<td>1.03</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Type of Experiments are Denser Wall Jet (d.w.j.) and Buoyant Surface Jet (b.s.j.).

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Table 8.1 Denser Wall Jet Data

<table>
<thead>
<tr>
<th>Case No.</th>
<th>$t_d$ (sec)</th>
<th>$t_i$ (sec)</th>
<th>$T_i$ ($t_d/t_i$)</th>
<th>Source†</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>90</td>
<td>31.5</td>
<td>0.35</td>
<td>t.t.</td>
</tr>
<tr>
<td>2</td>
<td>88</td>
<td>31.7</td>
<td>0.36</td>
<td>t.t.</td>
</tr>
<tr>
<td>3</td>
<td>149</td>
<td>38.5</td>
<td>0.28</td>
<td>t.t.</td>
</tr>
<tr>
<td>4</td>
<td>117</td>
<td>37.4</td>
<td>0.32</td>
<td>t.t.</td>
</tr>
<tr>
<td>5</td>
<td>91</td>
<td>16.5</td>
<td>0.17</td>
<td>p.d.t.</td>
</tr>
<tr>
<td>6</td>
<td>83</td>
<td>21.6</td>
<td>0.26</td>
<td>p.d.t.</td>
</tr>
<tr>
<td>7</td>
<td>83</td>
<td>32.4</td>
<td>0.39</td>
<td>f.d.t.</td>
</tr>
<tr>
<td>8</td>
<td>86</td>
<td>31.8</td>
<td>0.37</td>
<td>f.d.t.</td>
</tr>
</tbody>
</table>

† Source of Data are Temperature Tests (t.t.), Photographic Dye Tests (p.d.t.) and Fluorescent Dye Tests (f.d.t.).
### Table 8.2 Denser Wall Jet Data

**Splash at Water**

<table>
<thead>
<tr>
<th>Case No.</th>
<th>(X_s) cm</th>
<th>(H_s) cm</th>
<th>(H_0) cm</th>
<th>(H_0 / (V_j^2 / g'))</th>
<th>(V_r) cm/s</th>
<th>(V_r / V_j)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>11.8</td>
<td>16.0</td>
<td>11.5</td>
<td>0.389</td>
<td>1.3</td>
<td>0.27</td>
</tr>
<tr>
<td>2</td>
<td>9.4</td>
<td>6.8</td>
<td>0.9</td>
<td>0.094</td>
<td>0.4</td>
<td>0.13</td>
</tr>
<tr>
<td>3</td>
<td>9.5</td>
<td>5.1</td>
<td>1.8</td>
<td>0.496</td>
<td>0.1</td>
<td>0.04</td>
</tr>
<tr>
<td>4</td>
<td>10.3</td>
<td>7.4</td>
<td>4.0</td>
<td>0.593</td>
<td>0.2</td>
<td>0.10</td>
</tr>
<tr>
<td>5</td>
<td>10.0</td>
<td>8.0</td>
<td>3.2</td>
<td>0.078</td>
<td>2.3</td>
<td>0.31</td>
</tr>
<tr>
<td>6</td>
<td>10.0</td>
<td>15.0</td>
<td>8.8</td>
<td>0.134</td>
<td>1.0</td>
<td>0.48</td>
</tr>
</tbody>
</table>

### Table 8.3 Denser Wall Jet Data

**Moving Internal Hydraulic Jump**

<table>
<thead>
<tr>
<th>Case. No.</th>
<th>(Y_2) cm</th>
<th>(V_m) cm/s</th>
<th>(F_r'1)</th>
<th>(C_{1\text{max}})</th>
<th>Source†</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12.6-14.0</td>
<td>0.1-1.4</td>
<td>1.6</td>
<td>0.31</td>
<td>t.t.</td>
</tr>
<tr>
<td>2</td>
<td>12.0</td>
<td>1.4</td>
<td>1.3</td>
<td>0.42</td>
<td>t.t.</td>
</tr>
<tr>
<td>5</td>
<td>12.0-14.5</td>
<td>0.5-2.0</td>
<td>1.5-2.5</td>
<td>0.60</td>
<td>p.d.t.</td>
</tr>
<tr>
<td>6</td>
<td>14.0-16.0</td>
<td>1.2-2.0</td>
<td>1.6-4.0</td>
<td>0.33</td>
<td>p.d.t.</td>
</tr>
</tbody>
</table>

†Source of Data are Temperature Tests (t.t.), Photographic Dye Tests (p.d.t.) and Fluorescent Dye Tests (f.d.t.).
### Table 8.4 Denser Wall Jet Data

**Submerged Hydraulic Jump**

<table>
<thead>
<tr>
<th>Case. No.</th>
<th>$F'_{r1}$</th>
<th>$C_{i\text{max}}$</th>
<th>Source $^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.20</td>
<td>0.32</td>
<td>t.t.</td>
</tr>
<tr>
<td>2</td>
<td>0.18</td>
<td>0.45</td>
<td>t.t.</td>
</tr>
<tr>
<td>5</td>
<td>0.20</td>
<td>0.80</td>
<td>p.d.t.</td>
</tr>
<tr>
<td>6</td>
<td>0.18</td>
<td>0.32</td>
<td>p.d.t.</td>
</tr>
</tbody>
</table>

$^+$Source of Data are Temperature Tests (t.t.), Photographic Dye Tests (p.d.t.) and Fluorescent Dye Tests (f.d.t.).
<table>
<thead>
<tr>
<th>Case No.</th>
<th>$t_d$ (sec)</th>
<th>$t_i$ (sec)</th>
<th>$T_i$</th>
<th>Source†</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>209</td>
<td>41.8</td>
<td>0.20</td>
<td>t.t.</td>
</tr>
<tr>
<td>10</td>
<td>91</td>
<td>41.9</td>
<td>0.46</td>
<td>t.t.</td>
</tr>
<tr>
<td>11</td>
<td>170</td>
<td>42.5</td>
<td>0.25</td>
<td>t.t.</td>
</tr>
<tr>
<td>12</td>
<td>223</td>
<td>59.1</td>
<td>0.31</td>
<td>p.d.t.</td>
</tr>
<tr>
<td>13</td>
<td>69</td>
<td>28.0</td>
<td>0.34</td>
<td>p.d.t.</td>
</tr>
<tr>
<td>14</td>
<td>148</td>
<td>69.1</td>
<td>0.48</td>
<td>f.d.t.</td>
</tr>
<tr>
<td>15</td>
<td>71</td>
<td>36.9</td>
<td>0.52</td>
<td>f.d.t.</td>
</tr>
</tbody>
</table>

†Source of Data are Temperature Tests (t.t.), Photographic Dye Tests (p.d.t.) and Fluorescent Dye Tests (f.d.t.).
### Table 8.6 Buoyant Surface Jet Data

Moving Internal Hydraulic Jump

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Y₂ cm</th>
<th>Vₚ cm/s</th>
<th>F'ₚ₁</th>
<th>Source†</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>13.0-13.8</td>
<td>0.6</td>
<td>1.04</td>
<td>t.t.</td>
</tr>
<tr>
<td>10</td>
<td>11.8-14.3</td>
<td>0.8</td>
<td>1.05-1.20</td>
<td>t.t.</td>
</tr>
<tr>
<td>11</td>
<td>7.4</td>
<td>0.5-1.1</td>
<td>1.01-1.24</td>
<td>t.t.</td>
</tr>
<tr>
<td>12</td>
<td>18.0-18.0</td>
<td>2.0</td>
<td>1.15</td>
<td>p.d.t.</td>
</tr>
<tr>
<td>13</td>
<td>14.0-14.5</td>
<td>1.0</td>
<td>1.16</td>
<td>p.d.t.</td>
</tr>
</tbody>
</table>

†Source of Data are Temperature Tests (t.t.), Photographic Dye Tests (p.d.t.) and Fluorescent Dye Tests (f.d.t.).
### Table 9.1 Model Sensitivity to Entrainment Coefficient for the Denser Jet

<table>
<thead>
<tr>
<th>$K_a$</th>
<th>$Y$ (%)</th>
<th>$V$ (%)</th>
<th>$\Delta T$ (°C)</th>
<th>$F$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>+12</td>
<td>-11</td>
<td>0.0</td>
<td>-16</td>
</tr>
<tr>
<td>0.5</td>
<td>+40</td>
<td>-22</td>
<td>+0.3</td>
<td>-31</td>
</tr>
<tr>
<td>1.0</td>
<td>+60</td>
<td>-29</td>
<td>+0.5</td>
<td>-39</td>
</tr>
<tr>
<td>2.0</td>
<td>+103</td>
<td>-39</td>
<td>+0.7</td>
<td>-52</td>
</tr>
</tbody>
</table>

### Table 9.2 Model Sensitivity to Bed Shear for the Denser Jet

<table>
<thead>
<tr>
<th>$K_T$</th>
<th>$Y$ (%)</th>
<th>$V$ (%)</th>
<th>$\Delta T$ (°C)</th>
<th>$F$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>+83</td>
<td>-25</td>
<td>+0.57</td>
<td>-32</td>
</tr>
<tr>
<td>0.5</td>
<td>+58</td>
<td>-25</td>
<td>+0.53</td>
<td>-36</td>
</tr>
<tr>
<td>1.0</td>
<td>+60</td>
<td>-29</td>
<td>+0.50</td>
<td>-39</td>
</tr>
<tr>
<td>2.0</td>
<td>+75</td>
<td>-34</td>
<td>+0.45</td>
<td>-47</td>
</tr>
</tbody>
</table>

### Table 9.3 Model Sensitivity to Reynolds Number for the Denser Jet

<table>
<thead>
<tr>
<th>$R_N$</th>
<th>$F'$</th>
<th>$Q$ (m³/s/m)</th>
<th>$T_1$ (°C)</th>
<th>$Y$ (%)</th>
<th>$V$ (%)</th>
<th>$\Delta T$ (°C)</th>
<th>$T$ (%)</th>
<th>$F$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1995</td>
<td>2.57</td>
<td>0.145</td>
<td>33.5</td>
<td>+60</td>
<td>-20</td>
<td>+0.5</td>
<td>+14</td>
<td>-31</td>
</tr>
<tr>
<td>2875</td>
<td>2.57</td>
<td>0.290</td>
<td>19.9</td>
<td>+60</td>
<td>-29</td>
<td>+2.4</td>
<td>+14</td>
<td>-40</td>
</tr>
</tbody>
</table>
Table 9.4 Model Sensitivity to Jet Froude Number for the Denser Jet

<table>
<thead>
<tr>
<th>$F'_r$</th>
<th>$F'_r$ (%)</th>
<th>$V_2$ (%)</th>
<th>$V_s$ (%)</th>
<th>$F'_r1$ (%)</th>
<th>Time* (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.239</td>
<td>-52</td>
<td>+1.3</td>
<td>-38</td>
<td>+57</td>
<td>77.5</td>
</tr>
<tr>
<td>1.559</td>
<td>-39</td>
<td>+0.2</td>
<td>-28</td>
<td>+39</td>
<td>84.0</td>
</tr>
<tr>
<td>1.700</td>
<td>-31</td>
<td>+2.6</td>
<td>-18</td>
<td>+29</td>
<td>90.0</td>
</tr>
<tr>
<td>2.170</td>
<td>-16</td>
<td>+3.1</td>
<td>-18</td>
<td>+10</td>
<td>93.5</td>
</tr>
</tbody>
</table>

†Densitometric Froude Number of Jet at weir.

‡Percentage change in densitometric Froude number from gate to weir.

*Time for moving internal hydraulic jump to travel from weir to gate.

Table 9.5 Model Sensitivity to Jump Storage Losses and Jump Entrainment for the Denser Jet

<table>
<thead>
<tr>
<th>$K_1$</th>
<th>$K_e$</th>
<th>$Y_2$ (%)</th>
<th>$V_s$ (%)</th>
<th>$F'_r1$ (%)</th>
<th>Time* (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>0.0</td>
<td>-2.7</td>
<td>-17</td>
<td>+40</td>
<td>70.0</td>
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<tr>
<td>0.0</td>
<td>0.1</td>
<td>0.0</td>
<td>-24</td>
<td>+39</td>
<td>77.0</td>
</tr>
<tr>
<td>0.1</td>
<td>0.0</td>
<td>-2.8</td>
<td>-19</td>
<td>+40</td>
<td>78.0</td>
</tr>
<tr>
<td>0.1</td>
<td>0.1</td>
<td>+0.2</td>
<td>-26</td>
<td>+39</td>
<td>84.0</td>
</tr>
</tbody>
</table>

*Time for moving internal hydraulic jump to travel from weir to gate.
Table 9.6 Submerged Hydraulic Jump Comparison

Experimental Results and Model Predictions

<table>
<thead>
<tr>
<th>Case No.</th>
<th>1</th>
<th>2</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source*</td>
<td>t.t.</td>
<td>t.t.</td>
<td>p.d.t.</td>
<td>p.d.t.</td>
</tr>
<tr>
<td>$y_2/y_1$</td>
<td>3.00</td>
<td>1.78</td>
<td>3.89</td>
<td>3.00</td>
</tr>
<tr>
<td>$y_3/y_2$</td>
<td>0.69</td>
<td>0.88</td>
<td>0.48</td>
<td>0.47</td>
</tr>
<tr>
<td>$F_2$</td>
<td>0.30</td>
<td>0.21</td>
<td>0.21</td>
<td>0.15</td>
</tr>
<tr>
<td>$y_2/y_1$</td>
<td>3.67</td>
<td>1.78</td>
<td>3.68</td>
<td>1.91</td>
</tr>
<tr>
<td>$y_3/y_2$</td>
<td>0.44</td>
<td>0.70</td>
<td>0.44</td>
<td>0.68</td>
</tr>
<tr>
<td>$F_2$</td>
<td>0.38</td>
<td>0.54</td>
<td>0.38</td>
<td>0.52</td>
</tr>
</tbody>
</table>

*Source of Data are Temperature Tests (t.t.), Photographic Dye Tests (p.d.t.) and Fluorescent Dye Tests (f.d.t.).

†Experimental results.

‡Theoretical predictions.
Appendix D. LISTING OF DATA ACQUISITION PROGRAMS
10 HOME
40 DIM CH(93), ER(89)
45 DIM DA(70, 28)
70 D$ = CHR$(4): E$ = CHR$(13)
80 80% = 0
370 PRINT CHR$(12)
380 PRINT "FLUKE DATA ACQUISITION"
385 PRINT "**IF IT WORKS.... IT'S A FLUKE**"
387 PRINT : PRINT : PRINT "IS FLUKE TO BE PRESENT(Y/N)"
388 GET A$: IF A$ < > "Y" AND A$ < > "N" THEN 388
389 IF A$ = "N" THEN GOTO 916
390 PRINT : PRINT : PRINT "SET 'ALL DATA' ON FLUKE"
400 INPUT "PRESS RETURN WHEN READY"; Z$:
606 IF A$ = "N" THEN GOTO 916
720 CH(19) = 45
900 REM MAIN MENU
910 PRINT D$; "LOAD FLUKES.BJO,D1"
915 PRINT D$; "IN#2": INPUT "": A$:
PRINT D$; "IN#0"
916 HOME
920 PRINT "SINGLE SCAN..............
...'RETURN'"
930 PRINT "MULTIPLE SCAN............
...'M'
940 PRINT "STAGGERED SCAN CTRL
RESET&RUN ...'SS'
950 PRINT "STORAGE/OUTPUT............
...'D'
955 PRINT "QUIT.........................
...'Q"
960 INPUT S$: IF S$ = "D" THEN GOTO 6000
965 IF S$ = "Q" THEN END
970 IF S$ = "M" THEN 1100
980 IF S$ = "SS" THEN 1140
985 IF S$ < > "" THEN GOTO 916
990 GOTO 1190
1100 PRINT : INPUT "# OF SCANS";
SC
1110 GOSUB 4000
1120 GOTO 3000

274
1140 HOME: PRINT: PRINT "STAGGERED SCAN"
1150 PRINT: PRINT "BE SURE DATA IS ENTERED CORRECTLY IN"
1155 PRINT "AT LINE 4040-4500"
1160 PRINT "1=NOSKIP, 2=SKIP ONE INTERVAL, 3=SKIP 3"
1165 PRINT: INPUT ":# OF SCANS"; SC
1170 SO% = 1: GOSUB 4000
1180 GOTO 3000
1190 HOME: SO% = 0: SC = 0: PRINT: PRINT "SINGLE SCAN"
2000 GOTO 3000
3000 REM
3005 RT = 0
3010 PRINT: PRINT "SET FLUKE CHANNELS 0-19, 'ALL DATA'"
3020 PRINT "TURN OFF ALL SCAN CONTROL BUTTONS"
3025 INPUT "RETURN TO CONTINUE"; F$
3030 PRINT "PRESS INTERVAL TO START"
3150 FOR J = 1 TO SC
3160 S = 1: IF SO% = 1 THEN READ S
3170 FOR X = 1 TO S
3190 PRINT: PRINT "ONE MOMENT PLEASE"
3200 D$ = CHR$(4)
3210 C$ = "012345678901234567890"
3215 POKE 254, PEEK (131): POKE
3220 255, PEEK (132): K% = PEEK (255) * 256 + PEEK (254) + 1
3225 K1% = K% + 1
3230 CALL 768
3235 KK = 32768
3240 A = PEEK (KK): IF A = 65 THEN 3220
3250 POKE KK, 89
3255 KK = KK + 3
3260 KH% = KK / 256: POKE K1%, KH%
3270 PRINT DD;":"; HH;":"; MM;":"; SS

3280 KK = KK + 22
3290 KK = KK + 1: IF PEEK (KK) < 5 THEN GOTO 3290
3300 KHK% = KK / 256: POKE KHK%, KHK% * 256: CNK% = VAL (MID$(C$, 2, 3)): CH: CNK% = VAL (MID$(C$, 6, 7))
3306 KK = KK + 18: IF PEEK (KK) = 65 GOTO 3300
3310 IF PEEK (KK) < 20 THEN PRINT "ERROR UNPACKING WILL RESCAN": GOTO 3220
3320 PRINT "**SCAN COMPLETE**"
3330 CALL -198
3332 NEXT X
3335 PRINT "SCAN #": J: "OF": SC
3336 PRINT "CH": TAB(10) "CH": TAB(22) "CH": TAB(31) "CH"
3337 PRINT "--------------------------"
3338 FOR X = 1 TO 20 STEP 4
3340 I = X + 19
3355 DA(J, X) = CH(I): DA(J, X + 1) = CH(I + 1): DA(J, X + 2) = CH(I + 2): DA(J, X + 3) = CH(I + 3)
3360 NEXT X
3365 DA(J, 22) = DD: DA(J, 23) = HH: DA(J, 24) = MM: DA(J, 25) = SS
3368 IF J < 1 THEN RT = RT + IT * 8
3370 DA(J, 21) = RT
3375 DA(J, 21) = RT
3390 NEXT J
3395 PRINT "ANY KEY"
3395 GET A$: IF A$ = "": THEN GOTO 3980
3396 GOTO 16
4000 PRINT : PRINT "MINIMUM SCANNING INTERVAL- 10 SEC."
4010 INPUT "SCAN INTERVAL ON FLUKE": IT
4020 RETURN
4025 REM DATA FOR STAGGERED SCAN
DATA 1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,3,3,3,3,3,3,3,3,3,3,3,3,3

HOME: PRINT: PRINT "DISPLAY OPTIONS"
PRINT: PRINT "SCREEN.......
......."S""
PRINT "PRINTER............"
P"
PRINT "DISK L/S............."
D"
PRINT "RETURN TO MAIN.....
......."R""
INPUT F$
IF F$ = "S" THEN GOSUB 621
0: GOTO 6000
IF F$ = "P" THEN PR# 1: GOSUB 6210: PR# 3: GOTO 6000
IF F$ = "R" THEN GOTO 916
IF F$ = "D" THEN GOTO 6310
GOTO 6000
REM SCREEN DISP.
PRINT "SHIFT-1 TO EXIT LISTING"
PRINT SC; " SCANS IN MEMORY"

INPUT "BEGIN AT SCAN"; Q
FOR I = 0 TO 20
PRINT "SCAN#"; I; "OF"; SC; ";"; "TIME"; DA(I, 21); " SEC."
PRINT DA(I, 22); ";"; DA(I, 23) ";"; DA(I, 24); ""; DA(I, 25)
PRINT : PRINT "CH"; TAB(11 )"CH"; TAB(20)"CH"; TAB(31 )"CH"
PRINT "------------------
------------------"
FOR P = 1 TO 20 STEP 4
J = P - 1
PRINT J; TAB(4) DA(I, P); TAB(11) J + 1;
PRINT TAB(14) DA(I, P + 1);
TAB(20)J + 2; TAB(24)DA(I,P + 2);
6242 PRINT TAB(31)J + 3; TAB(34)DA(I,P + 3)
6250 NEXT P
6265 PRINT
6270 IF F$ < > "P" THEN PRINT
"ANY KEY"
6280 IF F$ < > "P" THEN GET A$ ; IF A$ = "" THEN 6280
6282 IF F$ < > "P" AND A$ = "!"
THEN I = SC + 1
6290 NEXT I
6300 RETURN
6310 REM DATA STORAGE
6315 D$ = CHR$(4)
6320 HOME : PRINT "'LOAD' OR 'SAVE''
6330 INPUT A$; IF A$ = "" THEN 6
6335 PRINT CHR$(12)
6340 IF A$ < > "LOAD" AND A$ <
> "SAVE" THEN GOTO 6330
6350 PRINT CHR$(4);"CATALOG.D2"
6560 PRINT : INPUT "FILENAME:";V
V$6570 F$ = A$; IF F$ = "LOAD" THEN
GOTO 6800
6580 PRINT D$; "OPEN";VV$
6590 PRINT D$; "WRITE";VV$
6600 PRINT SC$
6610 FOR I = 1 TO SC
6620 FOR J = 1 TO 25
6630 PRINT DA(I,J)
6640 NEXT J
6650 NEXT I
6660 PRINT D$; "CLOSE"
6670 GOTO 6000
6800 REM READ
6810 PRINT CHR$(4); "OPEN";VV$
6820 PRINT CHR$(4); "READ";VV$
6830 INPUT SC$
6840 FOR I = 1 TO SC
6850 FOR J = 1 TO 25
6860 INPUT DA(I,J)
6870 NEXT J; NEXT I
6880 PRINT D$; "CLOSE"
6890 GOTO 6000
Steps for Using Data Acquisition Program NEWFLUKE

1. Put diskette containing NEWFLUKE into drive.

2. Boot the system.

3. Type "RUN NEWFLUKE" and press return.

4. Type "Y" if the Fluke Data Logger is connected with the system. Type "N" if the Fluke Data Logger is not connected.

5. Choose Option Multiple Scan by typing "M" and press return. Input the number of scans required. Input the time interval between scans. Press return to start recording the temperature sample.

6. Choose Option Storage/Output by typing "D" and press return. Choose Option Disk by typing "D" and press return. To save data collected type "SAVE" and press return. A catalog of the existing files on the disk in drive 2 will appear on screen. Type "NAME" in which NAME is the assigned name for the data file and press return.

7. Repeat steps 5 and 6 for another experiment.

8. Other available options:

Choose Single Scan by pressing return. Press return to start recording the temperature sample.

Choose Staggered Scan by pressing CTRL RESET and typing "RUN" and press return and typing "SS" and press return. Input the number of scans required. Input the time interval between scans. Press return to start recording the temperature sample.
MAIN MENU: NEWFLUKE

The main menu is comprised of four options available to acquire and view the data.

SINGLE SCAN

This is used to take a single sample of the data. Press return to get into the SINGLE SCAN mode. Press return again to start sampling. This will take a sample at each thermocouple location once. As the sample is taken, it will appear on screen.

MULTIPLE SCAN

This is used to take several samples of the data with a specific time interval between scans. Type "M" and press return to get into the MULTIPLE SCAN mode. Input the number of scans required and the time interval. The maximum number of scans is 70 and the minimum time interval is 6 seconds. Press return to start sampling. This will take a sample at each thermocouple location at the specified time interval. As the sample is taken, the results will appear on screen.

STAGGERED SCAN

This is a modification of the MULTIPLE SCAN option. This will also take several samples of the data but with a
specified stagger in the time interval. The data for the staggered scan is in line 4040 in the NEWFLUKE program. Data of 1 indicates that there is no stagger. Data of 2 indicated that while there is a scan read at every time interval, only the first of every two sets of readings is saved. Data of 3 indicates that while there is a scan read at every time interval, only the first of every three sets of readings is saved.

To get into the STAGGERED SCAN mode, press CTRL RESET. Type "RUN" and press return. Type "SS" and press return. Input the number of scans and the base time interval. Press return to start sampling. As the sample is taken, the results will appear on the screen.

STORAGE/OUTPUT

This option allows the user to load or save data files on diskette and to view data files on screen. To select the STORAGE/OUTPUT option, type "O" and press return. The sub-options are to view files on the screen, "S", to send files to the printer, "P", and to load or save on a diskette. To return to the main menu, type "R".

To view a file on that is in the computer memory, type "S". Input which scan number at which to begin viewing the file. Press "I" to cease viewing before reaching the end of the file.

To print a file that is in the computer memory, type
"p". This will send the active file to the printer.

To load or save a file on a diskette, type "D". To load a file type "LOAD" or to save a file type "SAVE". A catalog of the existing files on the diskette in drive 2 will appear on screen. Type "NAME" in which NAME is the assigned name for the data file.

QUIT

To quit from the NEWFLUKE program, type "Q" and press return.
REM ** CONTROL INIT **
70 CB = 47486
90 D$ = CHR$ (4): PRINT D$:"BLOA D CONTROL BLOCK,A$960"
90 DEF FN HX(X) = PEEK (X) + PEEK (X + 1) * 256
100 HOME : HTAB 8: INVERSE : PRINT "INITIALIZE CONTROL BLOCK": NORMAL
105 POKE 34.1
110 FOR I = 0 TO 2: READ A$(I): NEXT
120 FOR I = 0 TO 1: READ B$(I): NEXT
130 AR$ = " -- > "
140 FOR I = 0 TO 2
147 A(I) = FN HX(CB + I * 2)
150 NEXT I
152 B(0) = PEEK (CB + 6)
154 B(1) = FN HX(CB + 9)
165 VTAB 23: HTAB 2: PRINT " (HEX ADDRESSES MUST START WITH A $)"
170 HTAB 8: PRINT " (ENTER A MEMORY ADDRESS)"
195 FOR I = 0 TO 2
200 VTAB 4 + I * 2
205 GOSUB 1500
210 IF QQ$ < > "" THEN A(I) = VAL (QQ$)
220 NEXT I
280 HOME
290 FOR I = 0 TO 1
295 VTAB 4 + I * 2
320 IF QQ$ < > "" THEN B(I) = VAL (QQ$)
330 B(1) = INT ((A(1) - A(0)) / (B(0) * 2) + 1)
340 NEXT I
400 GOSUB 2500
410 PRINT D$: "BSAVE CONTROL BLOC K,A$960,L$30"
998 POKE 34,0: END
1000 DATA START OF DATA STORAGE E,END OF DATA STORAGE,START OF GROUP STORAGE
1010 DATA NUMBER OF CHANNELS,# OF SAMPLES PER CHANNEL
1500 REM HEX TO DEC CONV.
1505 ER = 0
1510 IF LEFT$(QQ$,1) > "$" THEN RETURN
1520 FOR K = LEN (QQ$) TO 2 STEP -1
1530 C$ = MID$(QQ$,K,1)
1535 C = ASC (C$)
1540 IF C > 58 OR C < 48 THEN GOTO 1570
1550 VA = C - 48
1560 GOTO 1600
1570 IF C > 70 OR C < 65 THEN ER
1580 VA = C - 65 + 10
1600 SU = VA * (16 ^ (LEN (QQ$) - K)) + SU
1610 NEXT K
1620 QQ$ = STR$ (SU)
1650 RETURN
2000 HOME
2010 VTAB 11: HTAB 14: PRINT "BAD ENTRY FOR"
2020 VTAB 13: HTAB INT ((40 - LEN (A$)) / 2): PRINT A$;
2030 VTAB 23: HTAB 13: PRINT "PRESS ANY KEY": GET PPS
2060 RETURN
2500 REM SAVE CB
2510 FOR I = 0 TO 2
2520 HD = A(I): GOSUB 3000
2530 POKE CB + I * 2,LD
2535 POKE (CB + 1) + I * 2,HI
2540 NEXT I
2560 POKE CB + 6,B(0)
2563 POKE CB + 7,B(0) * 2 - 1
2566 POKE CB + 8,B(0) * 3
2570 HD = B(1): GOSUB 3000
2580 POKE CB + 9,LD; POKE CB + 10,HI
2590 M = 1: GB = 47456: REM GAIN BLOCK $B960
2595 POKE GB,64: POKE GB + 1,64
2597 B(0) = 3
2600 FOR J = B(0) TO 2 STEP -1
2610 POKE GB + J,64 + M
2620 M = M + 1
2640 NEXT J
3000 REM DEC TO HI/LD CONV.
3010 HI = INT (HD / 256)
3020 LD = HD - HI * 256
3040 RETURN
REM HEXZOOMER12
10 AI = 47360:GU = 47616:SH = 4787:
20 FK = 48048:Z0 = 48128:LFK = 48384:UN = 48784:CB = AI + 1:
30
40 HOME
50 HIMEM: 8192
60 IF PEEK (55) < 190 THEN VTABLE
70 HTAB 14: PRINT "DOS NOT MOVED": END
80 D$ = CHR$(4)
90 IF PEEK (AI + 2) > 161 THEN
100 GOTO 30
110 VTABLE 12: HTAB 16: INVERSE : PRINT "LOADING": NORMAL
120 PRINT D$; "LOAD BSUBROUTINES,
130 PRINT D$; "LOAD CONTROL BLOCK
140 PRINT D$; "LOAD BSUBROUTINES,
150 PRINT D$; "LOAD CONTROL BLOCK
160 DEF FN ZR(X) = 0.5 * (26 + 2
170 * X + 5 * X ^ 2)
180 DEF FN HX(X) = PEEK(X) + PEEK
190 + (X + 1) * 255
200 DEF FN C2(X) = X
210 A1$ = "SAMP": A2$ = "GROUP": WH$ = "WHICH"
220 OP$ = "OPTIONS: ": DE = 10
230 D1 = FN HX(CB): D2 = FN HX(CB + 4): NU = FN HX(CB + 9)
240 VV = 94:M2 = 5
250 DIM S$(15)
260 FOR I = 0 TO 15: READ S$(I): NEXT I
270 DATA 0.1,2.3,4.5,6,7,8,9,A,B,
280 C,D,E,F
290 DEF FN CO(X) = (X - 2060) / 41.8973
300 DEF FN CI(X) = (X - 2177.6) / 403.3
310 DEF FN RJ(X) = INT (X * 100
320 + .5) / 1000
330 NC = PEEK(CB + 6)
340 UP = 4096: MIN = 1500: RANGE = UP - MIN
350 PZ = 159
360 ZERO = PZ - (2048 - MIN) * PZ / RANGE
370 GOSUB 5515
380 MI = INT (NU / 278)
390 GOTO 372
400 INC = MAG * S
410
176 FI = BE + 278 * INC
180 IF INT ((BE - D1) / S) * S < 
    > (BE - D1) THEN BE = BE - 
    1; GOTO 180
185 L1 = BE; L2 = FI; L3 = MA; GOSUB 
    2500
190 GOSUB 2000
200 HGR:
210 HPlot 0,0 TO 279,0 TO 279,PZ 
    TO 0,PZ TO 0,0
220 FOR I = 0 TO 279 STEP 4; HPlot 
    I,ZE; IF INT (I / 20) * 20 = 
    I THEN HPlot I,ZE - 3 TO I,
    ZE + 3
225 NEXT
237 FOR K = 0 TO NC - 1
238 X = 0
240 FOR I = BE + K * S / NC TO F 
    I STEP INC
250 X1 = PEEK (I) + PEEK (I + 1 
    ) * R1 + PEEK (I + 2) * R2
270 IF A1$ = "GROUP" THEN X1 = X 
    1 / GP 
280 Y1 = PZ - (X1 - MIN) * PZ / R 
    ANGE
315 HPlot X,Y1
330 X = X + 1
340 NEXT I
350 NEXT K
365 CO = 0
370 IF FI + 278 * INC > 38400 THEN 
    CO = 1
372 POKE 34,20; HOME ; VTAB 21
375 PRINT "1) NEW DATA 2) SAMPL 
    E TIME 3) REGRAPH"
377 PRINT "4) CONTINUE 5) ";
378 INVERSE : PRINT A1$ ; NORMAL 
    : PRINT "/" ; A2$ ; " 6) ZOOM"
380 PRINT "7) GROUP 8) SMOOT 
    H 9) STORAGE"
385 PRINT WS$; INPUT SE$
386 IF SE$ = "" THEN GOSUB 2500 
    : GOSUB 2000: GET PQ$; GOTO 
    372
387 SE = VAL (SE$)
388 IF CO = 1 AND SE = 4 THEN BE 
    = FI; FI = 38400; GOTO 180
389 IF SE = 4 THEN BE = BE + 278 
    * INC; GOTO 170
390 HOME
400 ON SE GOSUB 5000,3000,1500,0
,5500,3500,4000,4500,6500
420 IF SE = 5 OR SE = 2 OR SE =
9 THEN GOTO 372
460 GOTO 170
1000 INPUT "INPUT DEC. ":HD
1010 DIM S$(15)
1015 FOR I = 0 TO 15: READ S$(I)
: NEXT I
1020 DATA 0,1,2,3,4,5,6,7,8,9,A
,B,C,D,E,F
1030 HIBYTE = INT (HD / 256)
1040 B1 = INT (HI / 16):B2 = HI -
B1 * 16
1060 LOBYTE = HD - HI * 256
1070 B3 = INT (LO / 16):B4 = LO -
B3 * 16
1090 HE$ = ":" + S$(B1) + S$(B2) +
S$(B3) + S$(B4)
1095 RETURN
1500 REM
1510 INPUT "START ADDRESS? ":QQ$
1512 IF PA = 0 AND A1$ = "GROUP"
THEN HOME : PRINT : PRINT
"NO GROUPED DATA": FOR UP =
1 TO 2500: NEXT UP: POP : GOSUB
5510: GOTO 372
1515 IF QQ$ = "A" THEN GOSUB 55
15: POP : GOTO 170
1520 BEG = VAL (QQ$)
1530 INPUT "MAGNIFICATION? ":MAG
1540 RETURN
2000 REM
2010 HOME : VTAB 23
2030 TIME = (( FN ZR( PEEK (AI)) +
VV) * NC * 20 * MA) * 1.023E
- 06 * 1000 * GF
2050 PRINT "SLASH TIME = ": FN R
3(TI);" ms"
2060 RETURN
2500 PRINT : POKE 34,20: VTAB 21
: INVERSE
2530 PRINT L1; TAB( 20);L3; TAB(36);L2
2535 NORMAL : POKE 34,21
2540 RETURN
3000 REM
3010 INPUT "SAMPLING DURATION (S
ECONDS)? ":QQ
3020 QQ = (QQ * 1E06 / 1.023) / 1000
3025 QQ = QQ - VV
3030 DE = ( - 27 + SQR (27 * 27 - 4 * 5 * (26 - 2 * QQ))) / (2 * 5)
3040 DE = INT (DE)
3050 HOME: PRINT "AMOUNT OF DELAY = " ; DE: FOR I = 1 TO 2000 NEXT I
3090 RETURN
3500 HOME
3510 PRINT OP$; "C/M/"; HTAB 7: PRINT WH$; " INPUT QQ$"
3515 FL = 0
3520 IF QQ$ = "" THEN POP : GOTO 372
3530 PRINT "USE <-- AND --> TO MOVE WINDOW"
3540 PRINT "SPACEBAR TO STOP"
3550 CALL Z0 + 7
3560 PP = Z0 + 3
3570 P1 = FN HX (FP)
3580 P2 = FN HX (PP + 2)
3590 XT = (P2 - P1) * TIME / 20
3600 P4 = BE + P2 * INC; P3 = BE + P1 * INC
3610 M2 = INT ((P4 - P3) / (278 * S))
3620 L1 = P3; L2 = P4; L3 = MA; GOSUB 2500
3630 PRINT "WINDOW TIME = "; FN R3(XT); " ms"
3635 IF FL = 1 THEN GOTO 3693
3640 PRINT "(SPACEBAR TO CHANGE WINDOW RETURN TO): PRINT "CONTINUE)": GET KE$
3650 IF KE$ < > "S" THEN GOTO 3790
3655 POKE -16302,0: POKE -16303,0: POKE 34,0
3660 HOME: HTAB 14: PRINT "DATA VALUES": VTAB 4: HTAB 13: PRINT "CHANNEL ": SPC( 6); "READIN
3665 FL = 0; ZL = BE + P1 * INC
3670 PRINT "LEFT LINE ";
3673 QQ = NC - 1
3675 ON NC GOTO 3684,3682,3680
3680 H TAB 17: PRINT QQ; TAB( 29)
3685 FN R3( FN C2( FN HX(ZL + 4) ) )
3681  QQ = QQ - 1
3682  HTAB 17: PRINT QQ; TAB( 29)
    ; FN R3( FN C1( FN HX(ZL + 2 )))
3683  QQ = QQ - 1
3684  HTAB 17: PRINT QQ; TAB( 29)
    ; FN R3( FN C0( FN HX(ZL)))
    ; CV = PEEK (37)
3687  IF FL = 0 THEN FL = 1; ZL =
    BE + P2 * INC; PRINT : PRINT
    : PRINT "RIGHT LINE ":: GOTO
3673
3690  VTAB 23; HTAB 7: PRINT "PRESS RETURN TO VIEW PLOT": VTAB
    CV + 3: PRINT "SCAN (L/R) ":
    ; GET RW$
3692  IF ASC (RW$) = 13 THEN HOME
    ; POKE - 16301,0; POKE - 1
    6304,0; GOTO 3590
3693  IF ASC (RW$) = 13 THEN VTAB
    24; HTAB 14: PRINT "PRESS AN
    Y KEY ":: GET RW$: POKE - 1
    6302,0; POKE - 16303,0; GOTO
    3655
3694  IF ASC (RW$) = 27 THEN KE$ = " "; POKE - 16301,0; POKE
    - 16304,0; POKE 34,21: GOTO
    3790
3695  PRINT : VTAB CV + 3: PRINT
    "USE <--- --> ":: GET SC$
3740  IF ASC (SC$) = 21 THEN ZC = 1
3750  IF ASC (SC$) = 8 THEN ZC = - 1
3760  IF RW$ = "L" THEN HD = P1: GOSUB
    3950;P1 = P1 + ZC; HD = P1: GOSUB
    3950; GOTO 3660
3770  HD = P2: GOSUB 3950;P2 = P2 +
    ZC; HD = P2: GOSUB 3950; GOTO
    3660
3790  IF KE$ = " "; THEN HD = P1: GOSUB
    1030; GOSUB 3950; HD = P2: GOSUB
    1030; GOSUB 3950; GOTO 3500
3800  IF QQ$ = "M" THEN KE$ = " ":
    ; GOTO 3790
3810  BE = P3; FI = P4; MA = MZ
3820  IF QQ$ = "Z" THEN RETURN
3830  IF INT (BE / 4) * 4 < > BE
    THEN BE = BE - 1: GOTO 3830

3840 IF INT (FI / 4) * 4 < > F
I THEN FI = FI + 1: GOTO 384
0
3850 NU = (FI - BE) / 4
3860 HD = BE: GOSUB 1030
3870 POKE GU + 31,LO: POKE GU + 16,HI
3880 HD = (FI - D1) * 3 / 4 + D1:
M1 = INT (NU / 278) + 1
3890 GOSUB 1030
3900 POKE GU + 3,LO: POKE GU + 4
,HI
3910 D1 = BE
3930 RETURN
3950 GOSUB 1030
3960 POKE 254,LO: POKE 255,HI
3970 CALL ZO + 137: CALL ZO + 20
9
3980 RETURN
4000 REM
4010 INPUT "GROUP SIZE? ":GP
4015 IF GP < = 5 THEN HOME: GOTO 4010
4016 PA = 1
4017 CALL PK: REM PACK DATA
4020 POKE GU,GP:
4025 CALL GU + 4
4030 FI = INT (NU / GP) * NC * 3 + 32889
4040 MG = INT ((FI - D2) / (S * 278)) + 1
4050 MA = MG
4060 INC = MAG * S
4070 POP ; GOTO 190
4500 PRINT OP$:"S/A": HTAB 7: PRINT
WH$:; INPUT SM$
4502 IF SM$ = "A" GOTO 4600
4505 POKE SH + 2, PEEK (CB + 7):
REM INCSIZE
4510 PRINT "SMOOTH WHAT CHANNEL?"
("0-":NC - 1:: INPUT ") "!:UO$
4520 IF Ud$ = "": THEN RETURN
4521 Ud = VAL (Ud$)
4522 POKE SH + 11, Ud * 2
4525 U1 = UD * 2; U2 = UD * 2 + S
4540 POKE SH + 26, U1: CALL SH + 5
4550 POKE SH + 26, U2: CALL SH + 5: REM DOWN ROUND
4560 GOTO 4510
4600  REM #1 ON SAME TIME DOWN ROND
4610  POKE SH + 2,3: POKE SH + 11,2: POKE SH + 26,6
4640  CALL SH + 5: POP : GOTO 372
4650  RETURN
5000  REM
5010  POKE 34,0: HOME : TEXT
5020  HTAB 8: VTAB 12
5030  PRINT "PRESS ANY KEY TO SAMPLE": GET FI$  
5040  POKE AI + 1,NC
5050  POKE AI,DE: CALL AI + 2
5060  BE = 16384: MA = M1
5090  RETURN
5500  REM
5505  IF SE < > 5 THEN GOTO 553
5510  TE$ = A1$: A1$ = A2$: A2$ = TE$
5515  R1 = 256: R2 = 65536: S = NC * 3: BE = D2: MA = MG
5520  IF A1$ = "SAMP" THEN R1 = 2
5525  R2 = 0: S = NC: 2: BEG = D  
5530  MA = M1: GP = 1: IF PA = 1 THEN  CALL UN: PA = 0  
5590  RETURN
6500  PRINT DP$; "S/L": HTAB 7: PRINT  
6505  WH$: ; INPUT SM$   
6510  PF$ = "SAVE": IF SM$ = "L" THEN PF$ = "LOAD"  
6515  HOME : PRINT PF$; " "; POKE 32,6
6516  IF IF I = 1 THEN POKE 32,6  
6517  PRINT "1) PLOT"
6530  PRINT "2) PACKED DATA"
6540  PRINT "3) GROUPED DATA": HTAB  
6545  POKE 32,0
6547  HOME : INPUT "DATA FILE NAME, DRIVE NUMBER ": NA$, DR$  
6548  IF SM$ = "L" THEN GOTO 667
6650  AA = 8192: LL = 8192
6650  IF QQ = 2 THEN AA = D1: LL = NU * NC * 2 / 3 / 4
6660  IF QQ = 3 THEN AA = D2: LL = INT (NU / GP) * 3 * NC
6670  PRINT D$: "SAVE "; NA$: , A":  
6680  AA: , LL; " "; DR$  
6690  RETURN
6700  PRINT D$: "LOAD "; NA$: , D  
6700  RETURN  
6700  RETURN
Steps for Using Data Acquisition Program Hexzoomer12

1. Put diskette containing Hexzoomer12 into drive.

2. Boot the system.

3. Type "RUN DDMOVER" and press return.

4. Type "RUN CONTROL INIT" and press return. Specify the number of channels and press return.

5. Type "RUN #12" and press return.

6. Choose Option 2 by typing "2"; input sample time and record the amount of delay shown on the screen.

7. Choose Option 1 by typing "1", this will enter sample mode.

8. Press any key to start recording the sample.

9. Choose Option 9 by typing "9", this will enter storage mode.

10. Type "S" to save the data.

11. Type "1"; this indicates that a plot is being saved.

12. Insert data disk into drive.

13. Type "NAME, DRIVE" in which NAME is the assigned name for the plot file and DRIVE is the assigned drive, either D1 or D2.

14. Repeat steps 6 through 13 for another experiment.
MAIN MENU: Hexzoomer12

The main menu is comprised of nine options available to acquire and view the data. Each option is explained and can be selected from the menu by pressing the corresponding number and pressing return.

1: NEW DATA

This is used to sample data for the duration set in option #2. The data resides in memory locations $4000$ to $9600$ in its unpacked form. Each sample consists of two bytes in low byte-high byte order. Channel #0 data resides in the first two memory locations followed by channel #1 in the next two and then channel #0 again, until the end which is $95FF$. After a new sample is taken the complete data is graphed on the screen.

2: SAMPLE TIME

This allows the time of sampling to be set from a minimum of 0.9 seconds to a maximum of 1500 seconds (25 minutes). The user is prompted to enter the duration of sampling in seconds and then the closest approximation to this value is computed and used. After this the main menu reappears.
3: REGRAPH

The REGRAPH options allow manual replotting of the data. The "start address" prompt asks for the first location in memory to begin the plot. "Magnification" is the number of points in the memory that one value for each channel represents on the screen. If an "A" is entered, the entire sample is plotted similar to the graph obtained after a new sample is taken.

4: CONTINUE

Selecting the CONTINUE option means the next plot will start where the last one left off with the same magnification. It will only plot until locations $95FE and $95FF are used.

5: SAMP/GROUP

This indicates which type of data is being used for the plots. If SAMP is in inverse then the data is unpacked and the sampled data is used. If the GROUP is in inverse then the original data is packed in locations $4000 to $807F and the grouped values of data are stored from $8080 to $9600 and this data is used for the plots displayed. If this option is selected, then the program assumes that the user wants to view the other type of data which is not in inverse display at that time. Option 5 is a flip-flop which means when it is selected it causes the name not in inverse
display to become inversed. Note: The program must be in GROUP mode before selecting the group option so that the data can be packed to allow room for the grouped samples to be stored.

6: ZOOM

When this option is chosen, two vertical lines will be displayed on the current plot. The left line can be moved left or right using the arrow keys. When it is positioned, press the spacebar to begin moving the right vertical line in the same manner. When the spacebar is pressed a second time to position the second line the next plot will appear where the lines of the window formed the start and finish. The magnification is computed to allow the window selected to be displayed completely.

7: GROUP

This option allows a number of points, set by the user, of the original data to be summed together and stored in memory. In order to store the grouped data the sample has to be packed. The A/D data consists of 12 bits, the low order byte has eight bits set and the high order byte has the lowest four bits set. The four bytes occupied by the channel $0$ and $1$ readings are packed together to fit into three bytes.

The low order byte of $0$ remains the same. The second
byte has the hi-byte of $0$ in the lower four bits and the 
hi-byte of $\#1$ in the higher four bits, following this 
combined byte is the low order byte of $\#1$.

8: SMOOTH

This option has two sub-options namely smooth data or 
adjust time base. Smooth data means that in the channel 
selected two consecutive samples are averaged and the result 
is stored in the first location of these two consecutive 
readings on the same channel. This averaging continues 
through all the data for the selected channel. The sampling 
program is unable to sample both channels simultaneously but 
rather the first channel and then the second. This results 
in readings being one sampling period apart. The actual 
time $\#1$ read was halfway between a $\#0$ reading and its 
successor. Therefore based on a linear change in $\#0$ the 
reading for $\#0$ at the same time as the one for $\#1$ is halfway 
between or an average of the two samples for channel $\#0$. 
This process is similar to smoothing but is called adjusting 
the time base. The program assumes that channel $\#1$ should 
be shifted back to coincide with channel $\#0$.

9: STORAGE

This option will save or load data from a sample to or 
from a diskette. It will do this for a plot of the data, 
packed data or grouped data.
Appendix E. COMPUTER PROGRAMS FOR MANIPULATION OF TEMPERATURE DATA
FLOW CHART OF TEMP4.FOR

START

REAL, INTEGER, CHARACTER

INITIALIZE MATRICES AND FLAGS

READ INPUT AND OUTPUT FILENAMES
OPEN INPUT AND OUTPUT FILES

READ INPUT FILE
CLOSE INPUT FILE

I = 1, IEND

OPEN, READ AND CLOSE DATA FILES

CHECK SCAN NUMBERS FOR CONSISTENCY IN DATA FILES READ
NO

YES

PRINT COMMENT

CHECK TIME INTERVALS FOR CONSISTENCY IN DATA FILES READ
NO

YES

B

A

C
SEARCH FOR INDEX WHERE
DELTA T_JET > TDIFF
FOR EACH DATA FILE

CREATE NEW COLUMN IN MATRIX
FOR FLUKE ADJUSTED TIME VALUES

CREATE NEW MATRICES
LONGITUDINAL DISTANCE, X TEMPERATURE, TEMP TIME, TIME

SEARCH FOR VALUE OF MAXIMUM COMMON TIME FOR EACH DATA FILE

CALCULATE AVERAGE VALUES OF TEMPERATURE AND TIME FOR STATIONARY POINTS IN FLUME

WRITE TO OUTPUT FILE
CLOSE OUTPUT FILE

STOP
C TEMP4.FOR
C PROGRAM TO SORT FLUKE ASCII DATA FILES AND MERGE THEM TO ONE DATA FILE
REAL Y(11),DIST(2,15),FLUKE(15,30,60),X(15),MAXT(15)
INTEGER JEND,NPROBE,PROBE(2,11),IEND,LOC(2,15),LJET,MAXTL(15),SC
REAL TEMP(15,30,60),TIME(15,30,60),XSTAT(5),YSTAT(5),ATEMP(5,60)
REAL ATIME(5,60),STEMP(5,60),STIME(5,60)
INTEGER SCAN(14),INTERVAL(14),TIMEO(14),NUHT(5,60),STAT(5)
CHARACTER*12 FN1,FN2,FNAME(14)

C
C KEY TO ALL VARIABLES:  FN1,FN2,FNAME(I)=FILENAME FOR INPUT AND OUTPUT
C JEND=# CHANNELS PER PROBE, NPROBE=# PROBES, IEND=# FLUKE DATA FILES
C LJET=CHANNEL OF JET THERMOCOUPLE, DELT=CHANGE IN JET TEMP FOR REFERENCE
C TIME, X(J),YSTAT(NSTAT)=ELEVATIONS OF CHANNELS, PROBE(I,J)=CHANNELS
C CORRESPONDING TO PROBE LOCATIONS, DIST(II,I),XSTAT(J)=LATERAL DISTANCE
C ALONG PLUME FROM GATE, LOC(II,I)=LOC REVERSE, IKOUNT=COUNTER,NSTAT=#
C STATIONARY CHANNELS, STAT(J)=CHANNELS CORRESPONDING TO STAT POINTS
C
C
C INITIALIZE ALL MATRICES
DO 101 J=1,11
   Y(J)=0.0
DO 101 I=1,2
   PROBE(I,J)=0
101 CONTINUE
DO 104 J=1,15
DO 104 I=1,2
   DIST(I,J)=0.0
   LOC(I,J)=15
104 CONTINUE
DO 102 I=1,15
   X(I)=0.0
   MAXT(J)=0.0
   MAXTL(J)=0
DO 102 J=1,30
DO 102 K=1,60
   FLUKE(I,J,K)=0.0
   TEMP(I,J,K)=0.0
   TIME(I,J,K)=0.0
102 CONTINUE
DO 103 J=1,5
   STAT(J)=0
   XSTAT(J)=0.0
   YSTAT(J)=0.0
DO 103 K=1,60
   ATEMP(J,K)=0.0
   ATIME(J,K)=0.0
   STEMP(J,K)=0.0
   STIME(J,K)=0.0
   NUHT(J,K)=0
103 CONTINUE
IKOUNT=0

WRITE(*,1000)
READ(*,1001) FN1
OPEN(60,FILE=FN1)
WRITE(*,1014)
READ(*,1001) FN2
OPEN(61,FILE=FN2)

READ FROM FILE FN1: JEND,NPROBE,IEND,LJET/DELT/Y(J)/PROBE(I,J)/
STAT/STAT(J)/XSTAT(J)/YSTAT(J)/
NAME(I),(DIST(I,I),LOC(I,I))/
READ(60,1002) JEND,NPROBE,IEND,LJET
IF (IEND.GT.14) THEN
  WRITE(*,1005)
  STOP
END IF
IF (NPROBE.GT.2) THEN
  WRITE(*,1009)
  STOP
END IF

READ(60,1003) DELT
READ(60,1003) (Y(J),J=1,JEND)
DO 100 I=1,NPROBE
     READ(60,1002) (PROBE(I,J),J=1,JEND)
100 CONTINUE
READ(60,1002) NSTAT
READ(60,1002) (STAT(J),J=1,NSTAT)
READ(60,1003) (XSTAT(J),J=1,NSTAT)
READ(60,1003) (YSTAT(J),J=1,NSTAT)
DO 1 I=1,IEND
     READ(60,1006) NAME(I),(DIST(I,I),LOC(I,I),II=1,NPROBE)
DO 12 II=1,NPROBE
       IKOUNT = IKOUNT + 1
     END IF
     IF (LOC(I,I).GT.15) THEN
       WRITE(*,1012)
       STOP
     END IF
12 CONTINUE
1 CONTINUE
CLOSE(60)

WRITE(*,1007) IEND,IKOUNT,NSTAT
DO 11 I=1,IEND
     WRITE(*,1008) NAME(I),(DIST(I,I),LOC(I,I),II=1,NPROBE)
11 CONTINUE
C READ DATA FILES
DO 2 I=1,IEND

C IF (I.EQ.1) THEN
OPEN(71,FILE=FNAME(1))
READ(71,*) SC
DO 2001 K=1,SC
DO 2001 J=1,25
READ(71,*) FLUKE(I,J,K)
2001 CONTINUE
CLOSE(71)
END IF
IF (I.EQ.2) THEN
OPEN(72,FILE=FNAME(2))
READ(72,*) SC
DO 2002 K=1,SC
DO 2002 J=1,25
READ(72,*) FLUKE(I,J,K)
2002 CONTINUE
CLOSE(72)
END IF
IF (I.EQ.3) THEN
OPEN(73,FILE=FNAME(3))
READ(73,*) SC
DO 2003 K=1,SC
DO 2003 J=1,25
READ(73,*) FLUKE(I,J,K)
2003 CONTINUE
CLOSE(73)
END IF
IF (I.EQ.4) THEN
OPEN(74,FILE=FNAME(4))
READ(74,*) SC
DO 2004 K=1,SC
DO 2004 J=1,25
READ(74,*) FLUKE(I,J,K)
2004 CONTINUE
CLOSE(74)
END IF
IF (I.EQ.5) THEN
OPEN(75,FILE=FNAME(5))
READ(75,*) SC
DO 2005 K=1,SC
DO 2005 J=1,25
READ(75,*) FLUKE(I,J,K)
2005 CONTINUE
CLOSE(75)
END IF
IF (I.EQ.6) THEN
OPEN(76,FILE=FNAME(6))
READ(76,*) SC

302
DO 2006 K=1,SC
DO 2006 J=1,25
READ(76,*) FLUKE(I,J,K)
2006 CONTINUE
CLOSE(76)
END IF
IF (I.EQ.7) THEN
OPEN(77,FILE=FNAME(7))
READ(77,*) SC
DO 2007 K=1,SC
DO 2007 J=1,25
READ(77,*) FLUKE(I,J,K)
2007 CONTINUE
CLOSE(77)
END IF
IF (I.EQ.8) THEN
OPEN(78,FILE=FNAME(8))
READ(78,*) SC
DO 2008 K=1,SC
DO 2008 J=1,25
READ(78,*) FLUKE(I,J,K)
2008 CONTINUE
CLOSE(78)
END IF
IF (I.EQ.9) THEN
OPEN(79,FILE=FNAME(9))
READ(79,*) SC
DO 2009 K=1,SC
DO 2009 J=1,25
READ(79,*) FLUKE(I,J,K)
2009 CONTINUE
CLOSE(79)
END IF
IF (I.EQ.10) THEN
OPEN(80,FILE=FNAME(10))
READ(80,*) SC
DO 2010 K=1,SC
DO 2010 J=1,25
READ(80,*) FLUKE(I,J,K)
2010 CONTINUE
CLOSE(80)
END IF
IF (I.EQ.11) THEN
OPEN(81,FILE=FNAME(11))
READ(81,*) SC
DO 2011 K=1,SC
DO 2011 J=1,25
READ(81,*) FLUKE(I,J,K)
2011 CONTINUE
CLOSE(81)
END IF

303
IF (I.EQ.12) THEN
OPEN(82,FILE=FNAME(12))
READ(82,*) SC
DO 2012 K=1,SC
DO 2012 J=1,25
READ(82,*) FLUKE(I,J,K)
2012 CONTINUE
CLOSE(82)
END IF
IF (I.EQ.13) THEN
OPEN(83,FILE=FNAME(13))
READ(83,*) SC
DO 2013 K=1,SC
DO 2013 J=1,25
READ(83,*) FLUKE(I,J,K)
2013 CONTINUE
CLOSE(83)
END IF
IF (I.EQ.14) THEN
OPEN(84,FILE=FNAME(14))
READ(84,*) SC
DO 2014 K=1,SC
DO 2014 J=1,25
READ(84,*) FLUKE(I,J,K)
2014 CONTINUE
CLOSE(84)
END IF
IF (I.EQ.IEND) WRITE(*,1015) I
C
C CHECK SCAN NUMBER AND TIME INTERVAL
SCAN(I)=SC
IF (I.EQ.1.) GOTO 20
DO 21 II=1,I-1
   IF (SCAN(II).NE.SCAN(I)) THEN
      WRITE(*,1010)
   END IF
21 CONTINUE
20 CONTINUE
INTERVAL(I)=FLUKE(I,21,2)
IF (I.EQ.1.) GOTO 22
DO 23 II=1,I-1
   IF (INTERVAL(II).NE.INTERVAL(I)) THEN
      WRITE(*,1011)
      STOP
   END IF
23 CONTINUE
22 CONTINUE
DO 24 K=2,SC
   TDIFF=FLUKE(I,LJET,1)-FLUKE(I,LJET,K)
   TIMES0(I)=K-1
   IF (ABS(TDIFF).GT.DELT) GOTO 25
24 CONTINUE
CONTINUE
CONTINUE
DO 26 K=1,SC
     FLUKE(I,26,K)=FLUKE(I,21,K)-FLUKE(I,21,TIME0(I))
CONTINUE
CONTINUE
C SET UP MATRIX TO BE SAVED
C X, SET OF LATERAL DISTANCES ALONG FLUME LENGTH
DO 3 I=1,IEND
   DO 3 II=1,NPROBE
       X(LOC(II,I))=DIST(II,I)
CONTINUE
C TEMPERATURE AND TIME MATRIX
WRITE(*,1018)
DO 4 J=1,JEND
   DO 4 K=TIME0(I),SCAN(I)
       KK=KK+1
   DO 4 II=1,NPROBE
       TEMP(LOC(II,I),J,KK)=FLUKE(I,PROBE(II,J),K)
   TIME(LOC(II,I),J,KK)=FLUKE(I,26,K)
CONTINUE
DO 41 K=1,SCAN(I)
   IF (TIME(I,1,K).GE.MAXT(I)) THEN
       MAXT(I)=TIME(I,1,K)
   MINTL(I)=K
END IF
CONTINUE
MINTL=SCAN(I)
DO 42 J=1,JEND
   IF(MAXT(I).LT.MINTL) MINTL=MAXT(I)
CONTINUE
DO 43 J=1,JEND
   DO 43 K=TIME0(I),SCAN(I)
       KK=KK+1
       STEMP(J,KK)=STEMP(J,KK)+FLUKE(I,STAT(J),K)
       STIME(J,KK)=STIME(J,KK)+FLUKE(I,26,K)
       NUMT(J,KK)=NUMT(J,KK)+1
CONTINUE
DO 44 J=1,JSTAT
   DO 44 K=1,MINTL
       ATEMP(J,K)=STEMP(J,K)/NUMT(J,K)
       ATIME(J,K)=STIME(J,K)/NUMT(J,K)
CONTINUE
WRITE(*,1019)
C WRITE TO ANOTHER FILE
WRITE(*,1022)
WRITE(61,1002) MINTL,NSTAT,IKOUNT,IEND,JEND
DO 5 K=1,MINTL
   DO 51 J=1,NSTAT
      WRITE(61,1013) XSTAT(J),YSTAT(J),ATEMP(J,K),ATIME(J,K)
   51 CONTINUE
   DO 5 I=1,IKOUNT
   DO 5 J=1,JEND
      WRITE(61,1013) X(I),Y(J),TEMP(I,J,K),TIME(I,J,K)
   5 CONTINUE
   XX=-1.0
   WRITE(61,1013) XX,XX,XX,XX
WRITE(*,1023)
CLOSE(61)

C WRITE TO SCREEN FILE
WRITE(*,1024) XSTAT(1),YSTAT(1),ATEMP(1,1),ATIME(1,1)
WRITE(*,1020) X(1),Y(1),TEMP(1,1,1),TIME(1,1,1)
WRITE(*,1024) XSTAT(NSTAT),YSTAT(NSTAT),ATEMP(NSTAT,MINTL),
   * ATIME(NSTAT,MINTL)
WRITE(*,1021) X(IKOUNT),Y(JEND),TEMP(IKOUNT,JEND,MINTL),
   * TIME(IKOUNT,JEND,MINTL)

C C
1000 FORMAT(' FILENAME OF FLUME INPUT PARAMETERS: ')
1001 FORMAT(A12)
1002 FORMAT(8110)
1003 FORMAT(8F10.2)
1005 FORMAT(' NUMBER OF FILES EXCEEDED'/ END OF PROGRAM')
1006 FORMAT(A12,8X,2(F10.2,110))
1007 FORMAT(' LISTING OF FILES/' # OF FILES =',I4,
   * '# OF PROBE LOCATIONS =',I4,' # OF STATIONARY ',
   * 'CHANNELS =',I4/)
1008 FORMAT(1X,A12,8X,2(F10.2,110))
1009 FORMAT(' NUMBER OF PROBES EXCEEDED'/ END OF PROGRAM')
1010 FORMAT(' SCAN NUMBERS NOT CONSISTENT'/ END OF PROGRAM')
1011 FORMAT(' TIME INTERVALS NOT CONSISTENT'/ END OF PROGRAM')
1012 FORMAT(' NUMBER OF PROBE POSTITIONS EXCEEDED'/ END OF PROGRAM')
1013 FORMAT(4F10.2)
1014 FORMAT(' FILENAME OF MERGED DATA: ')
1015 FORMAT( 'I5,' FILES OPENED, READ, CLOSED')
1018 FORMAT(' CREATING TEMP AND TIME MATRIX')
1019 FORMAT(' TEMP AND TIME MATRIX ASSIGNED')
1020 FORMAT(' FIRST POINT ',4F10.2)
1021 FORMAT(' LAST POINT ',4F10.2)
1022 FORMAT(' START WRITING TO OUTPUT FILE')
1023 FORMAT(' END WRITING TO OUTPUT FILE')
1024 FORMAT(' STAT POINT ',4F10.2)
STOP
END
Description of "TEMP4.FOR" Input File

The input file has nine groups of lines. The input is alphanumeric and follows specific formatting. All distances and elevations are given in millimeters. All temperatures are given in degrees Celsius.

The first line is comprised of indices which describe the layout of the tests to be merged into one file. The indices are JEND, NPROBE, IEND and LJBT. The format is 8 I10.

JEND corresponds to the number of thermocouple channels on each temperature probe.

NPROBE corresponds to the number of temperature probes.

IEND is the number of fluke data files that are read and merged.

LJBT is the thermocouple channel number that measures the temperature at the gate opening.

The second line contains DELT and the format is F10.2. DELT is the value of the change between two successive
temperature readings at the gate opening. It is used to set a time reference for each of the tests.

The third line group contains JEND values of Y. These are the elevations of the thermocouple channels on the temperature probe. The format is 8 F10.2.

The fourth line group contains JEND values and NPROBE lines of PROBE. The format is 8 I10. PROBE indicates to the channel numbers corresponding to the probe locations in order of minimum to maximum elevation. Values of PROBE are inputted on separate lines for each temperature probe.

The fifth line contains NSTAT. NSTAT is the number of thermocouple channels that are at stationary positions. The format is I10.

The sixth line group contains NSTAT values of STAT. These are the thermocouple channel numbers that correspond to the stationary points. The format is 8 I10.

The seventh line group contains NSTAT values of XSTAT. These are the longitudinal distances with reference to the gate position of the stationary thermocouple points. The format is 8 F10.2.
The eighth line group contains $N_{STAT}$ values of $Y_{STAT}$. These are the elevations of the stationary thermocouple points. The format is 8 F10.2.

The ninth line group has $I_{END}$ lines which contain $PNAME$ and $N_{PROBE}$ pairs of $DIST$ and $LOC$. The format is A12,8X,2(F10.2,I10).

$PNAME$ corresponds to the filename of the fluke data file to be read. The filename can have a maximum of twelve characters.

$DIST$ corresponds to the longitudinal distance along the flume from the gate to the probe position.

$LOC$ indicates the location reference order of the probe position. The probe closest to the gate has $LOC$ equal to 1. The probe closest to the weir has $LOC$ equal to the maximum number in the data set.
Description of "TEMP4.FOR" Output File

The output file has three groups of lines. The output is numeric and follows specific formatting. All distances and elevations are given in millimeters. All temperatures are given in degrees Celsius. All times are given in seconds.

The first line is comprised of flags which describe the size of the merged output file. The indices are MINTL, NSTAT, IKOUNT, IEND, and JEND. The format is 8 I10.

MINTL corresponds to the number of scan times recorded in the output file.

NSTAT corresponds to the number of thermocouple channels positioned at stationary points.

IKOUNT corresponds to the number of probe positions in the output file.

IEND is the number of fluke data files read from the input file.

JEND is the number of thermocouple channels that are
positioned on each temperature probe.

The second line group contains HINTL groups of lines. Each group contains information for a specific time elapsed during a test. Each line contains the longitudinal position, elevation, temperature and time for a thermocouple position at either a stationary point or on the grid formed by position of the temperature probes for each successive test. The format is 4 F10.2. The first NSTAT lines contain the information for the stationary points. The next IEND by JEND lines contain the information for the points from the temperature probe.

The last line in the output file contains flags to indicate the end of the file. There are four values of -1 in the last line. The format is 4 F10.2.
### Portion of output file from TEMP4.FOR

<table>
<thead>
<tr>
<th>44</th>
<th>4</th>
<th>14</th>
<th>14</th>
<th>11</th>
</tr>
</thead>
<tbody>
<tr>
<td>.00</td>
<td>25.00</td>
<td>32.33</td>
<td>.00</td>
<td></td>
</tr>
<tr>
<td>.00</td>
<td>140.00</td>
<td>32.47</td>
<td>.00</td>
<td></td>
</tr>
<tr>
<td>739.96</td>
<td>25.00</td>
<td>32.62</td>
<td>.00</td>
<td></td>
</tr>
<tr>
<td>739.96</td>
<td>140.00</td>
<td>32.74</td>
<td>.00</td>
<td></td>
</tr>
<tr>
<td>49.33</td>
<td>7.00</td>
<td>32.10</td>
<td>.00</td>
<td></td>
</tr>
<tr>
<td>49.33</td>
<td>22.00</td>
<td>32.30</td>
<td>.00</td>
<td></td>
</tr>
<tr>
<td>49.33</td>
<td>37.00</td>
<td>32.80</td>
<td>.00</td>
<td></td>
</tr>
<tr>
<td>49.33</td>
<td>52.00</td>
<td>32.80</td>
<td>.00</td>
<td></td>
</tr>
<tr>
<td>49.33</td>
<td>67.00</td>
<td>32.80</td>
<td>.00</td>
<td></td>
</tr>
<tr>
<td>49.33</td>
<td>82.00</td>
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FLOW CHART OF INTERP4.FOR

START
REAL, INTEGER, CHARACTER
READ INPUT AND OUTPUT FILENAMES
OPEN INPUT AND OUTPUT FILES
READ MINTL, NSTAT, ITKOUT, IEND, JEND
IF KK > MINTL
  YES
  NO
READ DATA SET
IF KK = 1
  NO
  YES
  CALCULATE AVERAGE TEMPERATURE FOR EACH LONGITUDINAL POSITION
  CALCULATE LINEAR SHIFT IN TEMPERATURE, XTEMP FOR EACH LONGITUDINAL POSITION TO ADJUST FOR INDIVIDUAL TEST INCONSISTENCIES
  KK = KK + 1
  B

A
C
YES IF KK < KSTART

NO SEARCH FOR MAXIMUM NUMBER OF POINTS AT EACH LONGITUDINAL POSITION

RESTRUCTURE STATIONARY AND TEMPERATURE PROBE POINTS INTO SINGLE MATRIX

OPTIONS:
1. INTERPOLATE SCAN
2. READ NEXT SCAN
3. QUIT

1. LOCATE MAXIMUM VALUE ON EACH GRID LINE

CALCULATE EXISTING GRID INCREMENT FOR X AND Y
INPUT NEW INCREMENT FOR X AND Y

ADJUST TEMPERATURES WITH XTEMP SHIFT

INTERPOLATE Y VALUES
INTERPOLATE X VALUES

WRITE TO OUTPUT FILE

CLOSE INPUT AND OUTPUT FILES

STOP
INTERP4.FOR
PROGRAM TO INTERPOLATE FLUKE TEMP DATA FILES TO RECTANGULAR GRID
AND DECREASE GRID INTERVALS
CHARACTER*12 FN1,FN2
REAL X(16,11),Y(16,11),TEMP(16,11),TIME(16,11),XTEMP(16),xsort(16)
INTEGER NUMY,NUMX,C,ANSWER
REAL XL(16,30),X2(75,30),Y(75,30),YMAX(16),YMIN(16)
REAL GRID1(16,30),G1(16,30),GRID2(75,30),G2(75,30)
INTEGER MINTL,NSTAT,IKOUNT,IEND,JEND,POS1,POS2,LASTJ,MARK,MARKX
INTEGER MARK0,MARKY,locmid,q,qq

WRITE(*,1026)
WRITE(*,1000)
READ(*,1001) FN1
WRITE(*,1004)
READ(*,1001) FN2
OPEN(60,FILE=FN1)
OPEN(61,FILE=FN2)
MARK0=0
KK=1
AA=0
MARKX=75
MARKY=30
WRITE(*,1024)
READ(*,*) KSTART

WRITE(*,1013)
READ(60,1002) MINTL,NSTAT,IKOUNT,IEND,JEND

CONTINUE
IF(KK.GT.MINTL) GOTO 2005
READ MERGED DATA FILE

WRITE(*,1013)
DO 107 J=1,11
DO 107 I=1,16
X(I,J)=0.0
Y(I,J)=0.0
TEMP(I,J)=0.0
TIME(I,J)=0.0

107 CONTINUE
DO 101 J=1,NSTAT
READ(60,1003) X(I,J),Y(I,J),TEMP(I,J),TIME(I,J)
101 CONTINUE
DO 104 I=2,IKOUNT+1
DO 104 J=1,JEND
READ(60,1003) X(I,J),Y(I,J),TEMP(I,J),TIME(I,J)
104 CONTINUE

C IF (KK.EQ.1) THEN
DO 108 I=2,IKOUNT+1
XTEMP(I)=0.0
DO 109 J=1,JEND
XTEMP(I)=XTEMP(I)+TEMP(I,J)
109 CONTINUE
TEMP(I)=TEMP(I)/JEND

CONTINUE
POS1=1
POS2=0
DO 110 J=2,NSTAT
   IF (X(1,J).NE.X(1,1)) THEN
      POS2=POS2+1
   ELSE
      POS1=POS1+1
   END IF

CONTINUE
I=1
TEMP(I)=0.0
DO 111 J=1,POS1
   TEMP(I)=TEMP(I)+TEMP(I,J)

CONTINUE
TEMP(I)=TEMP(I)/POS1
I=IKOUNT+2
TEMP(I)=0.0
DO 112 J=POS1+1,POS1+POS2
   TEMP(I)=TEMP(I)+TEMP(I,J)

CONTINUE
TEMP(I)=TEMP(I)/POS2
C CALCULATE SHIFT IN TEMP GRID TO ADJUST FOR TEST DISCREPENCIES
C    DO 116 Q=1,IKOUNT+2
C       XSORT(Q)=TEMP(Q)

CONTINUE
Q=1,IKOUNT+2-1
DO 113 QQ=Q+1,IKOUNT+2
   IF (XSORT(Q).GT.XSORT(QQ)) THEN
      TMPR=XSORT(Q)
      XSORT(Q)=XSORT(QQ)
      XSORT(QQ)=TMPR
   END IF

CONTINUE
LOCMD=INT((IKOUNT+2)/2)
XMD=(XSORT(LOCMD)+XSORT(LOCMD+1))/2
DO 114 I=1,IKOUNT+2
   TEMP(I)=XMD-TEMP(I)

CONTINUE
END IF
C
KK=KK+1
IF (KK.LT.KSTART) GOTO 2002
C
C SEARCH FOR MAXIMUM NUMBER OF POINTS ALONG GRID LINE
C AND RESTRUCTURE STATIONARY POINTS
POS1=1
POS2=0
317
DO 200 J=2,NSTAT
   IF(X(1,J).NE.X(1,1)) THEN
       POS2=POS2+1
   ELSE
       POS1=POS1+1
   END IF
200 CONTINUE
JJ=0
DO 201 J=2,NSTAT
   IF(X(1,J).NE.X(1,1)) THEN
      JJ=JJ+1
      X(IKOUNT+2,JJ)=X(1,J)
      Y(IKOUNT+2,JJ)=Y(1,J)
      TEMP(IKOUNT+2,JJ)=TEMP(1,J)
      TIME(IKOUNT+2,JJ)=TIME(1,J)
   END IF
201 CONTINUE
C WRITE(*,1005) TIME(2,1)
C WRITE(*,1023)
2003 READ(*,*) ANSWER
   IF((ANSWER.NE.1).AND.(ANSWER.NE.2).AND.(ANSWER.NE.3)) GOTO 2003
   BB=0
   IF((ANSWER.EQ.1).AND.(AA.EQ.0)) THEN
      AA=1
      BB=1
   END IF
   IF(ANSWER.EQ.2) GOTO 2002
   IF(ANSWER.EQ.3) GOTO 2005
C IF (BB.EQ.1) THEN
C ARRANGE MATRIX OF POINTS TO BE INTERPOLATED
C LOCATE MAXIMUM VALUES ON GRID LINE
XMAX=0.0
DO 207 I=1,IEND
   YMAX(I)=0.0
   YMIN(I)=1000.0
207 CONTINUE
DO 204 I=1,IKOUNT+2
   LASTJ=JEND
   IF(I.EQ.1) THEN
      LASTJ=POS1
   ELSE IF(I.EQ.IKOUNT+2) THEN
      LASTJ=POS2
   END IF
204 CONTINUE
   IF(X(I,J).GT.XMAX) THEN
      XMAX=X(I,J)
END IF
IF(Y(I,J).GT.YMAX(I)) THEN
   YMAX(I)=Y(I,J)
END IF
IF(Y(I,J).LT.YMIN(I)) THEN
   YMIN(I)=Y(I,J)
END IF

204 CONTINUE

C
C CALCULATE EXISTING MINIMUM GRID SPACING (X AND Y)
J=1
MARK=0
DELEX0=ABS(X(2,J)-X(1,J))
DELMX=DELEX0
DO 205 I=3,IKOUNT+2
II=I-1
DELEX=ABS(X(I,J)-X(II,J))
IF(DELEX.LT.DELEXM) THEN
   DELMX=DELEX
END IF
IF(DELEX.NE.DELEX0) THEN
   MARK=MARK+1
   DELEX0=DELEX
END IF

205 CONTINUE
IF(MARK.NE.0) THEN
   WRITE(*,1010)
END IF
WRITE(*,1009) DELMX

2000 WRITE(*,1015)
READ(*,*) XINC
NUMX=XMAX/XINC
NUMX=NUMX+2
IF(NUMX.GT.MARKX) THEN
   WRITE(*,1018) NUMX,MARKX
   GOTO 2000
END IF
MARK=0
DO 206 II=1,3
IF(II.EQ.1) THEN
   LASTJ=POS1
   I=1
ELSE IF(II.EQ.2) THEN
   LASTJ=POS2
   I=IKOUNT+2
ELSE IF(II.EQ.3) THEN
   LASTJ=JEND
   I=2
END IF
DELEY0=ABS(Y(I,2)-Y(I,1))
DELYM=DELEY0
DO 206  J=3,LASTJ
JJ=J-1
DELY=ABS(Y(I,J)-Y(I,JJ))
IF(DELY.LT.DELYM) THEN
   DELYM=DELY
END IF
IF(DELY.NE.DELOY) THEN
   MARK=MARK+1
   DELOY=DELY
END IF
206  CONTINUE
IF(MARK.NE.0) THEN
   WRITE(*,1022)
END IF
WRITE(*,1011) DELYM
2001 WRITE(*,1016)
READ(*,*) YINC
NUMY=YMAX(2)/YINC
NUMY=NUMY+2
IF(NUMY.GT.MARKY) THEN
   WRITE(*,1019) NUMY,MARKY
   GOTO 2001
END IF
WRITE(*,1025) NUMX,NUMY

C END IF
C C
C ADJUST TEMPS WITH SHIFT XTEMP(I)
DO 401  I=1,IKOUNT+2
   LASTJ=JEND
   IF(I.EQ.1) THEN
      LASTJ=POS1
   ELSE IF(I.EQ.IKOUNT+2) THEN
      LASTJ=POS2
   END IF
DO 401  J=1,LASTJ
   TEMP(I,J)=TEMP(I,J)+XTEMP(I)
401  CONTINUE
C
DO 402  J=1,JEND
   X(I,J)=X(I,1)
   Y(I,J)=Y(2,J)
   TEMP(I,J)=TEMP(2,J)
   TIME(I,J)=TIME(2,J)
   X(IKOUNT+2,J)=X(IKOUNT+2,1)
   Y(IKOUNT+2,J)=Y(IKOUNT+1,J)
   TEMP(IKOUNT+2,J)=TEMP(IKOUNT+1,J)
   TIME(IKOUNT+2,J)=TIME(IKOUNT+1,J)
402  CONTINUE
INTERPOLATE X AND Y GRIDS TO RECTANGULAR AND SOLVE FOR NEW VALUE
OF TEMPERATURE AND TIME
DO 400 I=1,IKOUNT+2
DO 400 J=1,NUMY
   L=J-1
   XL(I,J)=X(I,1)
   YY(I,J)=L*YINC
400 CONTINUE
C
DO 300 I=1,IKOUNT+2
DO 300 J=1,NUMY
   LASTJ=JEND
   C=1
   IF (YY(I,J).LT.YMIN(I)) THEN
      GRID1(I,J)=TEMP(I,1)
      G1(I,J)=TIME(I,1)
   ELSE IF (YY(I,J).GT.YMAX(I)) THEN
      GRID1(I,J)=TEMP(I,LASTJ)
      G1(I,J)=TIME(I,LASTJ)
   ELSE IF (Y(I,C).NE.YY(I,J)) THEN
      C=0
      C=C+1
      IF (Y(I,C+1).LT.YY(I,J)) GOTO 310
      C=C+1
      S1=(TEMP(I,C)-TEMP(I,C-1))/(Y(I,C)-Y(I,C-1))
      B1=TEMP(I,C)-S1*Y(I,C)
      GRID1(I,J)=B1+S1*YY(I,J)
      G1(I,J)=TIME(I,C)
   ELSE
      GRID1(I,J)=TEMP(I,C)
      G1(I,J)=TIME(I,C)
   ENDIF
300 CONTINUE
C
DO 450 J=1,NUMY
DO 450 I=1,NUMX
   L=I-1
   X2(I,J)=L*XINC
   YY(I,J)=YY(1,J)
450 CONTINUE
C
DO 350 J=1,NUMY
DO 350 I=1,NUMX
   C=1
   IF (X2(I,J).LT.X1(1,J)) THEN
      GRID2(I,J)=GRID1(I,J)
      G2(I,J)=G1(I,J)
   ELSE IF (X2(I,J).GT.XMAX) THEN
GRID2(I,J)=GRID1(IKOUNT+2,J)
G2(I,J)=G1(IKOUNT+2,J)
ELSE
IF (X1(C,J).NE.X2(I,J)) THEN
C=0
C=C+1
IF (X1(C+1,J).LT.X2(I,J)) GOTO 360
C=C+1
S2=(GRID1(C,J)-GRID1(C-1,J))/(X1(C,J)-X1(C-1,J))
B2=GRID1(C,J)-S2*X1(C,J)
GRID2(I,J)=B2+S2*X2(I,J)
G2(I,J)=G1(C,J)
ELSE
GRID2(I,J)=GRID1(C,J)
G2(I,J)=G1(C,J)
ENDIF
ENDIF
ENDC
WRITE TO OUTPUT FILE
WRITE(*,1020)
IF (MARK0.EQ.0) THEN
WRITE(61,1002) NUMX,NUMY
MARK0=1
ENDIF
DO 500 I=1,NUMX
DO 500 J=1,NUMY
WRITE(61,1003) X2(I,J),YY(I,J),GRID2(I,J),G2(I,J)
500 CONTINUE
GOTO 2002
2005 READ(60,1003) A1,A2,A3,A4
IF ((A1.NE.-1.) .OR. (A2.NE.-1.) .OR. (A3.NE.-1.) .OR. 
  (A4.NE.-1.)) THEN
WRITE(*,1012) FN1
ENDIF
WRITE(*,1014)
CLOSE(60)
XX=-1.0
WRITE(61,1003) XX,XX,XX,XX
WRITE(*,1021)
CLOSE(61)

C
FORMAT STATEMENTS
1000 FORMAT( 'FILENAME OF INPUT DATA:' )
1001 FORMAT(A12)
1002 FORMAT(8I10)
1003 FORMAT(8F10.2)
1004 FORMAT( 'FILENAME OF OUTPUT FILE: ' )
1005 FORMAT( 'AVAILABLE SCAN TIME IN SECONDS',F10.2)
1009 FORMAT( 'MINIMUM X INTERVAL =',3F10.2,2I5)
1010 FORMAT(' EXISTING X GRID NOT UNIFORM')
1011 FORMAT(' MINIMUM Y INTERVAL =', 3F10.2, 2I5)
1012 FORMAT(' DATA FILE ',A12, ' NOT PROPERLY CLOSED OR NOT READ IN',
     * ' ITS ENTIRETY')
1013 FORMAT(' START READING FILE')
1014 FORMAT(' END READING FILE')
1015 FORMAT(' REQUIRED X INCREMENT:')
1016 FORMAT(' REQUIRED Y INCREMENT:')
1018 FORMAT(' # OF X INTERVALS =', I3, ' AND EXCEEDS ALLOWABLE # =', I3)
1019 FORMAT(' # OF Y INTERVALS =', I3, ' AND EXCEEDS ALLOWABLE # =', I3)
1020 FORMAT(' START WRITING TO OUTPUT FILE')
1021 FORMAT(' END WRITING TO OUTPUT FILE')
1022 FORMAT(' EXISTING Y GRID NOT UNIFORM')
1023 FORMAT(' OPTIONS (1)INTERPOLATE SCAN (2)READ NEXT SCAN',
     * ' (3)QUIT')
1024 FORMAT(' START AT SCAN NUMBER ?')
1025 FORMAT(' # OF X INTERVALS =', I3, ' # OF Y INTERVALS =', I3)
1026 FORMAT(' INTERPOLATION WITH REFERENCE SHIFT AND WEIR/GATE ',
     * 'ADJUSTMENT')
STOP
END
Description of "INTERP4.FOR" Input File

The input file read by INTERP4.FOR is the output file created by TEMP4.FOR. Additional information required by the program is prompted from the monitor.

The name of the input and output file is read from the monitor. The format is A12.

The scan number at which the interpolation of the data set is to begin at is inputted in a free format form.

The increments for longitudinal position, x and elevation, y at which the grid is to be interpolated are inputted in a free format form.
Description of "INTERP4.FOR" Output File

The output file has three groups of lines. The output is numeric and follows specific formatting. All distances and elevations are given in millimeters. All temperatures are given in degrees Celsius. All times are given in seconds.

The first line is comprised of flags which describe the size of the merged output file. The indices are NUMX and NUMY. The format is 8 I10.

NUMX corresponds to the number of longitudinal positions in the data grid of the output file.

NUMY corresponds to the number of elevation positions in the data grid of the output file.

The second line group contains groups of lines for a specific time elapsed during a test. Each group has NUMX by NUMY lines. Each line contains the longitudinal position, elevation, temperature and time on the interpolated grid. The format is 4 F10.2.

The last line in the output file contains flags to
indicate the end of the file. There are four values of -1 in the last line. The format is 4 F10.2.
Portion of output file from INTERP4 FOR

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FLOW CHART OF TABLEFOR

START

DIMENSION INTEGER CHARACTER

READ INPUT AND OUTPUT FILENAMES
OPEN INPUT AND OUTPUT FILES

READ NUMX NUMY

KK = 1, 10

Y = 1, NUMX

J = 1, NUMY

READ X, Y, TEMP

IF X = -1

YES

NO

J = NUMY

YES

NO

T = NUMX

YES
WRITE SCAN NUMBER AND TIME ON SCREEN

DO YOU WANT TO CONTINUE
NO

DO YOU WANT TO TABULATE SCAN
YES

WRITE DATA IN TABULATED FORM TO OUTPUT FILE

NO

KK = 10

YES

CLOSE INPUT AND OUTPUT FILES

STOP
c program to develop table of values to be plotted in contour map
DIMENSION X(50,50),Y(50,50),TEMP(50,50),TIME(50,50)
INTEGER NUMX,NUMY
CHARACTER*12 FN1,FN2
WRITE(*,1001)
READ(*,1000) FN1
WRITE(*,1002)
READ(*,1000) FN2
OPEN (60,FILE=FN1)
OPEN (61,FILE=FN2)
READ(60,1003) NUMX,NUMY

C DO 3010 KK=1,10
C
C DO 3000 I=1,NUMX
   DO 3000 J=1,NUMY
      READ(60,1004) X(I,J),Y(I,J),TEMP(I,J),TIME(I,J)
      IF(X(I,J).EQ.-1.0) GOTO 999
3000 CONTINUE
WRITE(*,1009) KK,TIME(I,1)
WRITE(*,1010)
READ(*,*) ANS1
WRITE(*,1011)
READ(*,*) ANS2
IF (ANS2.EQ.0) GOTO 999
IF (ANS1.EQ.0) GOTO 3010
C
C LOOP=INT((NUMX-1)/8)+1
IND1=NUMX
IND2=IND1-7
C
C DO 3005 K=1,LOOP
   WRITE(61,1005) TIME(I,1)
   DO 3001 J=NUMY,1,-1
      WRITE(61,1006) Y(J,1),(TEMP(I,J),I=IND1,IND2,-1)
   3001 CONTINUE
   WRITE(61,1007) (X(I,J),I=IND1,IND2,-1)
   IND1=IND1-8
   IND2=IND2-8
   IF(IND2.LT.1) THEN
      IND2=1
   ENDIF
3005 CONTINUE
C
C 3010 CONTINUE
C
C 999 continue
C
1000 FORMAT(A12)
1001 FORMAT(' FILENAME OF INPUT FILE:')
1002 FORMAT(' FILENAME OF OUTPUT FILE:')
1003 FORMAT(8I10)
1004 FORMAT(8F10.2)
1005 FORMAT(' Y',T20,' TEMPERATURE AT TIME = ',F5.0,' SEC')
1006 FORMAT(F6.1,2X,F8.2)
1007 FORMAT(3X,'X',4X,F8.0)
1008 FORMAT(' END OF PROGRAM')
1009 FORMAT(' SCAN #',I3,' DATA AVAILABLE FOR TIME = ',F5.0,' SEC')
1010 FORMAT(' DO YOU WANT TO TABULATE THIS SCAN YES(1) OR NO(0) ?')
1011 FORMAT(' DO YOU WANT TO CONTINUE YES(1) OR NO(0) ?')
1012 FORMAT(' END OF FILE')
STOP
END
Description of "TABLE.FOR" Input File

The name of the input and output file is read from the monitor. The format is A12.

The input file read by TABLE.FOR is the output file created by INTERP4.FOR.
Description of "TABLE.FOR" Output File

The output file is in the form of a table. The output is numeric and follows specific formatting. All distances and elevations are given in millimeters. All temperatures are given in degrees Celsius. All times are given in seconds.

The first line is a title and indicates the time period for which the data corresponds to.

In the next group of lines, the leftmost column lists the elevations of the temperature readings. The other seven columns correspond to temperature readings.

The last line lists the longitudinal positions of the temperature readings. The position of the gate is zero and the position of the weir is 740 mm.
### Portion of output file from TABLE.FOR

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| X    | 148. | 111. | 74. | 37. | 0. |
Appendix F. FLOW CHART AND LISTING OF
COMPUTER MODE
FLOW CHART OF
JET AND MOVING INTERNAL HYDRAULIC JUMP: SUBMODEL
AND SUBMERGED INTERNAL HYDRAULIC JUMP EQUATION

START

DIMENSION, REAL, COMMON, EXTERNAL

READ
AMBIENT FLUID TEMPERATURE, \( T_0 \)
JET FLUID TEMPERATURE, \( T_1 \)
DISCHARGE PER UNIT WIDTH, \( Q_1 \)
JET DEPTH, \( y_1 \)
TEMPERATURE ENTRAINMENT CORRECTION FACTOR, SIGMA
STARTING LONGITUDINAL POSITION FOR HYDRAULIC JUMP, \( x_1 \)
LENGTH OF FLUME, \( x_3 \)
STARTING VELOCITY AT SEQUENT SECTION 2, \( v_2 \)
WATER DEPTH, \( y_{2\text{max}} \)
WEIR SHORT CIRCUITING COEFFICIENT, KLOSS
HYDRAULIC JUMP COEFFICIENT OF ENTRAINMENT, KENT

SET CONSTANTS FOR EQUATIONS FOR
DENSITY AS A FUNCTION OF TEMPERATURE
KINEMATIC VISCOSITY AS A FUNCTION OF TEMPERATURE

JET SUBMODEL
INITIALIZE MATRIX FOR
DATA POINTS TO BE PLOTTED

CALCULATE AND PRINT INITIAL CONDITIONS

A
SET RUNGE-KUTTA SOLUTION PARAMETERS
M1, L, X, DX

I = 1, M1

CALL RKS5ES
SUBROUTINE VECTR1
SUBROUTINE MINVS

CALCULATE ENERGY, E2, AT SECTION
ENERGY = ENERGY AT PREVIOUS SECTION

IF E2 > ENERGY

NO

YES

BACKSTEP ITERATION

CALL RKS5ES
SUBROUTINE VECTR2
SUBROUTINE MINVS

CALCULATE DEPENDENT VARIABLES

STORE POINTS FOR PLOTTING

PRINT OUTPUT VARIABLES

A

E

B
IF 0.005 < FDENS < 1.005

STORE POINTS FOR PLOTTING
SET FLAGS TO INDICATE CRITICAL JET CONDITION

NO

I = N

YES

INITIALIZE CURVE FITTING COEFFICIENTS

CALCULATE COEFFICIENTS TO DESCRIBE Y1, V1, T1
AS A POLYNOMIAL FUNCTION OF X
CALL LSQCF

SUBROUTINE MA1X2
SUBROUTINE MA1X1
SUBROUTINE CHLSKY

MOVING INTERNAL HYDRAULIC JUMP SUBMODEL
CALCULATE AND PRINT INITIAL CONDITIONS

CALCULATE Y2 AND VS FROM FIRST APPROXIMATION OF Y2
USING RECTANGULAR HYDRAULIC JUMP EQUATION
CALL FLSPS

IF NCONC = 0

YES

NO

F

C

G
CALCULATE INITIAL CONDITIONS

IF X - 0.01 > X2 → YES

IF X2 > x3 → NO

PRINT INITIAL CONDITIONS

SET RUNGE-KUTTA SOLUTION PARAMETERS
M10, L, TIME, DT

I = 1, M10

CALL RK555 → SUBROUTINE VECTR3

SUBROUTINE MINVRS

CALCULATE DEPENDENT VARIABLES

STORE POINTS FOR PLOTTING

CALCULATE VARIABLES TO CHECK
EQUATIONS USED IN SUBROUTINE VECTR3

PRINT OUTPUT VARIABLES
IF \( x_1 < 0 \) YES

IF \( f_{ir} < 1.01 \) YES

IF \( v_s < 0.001 \) YES

\( i = n_i \)

YES

SOLVE SUBMERGED INTERNAL HYDRAULIC JUMP EQUATION

STOP
Computer Model for Rectangular Flume

DIMENSION A(3,3),IR(3),IC(3),B(3),AAA(500),BBB(500)
DIMENSION AA(3,3),BB(3)
REAL*8 Y(25),W(25),DY(25),YY(25),DY(25)
REAL K0,K1,K2,K3,K4,K5,K6,N0,N1,L1
REAL DIST(75),DEPTH(75),VEL(75),TEMP(75),Froude(75)
REAL TIME(150),RX1(150),RVS(150),RY1(150),RX2(150),RY2(150)
REAL RV1(150),R2(150),R1R(150)
REAL WK1(75,6),WK2(6,75),WK3(6,7),WK4(6)
REAL CY1A(6),CY1B(6),CV1A(6),CV1B(6),CT1A(6),CT1B(6)
REAL KLOSS,KENT
COMMON/AREA1/DX,MARK1,DELY,ALPHA,TAU,TAU1,SIGMA
COMMON/AREA2/T0,C0,C1,C2,C3
COMMON/AREA2A/RH00,G
COMMON/AREA3/K0,K1,K2,K3,K4,K5,K6,N0
COMMON/AREA4/XC,CY1A,CY1B,CV1A,CV1B,CT1A,CT1B
COMMON/AREA5/Q1,X3,RH03,LJ,KLOSS,KENT,DELT,TCO
COMMON/AREA6/Y1,V1,RH01
COMMON/AREA7/STAU
EXTERNAL VECTR1,VECTR2,VECTR3,FUNC
CHARACTER*12 FN0,FN1,FN2,FN4

READ(*,*) FN0
READ(*,*) FN1
READ(*,*) FN2
READ(*,*) FN4
OPEN(60,FILE=FN0)
OPEN(61,FILE=FN1)
OPEN(62,FILE=FN2)
OPEN(64,FILE=FN4)

C
C**********************************************************************
C
C PART ONE: THE JET MODEL
C
C WHERE THIS PROGRAM CALCULATES Y1,T1,V1 USING
C THE MOMENTUM EQUATION IN VECTR1 AND
C THE ENERGY EQUATION IN VECTR2 USING RK5ES SUBROUTINE
C
C ENERGY LOSSES INCLUDE FRICTION AND EDDY LOSSES
C THERMAL MASS BALANCE EQUATION INCLUDES TEMP ENTRAIN CORRN TERM=
C SIGMA*ALPHA*DELTA T
C ALPHA = FUNCTION OF RICHARDSON'S NUMBER
C
C UNITS ARE KG,M,S,DEGREES CELCIUS
C Q1 IS DISCHARGE PER UNIT WIDTH
C
C**********************************************************************
C
C VALUES READ IN: TO AMBIENT FLUID TEMP, T1 JET FLUID TEMP
C Q1 DISCHARGE, Y1 HEIGHT OF JET, SIGMA TEMP ENTRAIN CORRN FACTOR
READ(61,10) T0,T1,Q1,Y1,SIGMA
C VALUES READ IN FOR JUMP MODEL: X1 POSITION OF BEGINNING OF
C JUMP, X3 LENGTH OF FLUME, LJ LENGTH OF JUMP
READ(61,10) X1,X3,V2,Y2MAX,KLOSS,KENT
READ(61,10) SALPHA,STAU,SQ,SY,SYMAX
10 FORMAT(8E10.3)
14 FORMAT(1110)
CLOSE(61)
C****READ****STATEMENTS*****
Q1=SQ*Q1
Y1=SY*Y1
Y2MAX=SYMAX*Y2MAX
DELT=T0-T1
C CONSTANTS FOR TEMP-DENSITY CURVE
C DENSITY = C0+C1*T+C2*T**2+C3*T**3
C TEMP IN DEGREES C AND DENSITY IN KG/M**3
C0=1000.017
C1=0.01910871
C2=-5.915939E-03
C3=1.569554E-05
C CONSTANTS FOR TEMP-KINEMATIC VISCOSITY CURVE
C NU=K0+K1*T+K2*T**2+K3*T**3+K4*T**4+K5*T**5+K6*T**6
C TEMP IN DEGREES C AND KV IN M**2/S
K0=1.791365E-06
K1=-6.129909E-08
K2=1.548239E-09
K3=-2.805845E-11
K4=3.245988E-13
K5=-2.076291E-15
K6=5.513761E-18
C ACCELERATION DUE TO GRAVITY (M/S**2)
G=9.81
C PERCENTAGE LOSS OR STORAGE IN HYDRAULIC JUMP
C CONTINUITY EQ'N , KLOSS
C INITIALIZE MATRIX OF DATA POINTS FOR CURVE FIT
DO 13 I=1,75
   DIST(I)=0.0
   DEPTH(I)=0.0
   VEL(I)=0.0
   TEMP(I)=0.0
   FROUDE(I)=0.0
13 CONTINUE
XC=+9.999E+25
NUMXC=0
C PRINT CONTROL SKIP FOR JET AND JUMP
PSKIP1=5.0
PSKIP2=25.0
TSKIP1=78.0
TSKIP2=78.0
GSKIP1=10.0
GSKIP2=40.0
ASKIP1=37.0
ASKIP2=200.0

C AMBIENT FLUID DENSITY
C RH00=C0+C1*T0+C2*T0**2+C3*T0**3
C INITIAL CONDITIONS
V1=Q1/Y1
YG=Y1
VG=V1
TG=T1
MARK3=MARK3
RH01=C0+C1*T1+C2*T1**2+C3*T1**3
NU1=X0+K1*T1+K2*T1**2+K3*T1**3+K4*T1**4+K5*T1**5+K6*T1**6
FDENS=V1/(G*(RH01-RH00)/RH00*Y1)**0.5
RI=G*(RH01-RH00)/RH00*Y1/V1**2.0
RN=V1*Y1/NU1

C CALCULATE ALPHA AS A FUNCTION OF RICHARDSON'S NUMBER
ALPHA=0.002/RI
ALPHA=SALPHA*ALPHA
ENERGY=V1**2/2/G+(RH01-RH00)/RH01*Y1
WRITE(60,1001) SALPHA, STAU, SQ, SY, SYMAX
WRITE(60,1000)
WRITE(60,1010) Q1,T0,RH00
WRITE(60,1015) T1,RH01,Y1,V1,SIGMA
WRITE(60,1016) DELT
WRITE(60,1017) RN
WRITE(62,1020)

C PARAMETERS FOR RUNGE-KUTTA SOLUTION
M1=740
L=3
X=0.00001
XSTEP=0.001
DX=XSTEP
WRITE(62,1031) X,Y1,V1,T1,RH01,FDENS,ALPHA,ENERGY
Y(1)=Y1
Y(2)=T1
Y(3)=V1

C STORE DATA
DIST(1)=X
DEPTH(1)=Y1
VEL(1)=V1
TEMP(1)=T1
FROUDE(1)=FDENS

C DO 1 I=1,M1
CALL RK5ES(X,Y,DY,DX,L,VECTR1)
C CHECK ENERGY CONTINUITY
EZ=Y(3)**2/2/G+(RH01-RH00)/RH01*Y(1)
IF (EZ.GT.ENERGY) THEN
   DELY=Y1-Y(1)
   IF (DELY.LT.0.0) DELY=0.0
C BACKSTEP ITERATION
   X=X-DX
   Y(1)=Y1
   Y(2)=T1
   Y(3)=V1
   CALL RK5ES(X,Y,DY,DX,L,VECTR2)
END IF
Y1=Y(1)
T1=Y(2)
V1=Y(3)
C CALCULATIONS WITH Y1,T1,V1
RH01=C0+C1*T1+C2*T1**2+C3*T1**3
NUL=K0*K1*T1*K2*T1**2*K3*T1**3+K4*T1**4+K5*T1**5+K6*T1**6
TAU1=0.02675*RH01*V1**1.75*(NUL/Y1)**0.25
FDENS=V1/(G*(RH01-RH00)/RH00*Y1/V1**2.0
QE=ALPHA*V1*DX
ENERGY=Y1**2/2/G+(RH01-RH00)/RH01*Y1
C WRITE TO OUTPUT FILES
JA=INT(I/ASKIPL)
C
   J=INT(I/GSKIPL)
   IF (J.EQ.(I/GSKIPL)) THEN
      DIST(J+1)=X
      DEPTH(J+1)=Y1
      VEL(J+1)=V1
      TEMP(J+1)=T1
      FROUDE(J+1)=FDENS
   END IF
C PRINT STATEMENTS
   IF (INT(I/PSKIPL/TSKIPL).EQ.(I/PSKIPL/TSKIPL)) WRITE(62,1020)
   IF (INT(I/PSKIPL).EQ.(I/PSKIPL)) THEN
      WRITE(62,1030) X,Y1,V1,T1,RH01,NUL,TAU1,FDENS,ALPHA,QE,ENERGY,MARK1
   END IF
C ALPHA = FUNCTION (RI)
   ALPHA=0.002/RI
   ALPHA=ALPHA*ALPHA
   IF ((FDENS.GT.0.995).AND.(FDENS.LT.1.005)) THEN
C WRITE TO OUTPUT FILES
      XA=X
      M2A=INT(M1/ASKIPL)
      WRITE(62,1210) X
J=INT(I/GSKIP1)
IF (J.EQ.(I/GSKIP1)) THEN
   JJ=J
ELSE
   JJ=J+1
END IF
IF (XC.EQ.+9.999E+25) THEN
   XC=X
   NUMXC=JJ
END IF
M2=INT(M1/GSKIP1)
DO 116 II=JJ,M2
   DIST(II+1)=DIST(II)+DX*GSKIP1
   DEPTH(II+1)=DEPTH(II)
   VEL(II+1)=VEL(II)
   TEMP(II+1)=TEMP(II)
   FROUDE(II+1)=FROUDE(II)
   WRITE(62,1032) DIST(II+1),DEPTH(II+1),VEL(II+1),TEMP(II+1),
   * FROUDE(II+1)
116  CONTINUE
GOTO 12
END IF
C CONTINUE
C DETERMINE EQUATION
12 M2=INT(M1/GSKIP1)
IF (XC.EQ.+9.999E+25) THEN
   NOBSC=M2+1
ELSE
   NOBSC=NUMXC
END IF
NOBS=M2+1
NCOEFS=4
DO 11 I=1,6
   CYiA(I)=0.0
   CV1A(I)=0.0
   CT1A(I)=0.0
   CY1B(I)=0.0
   CV1B(I)=0.0
   CT1B(I)=0.0
11  CONTINUE
IF (XC.NE.+9.999E+25) THEN
   CY1B(1)=DEPTH(NUMXC)
   CV1B(1)=VEL(NUMXC)
   CT1B(1)=TEMP(NUMXC)
END IF
WRITE(60,1100) NOBS,NCOEFS
C  EQUATION FOR DEPTH, Y1, VELOCITY, V1, AND TEMPERATURE, T1
C  VERSUS POSITION, X1, CURVES
CALL LSQCF(NCOEFS,NOBSC,DIST,DEPTH,CY1A,WK1,WK2,WK3,WK4)
CALL LSQCF(NCOEFS,NOBSC,DIST,VEL,CV1A,WK1,WK2,WK3,WK4)
CALL LSQCF(NCOEFS,NOBSC,DIST,TEMP,CT1A,WK1,WK2,WK3,WK4)
CLOSE(62)

C******************************************************************************
C  PART TWO: THE HYDRAULIC JUMP MODEL
C******************************************************************************
C  WHERE THIS PROGRAM CALCULATES X1, VS, Y2 BY RK5ES USING VECTR3
C  SUBROUTINE. FLR IS RELATIVE DENS FROUDE NUMBER FOR SECTION 1.
C  X2 IS CALCULATED FROM X2=X1+LJ. V2 IS CALCULATED USING THE
C  CONTINUITY EQUATION FOR THE RELATIVELY STATIONARY HYDRAULIC
C  JUMP. Y1, V1 ARE CALCULATED FROM THE EQUATIONS DERIVED IN
C  PART ONE (JET MODEL).
C  VALUES AT SECTION THREE (AT WEIR)
WRITE(60,2300)
999 CONTINUE
C  INITIAL CONDITIONS
IF (X1.LT.XC) THEN
  MARK2=6
  Y1=CY1A(1)+CY1A(2)*X1+CY1A(3)*X1**2+CY1A(4)*X1**3+CY1A(5)
* X1**4+CY1A(6)*X1**5
  V1=CV1A(1)+CV1A(2)*X1+CV1A(3)*X1**2+CV1A(4)*X1**3+CV1A(5)
* X1**4+CV1A(6)*X1**5
  T1=CT1A(1)+CT1A(2)*X1+CT1A(3)*X1**2+CT1A(4)*X1**3+CT1A(5)
* X1**4+CT1A(6)*X1**5
ELSE
  MARK2=1
  Y1=CY1B(1)
  V1=CV1B(1)
  T1=CT1B(1)
END IF
RH01=C0+C1*T1+C2*T1**2+C3*T1**3
Y20=1.1*Y1
C  SOLVE FOR Y2 AND VS FROM FIRST APPROXIMATION FOR Y2 USING
CALL FLSPS(Y20,Y2MAX,0.01,1.0E-06,100.0,Y2,VS,NCONV)
IF (NCONV.EQ.0) THEN
  WRITE(60,2051)
  GOTO 9999
END IF
LJ=Y2
FLR=(V1+VS)/(G*(RH01-RH00)/RH00*Y1)**0.5
X2=X1+LJ
WRITE(60,2201) X1
X2C=X2+0.005
IF (X2C.GE.X3) THEN
  WRITE(60,2200)
  X1=X1-0.01
  GOTO 999
END IF
RH02=(RH01+RH00*KENT)/(1.0+KENT)
RH03=RH02
WRITE(60,2000)
WRITE(60,2010) T0,RH00,X3,RH03,LJ
WRITE(60,2011)
IF (XC.NE.+9.999E+25) THEN
  WRITE(60,2013) XC
END IF
WRITE(60,2012) CY1A(1),CY1A(2),CY1A(3),CY1A(4),CY1A(5),CY1A(6),
* CV1A(1),CV1A(2),CV1A(3),CV1A(4),CV1A(5),CV1A(6),
* CT1A(1),CT1A(2),CT1A(3),CT1A(4),CT1A(5),CT1A(6)
IF (XC.NE.+9.999E+25) THEN
  WRITE(60,2011)
  WRITE(60,2014) XC
WRITE(60,2012) CY1B(1),CY1B(2),CY1B(3),CY1B(4),CY1B(5),CY1B(6),
* CV1B(1),CV1B(2),CV1B(3),CV1B(4),CV1B(5),CV1B(6),
* CT1B(1),CT1B(2),CT1B(3),CT1B(4),CT1B(5),CT1B(6)
END IF
WRITE(60,2015) X1,Y2,Y2
WRITE(60,2019) KLOSS*100,KENT*100
WRITE(60,2020)
C PARAMETERS FOR RUNGE-KUTTA SOLUTION
M10=6000
L=3
TIME=0.00001
TSTEP=0.02
DT=TSTEP
WRITE(64,2630) MARK2,TIME,X1,Y1,V1,F1R,X2,Y2,V2,V3,
YY(1)=X1
YY(2)=VS
YY(3)=Y2
C STORE DATA
RTIME(1)=TIME
RX1(1)=X1
RVS(1)=VS
RY1(1)=Y1
RX2(1)=X2
RY2(1)=Y2
RV1(1)=V1
RV2(1)=V2
RF1R(1)=F1R
X10P=X1
VS0P=VS
Y20P=Y2

DO 2 I=1,M10
CALL RK5ES(TIME,YY,DYY,DT,L,VECT3)
X1=YY(1)
VS=YY(2)
Y2=YY(3)
IF (X1.LT.XC) THEN
MARK2=6
Y1=CY1A(1)+CY1A(2)*X1+CY1A(3)*X1**2+CY1A(4)*X1**3+CY1A(5)
* *X1**4+CY1A(6)*X1**5
V1=CV1A(1)+CV1A(2)*X1+CV1A(3)*X1**2+CV1A(4)*X1**3+CV1A(5)
* *X1**4+CV1A(6)*X1**5
T1=CT1A(1)+CT1A(2)*X1+CT1A(3)*X1**2+CT1A(4)*X1**3+CT1A(5)
* *X1**4+CT1A(6)*X1**5
ELSE
MARK2=1
Y1=CY1B(1)
V1=CV1B(1)
T1=CT1B(1)
END IF
RHO1=C0+C1*T1+C2*T1**2+C3*T1**3
FIR=(V1+VS)/(G*(RHO1-RHO0)/(RHO0*Y1)**0.5
X2=X1+LJ
RHO2=(RHO1+RHO0*KENT)/(1.0+KENT)
V2=Y1/Y2*(V1+VS)*(1+KENT)-VS
DX1DT=(X1-X10P)/DT
DVSDT=(VS-VS0P)/DT
DY2DT=(Y2-Y20P)/DT
DRHODT=C1+2*C2*T1+3*C3*T1**2
IF (X1.LT.XC) THEN
DY1DX1=CY1A(2)+2*CY1A(3)*X1+3*CY1A(4)*X1**2+4*CY1A(5)*X1**3+
* 5*CY1A(6)*X1**4
DY1DX1=CV1A(2)+2*CV1A(3)*X1+3*CV1A(4)*X1**2+4*CV1A(5)*X1**3+
* 5*CV1A(6)*X1**4
DT1DX1=CT1A(2)+2*CT1A(3)*X1+3*CT1A(4)*X1**2+4*CT1A(5)*X1**3+
* 5*CT1A(6)*X1**4
ELSE
DY1DX1=0.0
DY1DX1=0.0
DT1DX1=0.0
END IF

C THE EASY EQUATION RELATING DX1DT AND VS

349
AA(1,1)=1.0
AA(1,2)=0.0
AA(1,3)=0.0
BB(1)=-1.0*VS
EQN1=AA(1,1)*DX1DT+AA(1,2)*DVSDT+AA(1,3)*DY2DT-BB(1)
C
FROM HYDRAULIC JUMP MOMENTUM EQUATION
TERM11=(RH01-RHO0)*G*Y1-2.0*(V1+VS)**2*(RH01+RHO0*KENT)
  *(1.0+KENT)*Y1/Y2+RH01*(V1+VS)**2
TERM12=0.5*G*Y1**2-0.5*G*Y2**2/(1.0+KENT)-(V1+VS)**2*(1.0+KENT)
  *(Y1**2/Y2+Y1*(V1+VS)**2
TERM13=-2.0*Y1**2*(1.0+KENT)*(RH01+RHO0*KENT)*(V1+VS)/Y2
  +2.0*RH01*Y1*(V1+VS)
AA(2,1)=(TERM11*DY1DX1+TERM12*DRHODT*DT1DX1+TERM13*DV1DX1)
AA(2,2)=TERM11
AA(2,3)=-1.0*(RH01-RHO0)/(1+KENT)*G*Y2+(1+KENT)*(RH01+RHO0*KENT)
  *(V1+VS)**2*Y1**2/Y2**2
BB(2)=0.0
EQN2=AA(2,1)*DX1DT+AA(2,2)*DVSDT+AA(2,3)*DY2DT-BB(2)
C
THE CONTINUITY EQUATION FOR THE ENTIRE CONTROL VOLUME
AA(3,1)=0.0
AA(3,2)=0.0
AA(3,3)=1.0*(RH02+RHO3)*(X3-X2)
BB(3)=RHO1*Y1*V1+RHO0*Y1*V1*KENT-Q1*RHO3*KLOSS
  *-1.0/2.0*(RHO1+RHO2)***(Y2-Y1)*VS-Y2*VS*RHO2
EQN3=AA(3,1)*DX1DT+AA(3,2)*DVSDT+AA(3,3)*DY2DT-BB(3)
CONT=(RHO1*Y1*V1+RHO0*Y1*V1*KENT-(Q1*RHO3*KLOSS)
  +1.0/2.0*(RHO1+RHO2)*VS*(Y2-Y1)+1.0/2.0*(RHO2+RHO3)*(X3-X2)
  *(Y2-Y20P)/DT+RHO2*Y2*VS)
  *(RHO1*Y1*V1+RHO0*Y1*V1*KENT)*100.00
IF (INT(I/PSKIP2/TSKIP2).EQ.(I/PSKIP2/TSKIP2)) WRITE(62,2020)
IF (INT(I/PSKIP2).EQ.(I/PSKIP2)) THEN
WRITE(62,2030) MARK2,TIME,X1,Y1,V1,F1R,X2,Y2,V2,VS,CONT,EQN1,EQN2,EQN3
END IF
X10P=X1
VS0P=VS
Y20P=Y2
IF (X1.LT.0.0) GOTO 20
IF (F1R.LT.1.01) GOTO 20
IF (VS.LT.0.001) GOTO 20
2
CONTINUE
20 WRITE(60,2050)
M10=1
C
PART THREE: THE SUBMERGED HYDRAULIC JUMP EQUATION

WHERE THIS PROGRAM CALCULATES YS FROM INFORMATION FROM THE
MOVING INTERNAL HYDRAULIC JUMP MODEL. Y2, V2, RHO2, Y1, V1,
RHO1 AND RHO0 ARE KNOWN FROM THAT MODEL.

THE EQUATION SOLVED IS BASED ON MOMENTUM AND CONTINUITY.

\[ YS = \frac{((G^*G(RHO2-RHO0)Y2^2+RHO2*V2^2*Y2-RHO1*V1^2*Y1)}{/(0.5G*(RHO1-RHO0))^0.5} \]

F2 = Y2 /((G*(RHO2-RHO0)/RHO0*Y2))^0.5

WRITE(60,2300)
WRITE(60,2301)
WRITE(60,2302) YS, RHO0, RHO2, Y2, V2, F2
WRITE(60,2303)

9999 CONTINUE
CLOSE(64)
CLOSE(60)

FORMAT STATEMENTS

1000 FORMAT('1',T10,'RESULTS FOR JET MODEL'//T10,'UNITS IN KG.M,S,'
*,'CELCIUS'/)
1001 FORMAT(T5,'MODEL SENSITIVITY ANALYSIS COEFFICIENT'/
* T5,'S ALPHA = ',E10.3/
* T5,'S TAU = ',E10.3/
* T5,'S Q = ',E10.3/
* T5,'S Y = ',E10.3/
* T5,'S YMAX = ',E10.3/)
1010 FORMAT(T10,'DISCHARGE PER UNIT WIDTH = ',E11.4/
* T10,'AMBIENT FLUID TEMPERATURE = ',F6.2,T50,'DENSITY OF,'
* ' AMBIENT FLUID = ',F8.2/)
1015 FORMAT(T10,'FIRST APPROX. T1 = ',F6.2,T50,'DENSITY = ',
* F8.2/T10,'HEIGHT OF JET = ',F8.5,T50,'VELOCITY OF JET = '
* 'E11.4/T10,'TEMP ENTRAIN CORN FACTOR, SIGMA = ',F4.2,
* ' ALPHA'/)
1016 FORMAT(T10,'TEMPERATURE DIFFERENCE, DELT = ',F6.2/)
1017 FORMAT(T10,'REYNOLDS NUMBER = ',F10.1/)
1020 FORMAT('1',T6,'POS X',T13,'HEIGHT Y1',T25,'VEL V1',T34,
* ' TEMP T1',T42,'DENS RHO1',T53,'K VISC NUL',T65,'SHEAR TAU1',
* T78,'F DENS',T88,'ALPHA',T101,'Q E',T113,'ENERGY',T125,'**/')
1030 FORMAT(T5, F6.3, T13, F8.5, T24, F8.5, T34, F7.2, T43, F7.2, T53, E10.3, 
  * T65, E10.3, T77, F7.4, T86, E10.3, T98, E10.3, T110, E12.5, T125, 12)
1031 FORMAT(T5, F6.3, T13, F8.5, T24, F8.5, T34, F7.2, T43, F7.2, 
  * T77, F7.4, T86, E10.3, T110, E12.5)
1032 FORMAT(T5, F6.3, T13, F8.5, T24, F8.5, T34, F7.2, T77, F7.4)
1100 FORMAT(/T10, 'PLOTS OF DEPTH, VELOCITY AND TEMPERATURE ', 
  * 'VERSUS DISTANCE'/T10, 'AND POLYNOMIAL LEAST SQUARES CURVE ', 
  * 'FIT FOR DATA'/T10, 'FOR ', 'I3', ' OBSERVATIONS'/T10, 'AND ', 
  * 'I2', ' COEFFICIENTS IN EQUATION'/)
1101 FORMAT(/T35, 'DEPTH (Y1) VERSUS DISTANCE (X)'/)
1102 FORMAT(/T35, 'VELOCITY (V1) VERSUS DISTANCE (X)'/)
1103 FORMAT(/T35, 'TEMPERATURE (T1) VERSUS DISTANCE (X)'/)
1104 FORMAT(/T35, 'DENSIMETRIC FROUDE NUMBER (FDENS) VERSUS ', 
  * 'DISTANCE (X)'/)
1200 FORMAT(/T35, 'CALCULATED POINTS (1) AND POINTS PREDICTED' 
  * ', FROM GENERATED CURVE (2)'/)
1210 FORMAT(/T10, 'JET APPROACH CRITICAL CASE. ESCAPE JET ROUTINE'/) 
2000 FORMAT('1', T10, 'RESULTS FOR HYDRAULIC JUMP MODEL'/) 
  * T10, 'UNITS IN KG, M, S, CELCIUS'/) 
2010 FORMAT(/T10, 'AMBIENT FLUID TEMPERATURE = ', F8.5/ 
  * T10, 'DENSITY OF AMBIENT FLUID = ', F8.2//T10, 
  * 'LENGTH OF FLUME = ', F6.3/ 
  * '/T10, 'DENSITY AT SECTION THREE = ', F8.2/ 
  * T10, 'LENGTH OF JUMP = ', F8.5/) 
2011 FORMAT(/T10, 'DEFINING EQUATIONS FOR Y1,V1,T1 AS A'/T10, 
  * 'FUNCTION OF X1 FROM JET MODEL'/) 
2012 FORMAT( 
  * T3, 'X1=','E14.7', '+','E14.7', 'X1+', 'E14.7', 'X1**2+', 'E14.7, 
  * 'X1**3+', 'E14.7', 'X1**4+', 'E14.7', 'X1**5'/ 
  * T3, 'V1=','E14.7', '+','E14.7', 'X1+', 'E14.7', 'X1**2+', 'E14.7, 
  * 'X1**3+', 'E14.7', 'X1**4+', 'E14.7', 'X1**5'/ 
  * T3, 'T1=','E14.7', '+','E14.7', 'X1+', 'E14.7', 'X1**2+', 'E14.7, 
  * 'X1**3+', 'E14.7', 'X1**4+', 'E14.7', 'X1**5'/) 
2013 FORMAT(T10, 'FOR 0.0 < X1 < ', F8.4/) 
2014 FORMAT(T10, 'FOR', F8.4, '< X1 ') 
2015 FORMAT(T10, 'INITIAL CONDITIONS'/T10, 'X1 = ', E10.3//T10, 
  * 'Y2 = ', E10.3//T10, 'V2 = ', E10.3/) 
2019 FORMAT(/T10, 'PERCENTAGE OF JET INFLOW EXITING OVER WEIR', 
  * 'IN CONTINUITY EQUATION = ', F8.2/ 
  * T10, 'PERCENTAGE OF JUMP ENTRAINMENT = ', F8.2/) 
2020 FORMAT('1', T2, '**', T6, 'TIME', T16, 'X1', T25, 'Y1', T35, 'V1', T45, 'F1R', 
  * T54, 'X2', T63, 'Y2', T73, 'V2', T83, 'VS', T90, 'CONTINUITY', 
  * 'EQM1 EQN2 EQN3 ')
2030 FORMAT(T2, T1, T4, F7.4, T13, F7.4, T22, F8.5, T32, F8.5, T42, F7.4, T51, F7.4, 
  * T60, 3(F8.5, 2X), T90, 4E10.3)
2050 FORMAT(/T10, 'END OF CALCULATION'/) 
2051 FORMAT(/T10, 'NO CALCULATION'/) 
2052 FORMAT(/T10, 'FOR ', 'I3', ' OBSERVATIONS'/)
2101 FORMAT(//T35,'SURGE VELOCITY (VS) VERSUS TIME'//)
2102 FORMAT(//T35,'X1 (1) AND X2 (2) VERSUS TIME'//)
2103 FORMAT(//T35,'Y1 (1) AND Y2 (2) VERSUS TIME'//)
2104 FORMAT(//T35,'SURGE VELOCITY (VS) VERSUS X1'//)
2105 FORMAT(//T35,'V1 (1) AND V2 (2) VERSUS TIME'//)
2106 FORMAT(//T35,'Y2 VERSUS X1'//)
2107 FORMAT(//T35,'V2 VERSUS X1'//)
2108 FORMAT(//T30,'RELATIVE DENSIMETRIC FROLDE NUMBER (F1R) ','
             * 'VERSUS DISTANCE (X)'//)
2200 FORMAT(T10,'X2 EXCEEDS LENGTH OF PLUME, X3. TRY NEW X1'//)
2201 FORMAT(T10,'DISTANCE X1 = ',E10.3)
2300 FORMAT('1'/)
2301 FORMAT(//T10,'SUBMERGED HYDRAULIC JUMP CALCULATION')
2302 FORMAT(//T10,'SUBMERGED DEPTH = ',F8.5/
             * T10,'DENSITY OF AMBIENT FLUID = ',F8.2//T10,
             * T10,'DENSITY AT SECTION TWO = ',F8.2/
             * T10,'SEQUENT DEPTH = ',F8.5/
             * T10,'VELOCITY AT SECTION TWO = ',F8.5/.
             * T10,'DENSIMETRIC FROLDE NUMBER AT SECTION TWO = ',F8.5)
2303 FORMAT(//T10,'END OF PROGRAM RUN'//)
3000 FORMAT(T5,F10.2,F5.2,F10.4,3X,12)
STOP
END
SUBROUTINE VECTRI(X,Y,W,W)

C****SUBROUTINE VECTRI**************************************************************************
C TO CALCULATE THE COEFFICIENT OF THE THREE
C ORDINARY DIFFERENTIAL EQUATIONS
C USING MOMENTUM EQUATION
REAL*8 X,Y(25),W(25),DY(25)
REAL K0,K1,K2,K3,K4,K5,K6,NUL
DIMENSION A(3,3),IR(3),IC(3),B(3)
COMMON/AREA1/DX,MARK1,DELY,ALPHA,TAU,TAU1,SIGMA
COMMON/AREA2/T0,C0,C1,C2,C3
COMMON/AREA3/RH00,G
COMMON/AREA7/NUL,C0,C1,C2,C3
COMMON/AREA7/NUL,C0,C1,C2,C3
C CONSTANTS DERIVED FROM COMMON VARIABLES
Y1=Y(1)
T1=Y(2)
V1=Y(3)
RH01=C0+C1*T1+C2*T1**2+C3*T1**3
NUL=K0+K1*T1+K2*T1**2+K3*T1**3+K4*T1**4+K5*T1**5+K6*T1**6
TAU=0.02675*RH01*V1**1.75*(NUL/Y1)**0.25
TAU1=TAU*STAU
C THE CONTINUITY EQUATION (OR MASS BALANCE EQUATION)
C A(1,1)=THE COEFFICIENT OF DYDX
C A(1,2)=THE COEFFICIENT OF DTDX
C A(1,3)=THE COEFFICIENT OF DVDX
C B(1)=A CONSTANT
A(1,1)=RH01*V1
A(1,2)=V1*Y1*(C1+C2*2*T1+C3*T1**2)
A(1,3)=RH01*Y1
B(1)=ALPHA*RH00*V1
C THE MOMENTUM EQUATION
C A(2,1)=THE COEFFICIENT OF DYDX
C A(2,2)=THE COEFFICIENT OF DTDX
C A(2,3)=THE COEFFICIENT OF DVDX
C B(2)=A CONSTANT
A(2,1)=(RH00-RH01)*G*Y1
A(2,2)=-(V1*Y1*V1-G*Y1**2/2)*(C1+C2*T1+C3*T1**2)
A(2,3)=RH01*V1*Y1
B(2)=TAU+RH01*V1**2*ALPHA
C THE TEMPERATURE CONTINUITY EQUATION (OR THERMAL MASS BALANCE)
C A(3,1)=THE COEFFICIENT OF DYDX
C A(3,2)=THE COEFFICIENT OF DTDX
C A(3,3)=THE COEFFICIENT OF DVDX
C B(3)=A CONSTANT
A(3,1)=RH01*T1*V1
A(3,2)=RH01*Y1+V1*Y1*T1*(C1+2*C2*T1+C3*T1**2)
A(3,3)=RH01*T1*Y1
B(3)=ALPHA*RH00*T0*V1+SIGMA*ALPHA*RH00*V1*(T0-T1)

CALL MINVRS(A,N)
DYDX = B(1)*A(1,1) + B(2)*A(1,2) + B(3)*A(1,3)
DTDX = B(1)*A(2,1) + B(2)*A(2,2) + B(3)*A(2,3)
DVDX = B(1)*A(3,1) + B(2)*A(3,2) + B(3)*A(3,3)

W(1) = DYDX
W(2) = DTDX
W(3) = DVDX
M = RK1 = 1
RETURN

C

SUBROUTINE VECTR2(X,Y,W,N)

C

C

C TO CALCULATE THE COEFFICIENT OF THE THREE
C ORDINARY DIFFERENTIAL EQUATIONS
C USING ENERGY EQUATION

REAL*8 X,Y(25),W(25),DY(25)
REAL K0,K1,K2,K3,K4,K5,K6,NUI
DIMENSION A(3,3),IR(3),IC(3),B(3)
COMMON/AREA1/DX,MARK1,DELY,ALPHA,TAU,TAU1,SIGMA
COMMON/AREA2/T0,C0,C1,C2,C3
COMMON/AREA2A/RH00,G
COMMON/AREA3/K0,K1,K2,K3,K4,K5,K6,NUI
COMMON/AREA7/STAU

C

C CONSTANTS DERIVED FROM COMMON VARIABLES
Y1 = Y(1)
T1 = Y(2)
V1 = Y(3)
RH01 = C0 + C1*T1 + C2*T1**2 + C3*T1**3
NUI = K0*K1*K2*K3*T1**3 + K4*T1**4 + K5*T1**5 + K6*T1**6
TAU1 = 0.02675*RH01*V1**1.75*(NUI/Y1)**0.25
STAU = TAU1

C THE CONTINUITY EQUATION (OR MASS BALANCE EQUATION)
C A(1,1) = THE COEFFICIENT OF DYDX
C A(1,2) = THE COEFFICIENT OF DTDX
C A(1,3) = THE COEFFICIENT OF DVDX
C B(1) = A CONSTANT
A(1,1) = RH01*V1
A(1,2) = V1*Y1*(C1 + C2*T1 + C3*T1**2)
A(1,3) = RH01*Y1
B(1) = ALPHA*RH00*V1

C THE ENERGY EQUATION
C A(2,1) = THE COEFFICIENT OF DYDX
C A(2,2) = THE COEFFICIENT OF DTDX
C A(2,3) = THE COEFFICIENT OF DVDX
C B(2) = A CONSTANT
A(2,1) = (RH01 - RH00)/RH01
A(2,2) = Y1*RH00/RH01**2*(C1 + C2*T1 + C3*T1**2)
A(2,3) = V1/G
B(2) = -TAU1/DX*(G*RH01*Y1) - DELY**3/(4*Y1*(Y1 + DELY))

C THE TEMPERATURE CONTINUITY EQUATION (OR THERMAL MASS BALANCE)
A(3,1)=THE COEFFICIENT OF DYDX
A(3,2)=THE COEFFICIENT OF DTXD
A(3,3)=THE COEFFICIENT OF DVDX
B(3)=A CONSTANT
A(3,1)=RHO1*T1*Y1
A(3,2)=RHO1*Y1+V1+Y1*T1*(C1+2*C2*T1+C3*T1**2)
A(3,3)=RHO1*T1*Y1
B(3)=ALPHA*RHO0*T0*V1+SIGMA*ALPHA*RHO0*V1*(T0-T1)
CALL MINVRS(A,N)
DYDX=B(1)*A(1,1)+B(2)*A(1,2)+B(3)*A(1,3)
DTDX=B(1)*A(2,1)+B(2)*A(2,2)+B(3)*A(2,3)
DVDX=B(1)*A(3,1)+B(2)*A(3,2)+B(3)*A(3,3)
W(1)=DYDX
W(2)=DTDX
W(3)=DVDX
MARK1=10
RETURN
END

SUBROUTINE VECTR3(X,Y,W,N)
*************************************************************************
SUBROUTINE VECTR3
*************************************************************************
C TO CALCULATE THE COEFFICIENT OF THE THREE
C ORDINARY DIFFERENTIAL EQUATIONS
C DIMENSION A(3,3),IR(3),IC(3),B(3)
REAL*8 X,Y(25),W(25),DY(25)
REAL CY1A(6),CY1B(6),CV1A(6),CV1B(6),CT1A(6),CT1B(6),LJ
REAL KLOSS,KENT
COMMON/AREA2/T0,C0,C1,C2,C3
COMMON/AREA2/RHO0,G
COMMON/AREA4/XC,CY1A,CY1B,CV1A,CV1B,CT1A,CT1B
COMMON/AREA5/Q1,X3,RHO3,LJ,KLOSS,KENT,DELT,TCON
C
C CONSTANTS USED IN EQUATIONS AS FUNCTIONS OF UNKNOWNS
X1=Y(1)
VS=Y(2)
Y2=Y(3)
IF (X1.LT.XC) THEN
  Y1=CY1A(1)+CY1A(2)*X1+CY1A(3)*X1**2+CY1A(4)*X1**3+CY1A(5)
  *X1**4+CY1A(6)*X1**5
  V1=CV1A(1)+CV1A(2)*X1+CV1A(3)*X1**2+CV1A(4)*X1**3+CV1A(5)
  *X1**4+CV1A(6)*X1**5
  T1=CT1A(1)+CT1A(2)*X1+CT1A(3)*X1**2+CT1A(4)*X1**3+CT1A(5)
  *X1**4+CT1A(6)*X1**5
ELSE
  Y1=CY1B(1)
  V1=CV1B(1)
  T1=CT1B(1)
ENDIF
RHO1=C0+C1*T1+C2*T1**2+C3*T1**3
DRHODT=C1+2*C2*T1+3*C3*T1**2
IF (X1.LT.XC) THEN
  DY1DX1=CY1A(2)+2*CY1A(3)*X1+3*CY1A(4)*X1**2+4*CY1A(5)*X1**3+
  5*CY1A(6)*X1**4
  DV1DX1=CV1A(2)+2*CV1A(3)*X1+3*CV1A(4)*X1**2+4*CV1A(5)*X1**3+
  5*CV1A(6)*X1**4
  DT1DX1=CT1A(2)+2*CT1A(3)*X1+3*CT1A(4)*X1**2+4*CT1A(5)*X1**3+
  5*CT1A(6)*X1**4
ELSE
  DY1DX1=0.0
  DV1DX1=0.0
  DT1DX1=0.0
END IF

X2=X1+LJ

RHO2=(RHO1+RHO0*KENT)/(1.0+KENT)
V2=Y1/Y2*(V1+VS)*(1+KENT)-VS

C THE EASY EQUATION RELATING DX1DT AND VS
A(1,1)=THE COEFFICIENT OF DX1DT
A(1,2)=THE COEFFICIENT OF DVSDT
A(1,3)=THE COEFFICIENT OF DY2DT
B(1)=A CONSTANT
A(1,1)=1.0
A(1,2)=0.0
A(1,3)=0.0
B(1)=-1.0*VS

C FROM HYDRAULIC JUMP MOMENTUM EQUATION
A(2,1)=THE COEFFICIENT OF DX1DT
A(2,2)=THE COEFFICIENT OF DVSDT
A(2,3)=THE COEFFICIENT OF DY2DT
B(2)=A CONSTANT
TERM11=(RHO1-RHO0)*G*Y1-2.0*(V1+VS)**2*(RHO1+RHO0*KENT)
  *(1.0+KENT)*Y1/Y2+RHO1*(V1+VS)**2
TERM1R=0.5*G*Y1**2-0.5*G*Y2**2/(1.0+KENT)-(V1+VS)**2*(1.0+KENT)
  *(Y1**2/Y2+Y1*(V1+VS)**2)
TERM1=-2.0*Y1**2*(1.0+KENT)*(RHO1+RHO0*KENT)*(V1+VS)/Y2
  +2.0*RHO1*Y1*(V1+VS)
A(2,1)=(TERM11*DY1DX1+TERM1R*DRHODT*DT1DX1+TERM1*DV1DX1)
A(2,2)=TERM11
A(2,3)=-1.0*(RHO1-RHO0)/(1+KENT)*G*Y2+(1+KENT)*(RHO1+RHO0*KENT)
  *(V1+VS)**2*Y1**2/Y2**2
B(2)=0.0

C THE CONTINUITY EQUATION FOR THE ENTIRE CONTROL VOLUME
A(3,1)=THE COEFFICIENT OF DX1DT
A(3,2)=THE COEFFICIENT OF DVSDT
A(3,3)=THE COEFFICIENT OF DY2DT
B(3)=A CONSTANT
A(3,1)=0.0
A(3,2)=0.0
A(3,3)=-1.0/2.*(RHO2+RHO3)*(X3-X2)
B(3)=RHO1*Y1*V1-RHO0*Y1*V1*KENT-RHO3*Q1*KLOSS
  -1.0/2.*(RHO1+RHO2)*(Y2-Y1)*VS-Y2*VS*RHO2

367
CALL MINVRS(A,N)
DX1DT=B(1)*A(1,1)+B(2)*A(1,2)+B(3)*A(1,3)
DVSDT=B(1)*A(2,1)+B(2)*A(2,2)+B(3)*A(2,3)
DY2DT=B(1)*A(3,1)+B(2)*A(3,2)+B(3)*A(3,3)
W(1)=DX1DT
W(2)=DVSDT
W(3)=DY2DT
RETURN
END

SUBROUTINE LSQCF(M,N,X,Y,C,F,FT,A,B)
C
C LEAST SQUARES CURVE FITTING METHOD
C
C DIMENSION X(75),Y(75),F(75,6),FT(6,75),A(6,7),B(6),C(6)

C GENERATE TO F MATRIX
DO 4 I=1,N
   DO 4 J=1,M
      F(I,J)=X(I)**(J-1.0)
4 CONTINUE

C GENERATE THE TRANSPOSE OF THE F MATRIX
DO 5 I=1,N
   DO 5 J=1,M
      FT(J,I)=F(I,J)
5 CONTINUE

C DETERMINE COEFFICIENT MATRIX A OF SIMULTANEOUS EQUATION SYSTEM
CALL MATX2(FT,F,A,M,N,M)
C DETERMINE COLUMN OF CONSTANTS FOR SIMULTANEOUS EQUATION SYSTEM
CALL MATX1(FT,Y,B,M,N,1)
DO 6 I=1,M
   A(I,M+1)=B(I)
6 CONTINUE

C DETERMINE C VALUES BY SOLVING SIMULTANEOUS EQUATIONS USING
C CHOLESKY METHOD
MP1=M+1
CALL CHLSKY(A,M,MP1,C)

C WRITE OUT THE C VALUES
WRITE(60,7) M-1
7 FORMAT(///T10,'C(0) THROUGH C('',I1,'').')
DO 9 I=1,M
   J=I-1
   WRITE(60,8) J,C(I)
9 CONTINUE
8 FORMAT(T10,'C('',I1,'')=',E14.7/)
RETURN
END
C
C
SUBROUTINE MATX2(A,B,C,M,N,L)
C*****SUBROUTINE MATX2*************************************************************************
C DETERMINES MATRIX C AS PRODUCT OF A AND B
DIMENSION A(6,75),B(75,6),C(6,7)
DO 2 I=1,M
   DO 2 J=1,L
      C(I,J)=0.0
   2 CONTINUE
   RETURN
END
C
C
SUBROUTINE MATX1(A,B,C,M,N,L)
C*****SUBROUTINE MATX1*************************************************************************
C DETERMINES VECTOR C AS PRODUCT OF MATRIX A AND VECTOR B
DIMENSION A(6,75),B(75,6),C(6)
DO 2 I=1,M
   C(I)=0.0
   DO 2 K=1,N
      C(I)=C(I)+A(I,K)*B(K)
   2 CONTINUE
RETURN
END
C
C
SUBROUTINE CHLSKY(A,N,M,X)
C*****SUBROUTINE CHLSKY*************************************************************************
C CALCULATE FIRST ROW OF UPPER UNIT TRIANGULAR MATRIX
DIMENSION A(6,7),X(6)
C DO 3 J=2,M
   A(1,J)=A(1,J)/A(1,1)
3 CONTINUE
C CALCULATE OTHER ELEMENTS OF U AND L MATRICES
DO 8 I=2,N
   J=I
   DO 5 II=J,N
      SUM=0.0
      JM1=J-1
      DO 5 K=1,JM1
         SUM=SUM+A(II,K)*A(K,J)
   5 CONTINUE
   A(II,J)=A(II,J)-SUM
8 CONTINUE
IP1=I+1
DO 7 JJ=IP1,M
  SUM=0.0
  IM1=I-1
  DO 6 K=1,IM1
    SUM=SUM+A(I,K)*A(K,JJ)
  CONTINUE
  A(I,JJ)=(A(I,JJ)-SUM)/A(I,I)
  CONTINUE
  CONTINUE
  CONTINUE
C
SOLVE FOR X(I) BY BACK SUBSTITUTION
X(N)=A(N,N+1)
L=N-1
DO 10 NN=1,L
  SUM=0.0
  I=N-NN
  IP1=I+1
  DO 9 J=IP1,N
    SUM=SUM+A(I,J)*X(J)
  CONTINUE
  X(I)=A(I,M)-SUM
  CONTINUE
  RETURN
END

C
C
SUBROUTINE FUNC(X,Y)
C
C**SUBROUTINE FUNC**************************************************************************
C A DUMMY SUBROUTINE
RETURN
END

C
SUBROUTINE FLSPS(X1,XMAX,DELX,EP0,FMAX,Y2,VS,NCONV)
C**SUBROUTINE FLSPS**************************************************************************
COMMON/AREA2A/RH00,G
COMMON/AREA6/Y1,V1,RH01
WRITE(60,1001) G,Y1,V1,RH01,RH00,XMAX
GPRIME=G*(RH01-RH00)/RH00
FX1=X1-0.5*Y1*((1.0+8.0*(V1+V1*Y1/(X1-Y1)))**2/(GPRIME*
  * Y1)**0.5-1.0)
55 X2=X1+DELX
FX2=X2-0.5*Y1*((1.0+8.0*(V1+V1*Y1/(X2-Y1)))**2/(GPRIME*
  * Y1)**0.5-1.0)
STORE=FX1*FX2
IF (STORE.LT.0) GOTO 105
IF (STORE.EQ.0) GOTO 70
IF (STORE.GT.0) GOTO 85
70 WRITE(60,102) X2
Y2=X2
GOTO 999
85 IF (X2.GT.XMAX) THEN
    CASE=1.
    GOTO 900
END IF
X1=X2
FX1=FX2
GOTO 55
105 X3=(X1*FX2-X2*FX1)/(FX2-FX1)
FX3=X3-0.5*Y1*((1.0+8.0*(V1+V1*Y1/(X3-Y1)))**2/(GPRIME*Y1))**0.5-1.0)
IF (ABS(FX3).LT.EPS) GOTO 160
IF (FX3.GT.FMAX) THEN
    CASE=2.
    GOTO 900
END IF
STORE=FX1*FX3
IF (STORE.LT.0) GOTO 145
IF (STORE.EQ.0) GOTO 160
IF (STORE.GT.0) GOTO 130
130 X1=X3
FX1=FX3
GOTO 105
145 X2=X3
FX2=FX3
GOTO 105
900 WRITE(60,1002)
    IF (CASE.EQ.1.) WRITE(60,910)
    IF (CASE.EQ.2.) WRITE(60,920)
NCONV=0
GOTO 901
160 WRITE(60,102) X3
    Y2=X3
999 VS=V1*Y1/(Y2-Y1)
    NCONV=1
    WRITE(60,1000) VS
901 CONTINUE
102 FORMAT(T10,'CONVERGENCE FOR Y2'/T10,'Y2 = ',E14.7)
910 FORMAT(/T10,'Y2 GREATER THAN WEIR HEIGHT'/)
920 FORMAT(/T10,'FUNCTION APPROACHING INFINITY'/)
1000 FORMAT(T10,'VS = ',E14.7)
1001 FORMAT(/T10,'TERMS USED TO SOLVE FOR Y2 AND VS'/
    * T10,'ACCELERATION G = ',E10.3/
    * T10,'DEPTH Y1 = ',E10.3/T10,'VELOCITY V1 = ',E10.3/
    * T10,'DENSITY RH01 = ',F7.2/T18,'RH00 = ',F7.2/
    * T10,'WEIR HEIGHT = ',E10.3)
1002 FORMAT(/T10,'NO CONVERGENCE'/)
RETURN
END

C
C
SUBROUTINE MINVRS(A,N)
C MATRIX INVERSION SUBPROGRAM
REAL A(3,3)
C CALCULATE ELEMENTS OF REDUCED MATRIX
DO 6 K=1,N
C CALCULATE NEW ELEMENTS OF PIVOT ROW
DO 4 J=1,N
   IF(J.EQ.K) GOTO 4
   A(K,J)=A(K,J)/A(K,K)
  4 CONTINUE
C CALCULATE ELEMENT REPLACING PIVOT ELEMENT
DO 5 I=1,N
   IF(I.EQ.K) GOTO 5
   DO 50 J=1,N
      IF(J.EQ.K) GOTO 50
      A(I,J)=A(I,J)-A(K,J)*A(I,K)
  50 CONTINUE
  5 CONTINUE
C CALCULATE REPLACEMENT ELEMENTS FOR PIVOT COLUMN EXCEPT PIVOT ELEMENT
DO 6 I=1,N
   IF(I.EQ.K) GOTO 6
   A(I,K)=-1.0*A(I,K)*A(K,K)
  6 CONTINUE
RETURN
END

C SUBROUTINE RK56(X,Y,DY,DX,L,VECTOR)
C RUNGE-KUTTA SUB-PROGRAM
REAL*8 X,Y(25),W(25),DY(25)
REAL*8 XI,YI(25),K1(25),K2(25),K3(25),K4(25),K5(25),K6(26)
EXTERNAL VECTOR
XI=X
DO 10 I=1,L
   YI(I)=Y(I)
   CALL VECTOR(XI,YI,K1,L)
  10 DO 11 I=1,L
      K1(I)=DX*K1(I)
      XI=X+DX/4.
  11 DO 20 I=1,L
      YI(I)=Y(I)+K1(I)/4.
      CALL VECTOR(XI,YI,K2,L)
  20 DO 21 I=1,L
      K2(I)=DX*K2(I)
      XI=X+DX/4.
  21 DO 30 I=1,L
     30
CALL VECTOR(X1,Y1,K3,L)
DO 31 I=1,L
   31 K3(I) = DX*K3(I)
   XI = X + DX/2.
   DO 40 I=1,L
   40 Y1(I) = Y(I) - K2(I) + K3(I)/2.*K3(I)
   CALL VECTOR(XI,Y1,K4,L)
   DO 41 I=1,L
   41 K4(I) = DX*K4(I)
   XI = X + 3./4.*DX
   DO 50 I=1,L
   50 Y1(I) = Y(I) + 3./16.*K1(I) + 9./16.*K4(I)
   CALL VECTOR(XI,Y1,K5,L)
   DO 51 I=1,L
   51 K5(I) = DX*K5(I)
   XI = X + DX
   DO 60 I=1,L
   60 Y1(I) = Y(I) - 3./7.*K1(I) + 2./7.*K2(I) + 12./7.*K3(I) - 12./7.*K4(I)
       * + 8./7.*K5(I)
   CONTINUE
CALL VECTOR(X1,Y1,K6,L)
DO 61 I=1,L
   61 K6(I) = DX*K6(I)
   DO 70 I=1,L
   70 Y(I) = Y(I) + 1./90.*(7.*K1(I) + 32.*K3(I) + 12.*K4(I) + 32.*K5(I)
       * + 7./16.*K6(I))
   CONTINUE
RETURN
END
Appendix G. LISTING OF COMPUTER MODEL OUTPUT
MODEL SENSITIVITY ANALYSIS COEFFICIENT

S ALPHA = 0.100E 01
S TAU = 0.100E 01
S Q = 0.100E 01
S Y = 0.100E 01
S YMAX = 0.100E 01

RESULTS FOR JET MODEL

UNITS IN KG,M,S,CELCIUS

DISCHARGE PER UNIT WIDTH = 0.14508E-02
AMBIENT FLUID TEMPERATURE = 37.00  DENSITY OF AMBIENT FLUID = 993.42
FIRST APPROX. T1 = 33.50  DENSITY = 994.61
HEIGHT OF JET = 0.03000  VELOCITY OF JET = 0.48338E-01
TEMP ENTRAIN CORR FACTOR, SINHA = 0.01 x ALPHA
TEMPERATURE DIFFERENCE, DELT = 3.50

REYNOLDS NUMBER = 1934.6
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TERMS USED TO SOLVE FOR Y2 AND VS
ACCELERATION G = 0.981E 01
DEPTH Y1 = 0.458E-01
VELOCITY V1 = 0.364E-01
DENSITY RH01 = 994.46
            RH00 = 993.42
WEIR HEIGHT = 0.170E 00
CONVERGENCE FOR Y2
Y2 = 0.1400477E 00
VS = 0.1766495E-01
DISTANCE X1 = 0.590E 00
Y2 BICHERS LENGTH OF FLUME, X3. Y1 BICHERS XI

TERMS USED TO SOLVE FOR Y2 AND VS
ACCELERATION G = 0.981E 01
DEPTH Y1 = 0.458E-01
VELOCITY V1 = 0.365E-01
DENSITY RH01 = 994.46
            RH00 = 993.42
WEIR HEIGHT = 0.170E 00
CONVERGENCE FOR Y2
Y2 = 0.1398578E 00
VS = 0.1762073E-01
DISTANCE X1 = 0.590E 00

RESULTS FOR HYDRAULIC JUMP MODEL

UNITS IN KG,M,S,Celsius

AMBIENT FLUID TEMPERATURE = 37.00000
DENSITY OF AMBIENT FLUID = 993.42
LENGTH OF FLUME = 0.740
DENSITY AT SECTION THREE = 994.37
LENGTH OF JUMP = 0.13990
DEFINING EQUATIONS FOR Y1, Y2, T1 AS A FUNCTION OF X1 FROM JET MODEL

\[
\begin{align*}
Y1 &= 0.30030038 - 0.1 + 0.33725759 - 0.1 \times X1 + 0.17897808 - 0.1 \times X1^2 + 0.90056176 - 0.2 \times X1^3 + 0.00000000 - 0.1 \times X1^4 + 0.00000000 - 0.1 \times X1^5 \\
Y2 &= 0.48230028 - 0.1 + 0.31599988 - 0.1 \times X1 + 0.28198678 - 0.1 \times X1^2 + 0.14072856 - 0.1 \times X1^3 + 0.00000000 - 0.1 \times X1^4 + 0.00000000 - 0.1 \times X1^5 \\
T1 &= 0.33495618 + 0.1528621 + 0.1 \times X1 + 0.15607346 + 0.1 \times X1^2 + 0.11302428 + 0.1 \times X1^3 + 0.00000000 + 0.1 \times X1^4 + 0.00000000 + 0.1 \times X1^5 \\
\end{align*}
\]

INITIAL CONDITIONS

\[
\begin{align*}
X1 &= 0.59000 \\
Y2 &= 0.14000 \\
V2 &= 0.00000 \\
\end{align*}
\]

PERCENTAGE OF JET INFLOW EXITING OVER WEIR IN CONTINUITY EQUATION = 10.00

PERCENTAGE OF JUMP ENRAINTMENT = 10.00

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<th>V1</th>
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<td>0.182E-02 - 0.175E-05 - 0.120E-06 - 0.330E-00</td>
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SUBMERGED HYDRAULIC JUMP CALCULATION

SUBMERGED DEPTH = 0.03261
DENSITY OF AMBIENT FLUID = 993.42

DENSITY AT SECTION TWO = 994.50
SEQUENT DEPTH = 0.11026
VELOCITY AT SECTION TWO = 0.01010
DENSIMETRIC Froude NUMBER AT SECTION TWO = 0.29418

END OF PROGRAM RUN
Appendix H. FIGURES OF THERMAL CONTOUR PLOTS
Figure H.1 Denser Wall Jet Case Thermal Contour Plot
G=5 cm, hw=17 cm, Q=0.189 L/s at t=12 s
Figure H.2 Denser Wall Jet Case Thermal Contour Plot
G=5 cm, hw=17 cm, Q=0.189 L/s at t=30 s
Figure H.3 Denser Wall Jet Case Thermal Contour Plot
G=5 cm, hw=17 cm, Q=0.189 L/s at t=42 s
Figure H.4: Denser Wall Jet Case Thermal Contour Plot
G=5 cm, hw=17 cm, Q=0.189 L/s at t=60 s
Figure H.5 Denser Wall Jet Case Thermal Contour Plot
G=5 cm, hw=17 cm, Q=0.189 L/s at t=72 s

Temperature (Degrees Celsius)

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</table>
Figure H.6  Denser Wall Jet Case Thermal Contour Plot
G=5 cm, hw=17 cm, Q=0.189 L/s at t=90 s
Figure H.7  Denser Wall Jet Case Thermal Contour Plot
G=5 cm, hw=17 cm, Q=0.189 L/s at t=120 s
Figure H.8  Denser Wall Jet Case Thermal Contour Plot
G=5 cm, hw=17 cm, Q=0.189 L/s at t=150 s
Figure H.9 Denser Wall Jet Case Thermal Contour Plot
G=5 cm, hW=17 cm, Q=0.189 L/s at t=210 s

Temperature (Degrees Celsius)

- 17
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- 20
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- 22
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- 26
- 27
- 28
- 29
- 30
- 31
- 32
Figure H.10 Buoyant Surface Jet Case Thermal Contour Plot
G=5 cm, hw=17 cm, Q=0.179 L/s at t=12 s
Figure H.11  Buoyant Surface Jet Case Thermal Contour Plot
G=5 cm, h_w=17 cm, Q=0.179 L/s at t=30 s
Figure H.12  Buoyant Surface Jet Case Thermal Contour Plot
G=5 cm, hw=17 cm, Q=0.179 L/s at t=42 s
Figure H.13  Buoyant Surface Jet Case Thermal Contour Plot
G=5 cm, hw=17 cm, Q=0.179 L/s at t=80 s
Figure H.14  Buoyant Surface Jet Case Thermal Contour Plot
G=5 cm, h_w=17 cm, Q=0.179 L/s at t=72 s

Temperature (Degrees Celsius)

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Depth (mm)

GATE

Longitudinal Position (mm)

WEB
Figure H.15  Buoyant Surface Jet Case Thermal Contour Plot
Q=5 cm, hw=17 cm, Q=0.179 L/s at t=90 s

Temperature (Degrees Celsius)

1  25  26  27  28
29  30  31  32
33  34  35  36
37  38  39  40
41  42  43
Figure H.16 Buoyant Surface Jet Case Thermal Contour Plot
G=5 cm, hw=17 cm, Q=0.179 L/s at t=120 s

Temperature (Degrees Celsius)

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</table>
Figure H.17  Buoyant Surface Jet Case Thermal Contour Plot  
G=5 cm, hw=17 cm, Q=0.179 L/s at t=150 s
Figure H.18  Buoyant Surface Jet Case Thermal Contour Plot
G=5 cm, hw=17 cm, Q=0.179 L/s at t=180 s

Temperature (Degrees Celsius)

1  25  26  27  28
25  30  31  32
33  34  35  36
37  38  39  40
41  42  43
Figure H.19 Buoyant Surface Jet Case Thermal Contour Plot
$G=5\text{ cm},\ hw=17\text{ cm},\ Q=0.179\text{ L/s at } t=210\text{ s}$
Figure H.20  Buoyant Surface Jet Case Thermal Contour Plot
G=5 cm, hw=17 cm, Q=0.179 L/s at t=240 s
Figure H.21 Denser Wall Jet Case Thermal Contour Plot
G=3 cm, hw=8.5 cm, Q=0.057 L/s at t=10 s

Temperature (Degrees Celsius)

1  29  30  31  32
33  34  35  36
37  38  39  40
Figure H.22  Denser Wall Jet Case Thermal Contour Plot
G=3 cm, hw=8.5 cm, Q=0.057 L/s at t=24 s
Figure H.23  Denser Wall Jet Case Thermal Contour Plot
G=3 cm, hw=8.5 cm, Q=0.057 L/s at t=38 s
Figure H.24  Denser Wall Jet Case Thermal Contour Plot
G=3 cm, hw=8.5 cm, Q=0.057 L/s at t=52 s

Temperature (Degrees Celsius)

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</table>
Figure H.25  Denser Wall Jet Case Thermal Contour Plot
G=3 cm, hw=8.5 cm, Q=0.057 L/s at t=68 s
Figure H.26  Denser Wall Jet Case Thermal Contour Plot
G=3 cm, hw=8.5 cm, Q=0.057 L/s at t=87 s
Figure H.27  Buoyant Surface Jet Case Thermal Contour Plot
G=3 cm, hw=8.5 cm, Q=0.050 L/s at t=14 s
Figure H.28  Buoyant Surface Jet Case Thermal Contour Plot
G=3 cm, hw=8.5 cm, Q=0.050 L/s at t=28 s

Temperature (Degrees Celsius)

1  20  21  22  23
24  25  26  27
28  29  30  31
32  33
Figure H.29  Buoyant Surface Jet Case Thermal Contour Plot
Q=3 cm, hw=8.5 cm, Q=0.050 L/s at t=42 s
Figure H.30  Buoyant Surface Jet Case Thermal Contour Plot
\( Q=3\) cm, \( h_w=8.5\) cm, \( Q=0.050\) L/s at \( t=55\) s
Figure H.31 Buoyant Surface Jet Case Thermal Contour Plot
G=3 cm, hw=8.5 cm, Q=0.050 L/s at t=70 s

Temperature (Degrees Celsius)

1  20  21  22  23
24  25  26  27
28  29  30  31
32  33
Figure H.32 Buoyant Surface Jet Case Thermal Contour Plot
G=3 cm, hw=8.5 cm, Q=0.050 L/s at t=91 s
Figure H.33 Buoyant Surface Jet Case Thermal Contour Plot
G=3 cm, hw=8.5 cm, Q=0.050 L/s at t=119 s
Figure H.34 Buoyant Surface Jet Case Thermal Contour Plot
G=3 cm, hw=8.5 cm, Q=0.050 L/s at t=147 s
Figure H.35  Buoyant Surface Jet Case Thermal Contour Plot
G=3 cm, hw=8.5 cm, Q=0.050 L/s at t=182 s
Figure H.36 Buoyant Surface Jet Case Thermal Contour Plot
G=3 cm, hw=8.5 cm, Q=0.050 L/s at t=210 s
Figure H.37  Denser Wall Jet Case Thermal Contour Plot
G=5 cm, hw=8.5 cm, Q=0.072 L/s at t=21 s
Figure H.38 Denser Wall Jet Case Thermal Contour Plot
G=5 cm, hw=8.5 cm, Q=0.072 L/s at t=35 s
Figure H.39  Denser Wall Jet Case Thermal Contour Plot
G=5 cm, hw=8.5 cm, Q=0.072 L/s at t=49 s

Temperature (Degrees Celsius)

1  29  30  31  32
33  34  35  36
37  38  39  40
41  42  43
Figure H.40  Denser Wall Jet Case Thermal Contour Plot
G=5 cm, hw=8.5 cm, Q=0.072 L/s at t=63 s
Figure H.41 Denser Wall Jet Case Thermal Contour Plot
G=5 cm, hw=8.5 cm, Q=0.072 L/s at t=77 s

Temperature (Degrees Celsius)

\[ i \quad 29 \quad 30 \quad 31 \quad 32 \\
\quad 33 \quad 34 \quad 35 \quad 36 \\
\quad 37 \quad 38 \quad 39 \quad 40 \\
\quad 41 \quad 42 \quad 43 \]
Figure H.42 Denser Wall Jet Case Thermal Contour Plot
G=5 cm, hw=8.5 cm, Q=0.072 L/s at t=98 s
Appendix I. PHOTOGRAPHS OF DYE TESTS
Photo I.1  Denser Wall Jet Case at time = 11.2 seconds for
  \[ G = 5 \text{ cm}, \ h = 17 \text{ cm}, \ Q = 0.189 \text{ L/s} \]

Photo I.2  Denser Wall Jet Case at time = 17.1 seconds for
  \[ G = 5 \text{ cm}, \ h = 17 \text{ cm}, \ Q = 0.189 \text{ L/s} \]
Photo I.3  Denser Wall Jet Case at time = 28.1 seconds for
$G = 5\, \text{cm}, h = 17\, \text{cm}, Q = 0.189\, \text{L/s}$

Photo I.4  Denser Wall Jet Case at time = 31.6 seconds for
$G = 5\, \text{cm}, h = 17\, \text{cm}, Q = 0.189\, \text{L/s}$
Photo I.5  Denser Wall Jet Case at time = 32.9 seconds for
G = 5 cm, h_w = 17 cm, Q = 0.189 L/s

Photo I.6  Denser Wall Jet Case at time = 39.7 seconds for
G = 5 cm, h_w = 17 cm, Q = 0.189 L/s
Photo I.7  Denser Wall Jet Case at time = 48.3 seconds for
\[ G = 5 \text{ cm}, \ h_w = 17 \text{ cm}, \ Q = 0.189 \text{ L/s} \]

Photo I.8  Denser Wall Jet Case at time = 56.9 seconds for
\[ G = 5 \text{ cm}, \ h_w = 17 \text{ cm}, \ Q = 0.189 \text{ L/s} \]
Photo I.9  Denser Wall Jet Case at time = 67.3 seconds for
G = 5 cm, h_w = 17 cm, Q = 0.189 L/s

Photo I.10  Denser Wall Jet Case at time = 71.8 seconds for
G = 5 cm, h_w = 17 cm, Q = 0.189 L/s
Photo I.11 Denser Wall Jet Case at time = 94.0 seconds for
\[ G = 5 \text{ cm}, \ h_w = 17 \text{ cm}, \ Q = 0.189 \text{ L/s} \]

Photo I.12 Denser Wall Jet Case at time = 174.1 seconds for
\[ G = 5 \text{ cm}, \ h_w = 17 \text{ cm}, \ Q = 0.189 \text{ L/s} \]
Photo I.13 Buoyant Surface Jet Case at time = 5.1 seconds
for $G = 5 \text{ cm}$, $h_w = 17 \text{ cm}$, $Q = 0.191 \text{ L/s}$

Photo I.14 Buoyant Surface Jet Case at time = 7.6 seconds
for $G = 5 \text{ cm}$, $h_w = 17 \text{ cm}$, $Q = 0.191 \text{ L/s}$
Photo I.15 Buoyant Surface Jet Case at time = 14.3 seconds for $G = 5$ cm, $h_w = 17$ cm, $Q = 0.191$ L/s

Photo I.16 Buoyant Surface Jet Case at time = 19.5 seconds for $G = 5$ cm, $h_w = 17$ cm, $Q = 0.191$ L/s
Photo I.17 Buoyant Surface Jet Case at time = 28.6 seconds for $G = 5 \text{ cm}$, $h_w = 17 \text{ cm}$, $Q = 0.191 \text{ L/s}$

Photo I.18 Buoyant Surface Jet Case at time = 32.9 seconds for $G = 5 \text{ cm}$, $h_w = 17 \text{ cm}$, $Q = 0.191 \text{ L/s}$
Photo I.19  Buoyant Surface Jet Case at time = 41.3 seconds
for G = 5 cm, h_w = 17 cm, Q = 0.191 L/s

Photo I.20  Buoyant Surface Jet Case at time = 80.9 seconds
for G = 5 cm, h_w = 17 cm, Q = 0.191 L/s
NOMENCLATURE

\( C_0, C_1, C_2, C_3 \) = Coefficients in the equation of the density of water as a function of temperature

\( C_{\text{max}} \) = Maximum factor of the discharge entrained by the moving internal hydraulic jump

\( C_{\text{min}} \) = Minimum factor of the discharge entrained by the moving internal hydraulic jump

\( C_p \) = Specific heat of the fluid

\( D_1 \) = Gross dilution factor of the surface jet

\( D_2 \) = Cold water wedge dilution factor for the buoyant surface jet

\( G \) = Gate opening

\( F' \) = Densimetric Froude number of jet

\( F'_{r2} \) = Densimetric Froude number at sequent section of hydraulic jump

\( F'_{r1} \) = Relative densimetric Froude number at initial section of hydraulic jump

\( H_0 \) = Height of splash above jet = \( H_s - y \)

\( H_s \) = Height of splash

\( K_e \) = Hydraulic jump entrainment coefficient

\( K_1 \) = Weir short circuiting coefficient

\( K_{a}, K_r \) = Computer model sensitivity coefficients for jet entrainment coefficient and bed shear

\( L_j \) = Length of the hydraulic jump
\( P_1, P_2 \) = Hydrostatic pressure force per unit width
\( Q \) = Discharge
\( Q_{DI} \) = Gross dilution discharge of the surface jet
\( Q_{DE} \) = Cold water wedge dilution discharge
\( R_N \) = Reynolds number
\( R_l \) = Richardson number
\( T \) = Temperature (°C)
\( T_0 \) = Ambient fluid temperature
\( T_1 \) = Temperature of the fluid at section 1
\( T_2 \) = Temperature of the fluid at section 2
\( T_{23}, T_{34} \) = Dimensionless time to peaks in dye
\( T_{12}, T_{23}, T_{34} \) = Dimensionless time between peaks in dye concentration in influent
\( T_{11}, T_{1e} \) = Dimensionless time of initial peak in dye concentration in influent, effluent
\( T_i \) = Dimensionless time of initial appearance of dye in the effluent
\( T_e \) = Dimensionless time to reach equilibrium
\( U_m \) = Maximum velocity
\( V \) = Velocity of jet
\( V_0 \) = Velocity of ambient fluid \( \neq 0 \)
\( V_1 \) = Velocity at section 1 of hydraulic jump
\( V_2 \) = Velocity at section 2 of hydraulic jump
\( V_{1r}, V_{2r} \) = Relative velocity of hydraulic jump at sections 1 and 2
\( V_g \) = Velocity of jet at gate
\[ V_j \] = Velocity of jet

\[ V_r \] = Rate of rise of splash

\[ V_s \] = Surge velocity of moving internal hydraulic jump

\[ X_s \] = Longitudinal extent of splash above jet

\[ b \] = Width of tank

\[ g \] = Acceleration due to gravity = 9.81 m/s\(^2\)

\[ h_f \] = Energy losses due to friction

\[ h_w \] = Height of weir

\[ q \] = Discharge per unit width

\[ q_1 \] = Discharge short circuiting at weir

\[ t_{1i} \] = Time for initial appearance of dye in the effluent

\[ t_d \] = Tank detention time

\[ x_1, x_2 \] = Longitudinal position of section 1, 2

\[ x_3 \] = Longitudinal position of weir

\[ y \] = Depth of jet

\[ y_1 \] = Initial depth of hydraulic jump

\[ y_2 \] = Sequent depth of hydraulic jump

\[ y_g \] = Depth of jet at gate

\[ y_s \] = Submerged depth of hydraulic jump

\[ z \] = Elevation of the bed

\[ \Delta E \] = Other energy losses or gains

\[ \Delta t \] = Time increment

\[ \Delta x \] = Space increment

\[ \Delta y \] = Difference in depth of jet between sections
\( \Delta Q_e \) = Discharge entrained by jet
\( \Delta q_e \) = Discharge entrained by jet or hydraulic jump per unit width
\( \alpha \) = Entrainment coefficient of the jet
\( \alpha_1 \) = Kinetic energy correction factor
\( \beta \) = Momentum coefficient
\( \delta \) = Distance from boundary to point of maximum velocity
\( \delta t \) = Time increment
\( \delta x \) = Space increment
\( \nu \) = Kinematic viscosity of the fluid
\( \rho \) = Density of water \( (\text{kg/m}^3) \)
\( \rho_0 \) = Density of the ambient fluid
\( \rho_1 \) = Density of the fluid at section 1
\( \rho_2 \) = Density of the fluid at section 2
\( \sigma \) = Thermal entrainment correction factor
\( \tau \) = Shear stress at the bed
REFERENCES


VITA AUCTORIS

1963 Born on the 24th day of June in Windsor, Ontario, Canada.

1982 Graduated from St. Anne's High School, Tecumseh, Ontario, Canada.

1986 Graduated from the University of Windsor, Windsor, Ontario, Canada, with the degree of Bachelor of Applied Science in Civil Engineering.

1986 Accepted into the Faculty of Graduate Studies and Research, University of Windsor, Windsor, Ontario, Canada, in a programme leading to the degree of Master of Applied Science in Civil Engineering.