AN EXPERIMENTAL INVESTIGATION OF SELECTIVE WITHDRAWAL FROM A TWO LAYER FLUID BODY

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CERTIFICATE OF RESEARCH

This is to certify that the work presented in this dissertation is the outcome of the investigation carried out by the candidate under the supervision of Dr. Md. Quamrul Islam, Professor, Department of Mechanical Engineering, Bangladesh University of Engineering and Technology (BUET), Dhaka, Bangladesh.

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ABSTRACT

Selective withdrawal from stable stratified fluid system is a well known technique of water quality management. Stratification is caused due to density variation in an incompressible fluid or entropy variation in compressible fluid. The causes of density variation are primarily temperature variation with depth and secondarily, by a variable concentration of dissolved or suspended solid. Selective withdrawal is one, where one can select the strata of the fluid at the sink level. Hence, the flow is restricted into horizontal layer which enables the water to be withdrawn in horizontal layers.

Flow from stratified fluid system depends on many parameters like nature of stratification, thickness of interface, flow-rate, shape of sink, location of sink, rotation etc. But for characterizing the flow, the above physical parameters are converted into fluid dynamic parameters as drawdown, Froude numbers (densimetric Froude number, interface Froude number and intake Froude number) etc. In the present thesis, sinks were taken capped and observed that cap size on sink effects percentage of drawdown significantly. Hence, it is also found that a generalized relationship between drawdown, Froude numbers and cap dimension parameter from observed data can be made.

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NOMENCLATURE

a	Intake diameter normalized by full radius, d/R
a_i	Description coefficients
C_n	Speed of internal wave of mode n
b	Half thickness of interface, mm
d	Intake hole diameter, mm
d_c	Cap diameter
ddn	Drawdown
D	Molecular thermal diffusivity, m^2/s
Ex	Extension of the intake from the ground level of the tank, mm
F	Densimetric Froude number at cross flow, $U/(g'/H^5)^{1/2}$
F_i	Froude number defined as $q/(2g'h^3)^{1/2}$
F_r	Densimetric Froude number for line sink, $(q/g'h^3)^{1/2}$
Fr	Densimetric Froude number for axisymmetric sinks, $Q/(g'H^5)^{1/2}$
F_{rs}	Critical densimetric Froude number
F_δ	Intake Froude number, $(Q/g'd^5)^{1/2}$
F_l	Interface Froude number $q/(g'l^5)^{1/2}$
F_{rs}	Intake Froude number based on cap height $Q/(g'S^5)^{1/2}$
F_{rd}	Froude number based on withdrawal layer thickness, U/Nd
F_R	Froude number based on tank radius, $(Q2/g'R^5)^{1/2}$
g	Gravitational acceleration, mm/sec^2
g'	Reduced gravitational acceleration, $g\Delta\rho/\rho$, mm/sec^2
h	Difference between the elevation of the interface and intake, mm
H	Initial mean height of interface from the base of the tank, mm
l	Interface thickness, mm; characteristic length scale
L	Length of the tank
mV	Millivolt reading
n	Mode number of internal wave
N	Buoyancy frequency, $(\gamma g)^{1/2}$
P	Pressure, central node of a discretization cell
Pe	Peclet number, Ul/D
q	Withdrawal rate per unit with of a line sink, m^2/sec
Q	Withdrawal rate in a axisymmetric sink, m^3/sec

Contd.

r	Radial axis of cylindrical coordinate system
R	Tank radius
R_a	Raleigh number, $(\nu D)^{1/2}/NH^2$
R_e	Reynolds number, UH/ν
R_i	Richardsons number
S	Cap height
Sc	Schmidt number
S_t	Cap thickness, mm
t	Time, sec.
Δt	Time step, sec
T	Temperature, ^oC
ΔT	Temperature difference, ^oC
u	Axial velocity in cylindrical coordinate system
U	Cross-flow velocity, m/s
x_c	Critical distance $(2F)^{3/2}$ Ra^{-1}

Greek Symbols

β	$\Delta\rho/(\rho_1 + \rho_2)$
γ	length scale for density gradient, $(\delta\rho/\rho_o\delta_y)$, m^{-1}
Γ	Coefficient of diffusivity transport of φ, kg/ms.
δ	Withdrawal layer thickness
θ	Normalized temperature $(T-T_2)/T_1-T_2)$
ν	Kinematic viscosity, μ/ρ, m^2/s
ρ	Density, kg/m^3
ρ_o	Reference density, kg/m^3
$\Delta\rho$	Density difference, kg/m^3
τ	Time scale, 1/N
λ	Drawdown fraction
Λ	Percentage drawdown, 100λ
φ	Dependent variable for transport equation
ψ	Stream function
∞	infinity
$\propto$	Proportional to

Contd.

Subscript

c	Critical
1	Upper layer
2	Lower layer
o	Incipient Condition
m	Mixed

CHAPTER-1

INTRODUCTION

1.1 STRATIFIED FLUID SYSTEM

The word "Stratified" comes from "Strata" means layer. The fluid system which could be called stratified when its physical property will vary layerwise. In Fluid Mechanics, stratified fluid system means, density variation in incompressible fluid or entropy variation in compressible fluid in most commonly gravitational field. Similarly, non-homogeneous charge distribution in electromagnetic field causes also a stratified fluid system which are interesting phenomena in plasma physics. But from purely mechanical point of view, density or entropy variation is of prime concern. For incompressible fluid, density gradient effected to gravity may occur due to temperature differentials, suspended solid or variable concentration stable stratified fluid system (density decrease or entropy increase vertically upward direction), where flow in horizontal is restricted and thus enables the fluid to be withdrawn in horizontal layers, has become a popular practice in a number of engineering fields. In the following subsections only a few examples are mentioned to demonstrate the economic and inquisitive necessity of large scale control of stratified flows.

1.1.1 Layering of miscible fluids

There are two examples in which there exists a more clearly defined layering of water body; one cooling pond in power station and other solar pond used for storing solar energy. Cooling ponds usually have a layer consisting of warm, recently used water, above a cooled denser layer. In solar pond, heat energy is stored by building a two-layered system of cold fresh water above warm saline water; cause of this stratification is to increase density of saline water at higher rate at higher temperature as well as solubility of dissolved salt increases rapidly. The lower layer traps the solar radiation naturally at that way without any physical separation in the layer and heats up, storing the energy. This energy may be used for power generation, cooking food, heating and other purposes.

Lakes and artificial reservoirs have been proposed as large heat exchangers for nuclear power plants, thereby making it necessary to design intakes to withdraw the low level cool water and to distribute the inflow of warm water near the surface. The use of thermal stratification which exists in tropical or non-tropical seas as a source of energy to be used in thermal power plant, has drawn the great interest to the researchers on the context of energy management.

Pumped sampling system are often used by marine biologists, for example, to determine phytoplankton concentrations in stratified oceans on lakes [Fasham, 1978], and the vertical of sampling is of fundamental interest. Magmas from active volcanoes is also a problem of selective withdrawal [Blake & Ivey, 1985] and this phenomena is not only terrestrial but also extraterrestrial fact; that was observed in many natural satellite of planet or planet in our solar system. The reduction of reservoir sedimentation by removal at the dam of water containing large amount of suspended sediment has been suggested as a means of prolonging the useful life of major structures. In the area of density variations due to dissolved salts, the control of salinity intrusion by barriers and locks separating fresh water channels from an ocean or estuary may be mentioned.

1.1.2 Layering of immiscible fluids

Although common feature of application described earlier is the fact that in all cases fluids are considered miscible, in practice where fluids are incompressible and similar in viscosity there exists density differences are insignificant. Additional applications in cases of immiscible fluids of different viscosities might arise in separation of petroleum products and in other liquid-liquid separation process.

Stable entropy stratification occurs also in the atmosphere and is important in several flow problems of scientific interest examples like Lee mountain waves; radial flow of stellar material during various phases of its evoluation etc. as well as engineering interest; examples are cooling tower and chimney plume dispersion in the lower layer of the atmosphere, flame spread near the ceiling of room fires, dense gas dispersion from chemical plant or tanker accidents etc.

The advent of low cost atomic energy source should bring a degree of atmospheric pollution control, through selective withdrawal within the realm of possibility.

In many of these flow situations, the density variation combines with gravity to produce body force effects (buoyancy effects) which can crucially influence the fluid dynamic behaviour. The buoyancy effects are similar in many of the applications given above.

1.2 NATURE OF DENSITY VARIATION IN TWO-LAYERED FLUID SYSTEMS

Most of incompressible fluid stored in reservoirs is usually stratified into layers of different temperature or salinity and hence density, by the action of any physical external environment. This stratification has a rather irregular structure, although it typically consists of a reasonably well mixed surface of several meter thickness called the epilimnion, above a sharp density interface, the thermocline (pycnocline), which in turn lies above a weakly stratified lower layer the hypolimnion, reaching down to the bottom. This naturally occurring stratification is of stable type (lighter fluid overlying denser fluid) and is sometimes enhanced by the inflow of warm liquid from some external sources. In such cases, it is usually permissible to treat the fluid as a simple two-layered system. The detailed nature of stratification may vary widely depending on many physical factors such as a cyclic variation of solar radiation, wind shear, tidal motions, quality and quantity of inflow and outflow of water etc. in case of natural occurrence. In laboratories this wide range is simulated generally in terms of various types of profiles suited to different types of situations (Fig. 1.1); for example:

a. Linear stratification; density increases linearly with depth. This type of density profile simulates the nearly linear stable temperature gradient in deep water when the surface heated mainly due to solar radiation [Imberger and Fischer, 1970; Ho, 1973; Rahman, 1978].

b. Two-layered stratification; a homogeneous layer of lower density fluid lies atop another homogenous layer of higher density fluid. Ideally, this type of profile simulates the layers of two immiscible fluids.

c. Two-layered stratification; a homogeneous epilimnion, overlies a linearly stratified hypolimnion. Lawrence and Imberger [1979] claimed that the impounded water of some reservoirs may be represented by this type of profile with a sharp pycncline or without any pycnocline between the two layers.

d. Two-layered stratification; a mixed steep gradient interfacial region known as thermocline or pycnocline exists between the two homogeneous layers namely epilimnion and hypolimnion. This mode simulates in shallow water bodies or near surface zone of larger bodies (Islam, 1988). A two-layer fluid system of this type of density profile has been studied in this thesis.

1.3 SELECTIVE WITHDRAWAL

In many applications (an important example is the design of cooling intakes for power stations) it is necessary to be able to predict the maximum rate of withdrawal of fluid with desired properties which can be attained before fluid from a different level also begins to flow. The simplest of approach to this problem is to use the hydraulic method, and one problem of this kind has already been solved implicitly. The flow of a layer of heavy fluid through a control section (or over a barrier), where $F = 1$ represents the maximum flow-rate for which the lighter fluid is at rest. If fluid is removed at line located on the bottom down stream of the control at any rate less than this, then only the lower fluid will flow out, but if F (based on the mass flux and h_c) rises above a critical value of order unity, then the upper fluid will be drawn in too. Wood (1968, 1970) has introduced how this idea can be extended into multi-layer system flowing through horizontal contractions which acts as a control, and has calculated the fluxes in each layer as the total withdrawal rates is increased.

Theory becomes considerably more difficult when a sink discharges from a large body of fluid where there is no clear point of control. Craya (1949) and Huber (1960) considered various cases of sinks in the end wall of a channel, at a different level from the interface between two layers, and proposed methods for calculating the form of the interface as well as the critical condition. Such calculations are at best approximate, and it is often necessary to find the conditions for "drawdown" experimentally. A fundamental difficulty is that such experiments can never be really steady, because the upper stream boundary conditions as altered as the flow continues. Nevertheless, practically useful estimates can be made and Fig. 1.2 summarizes some of these results for a two-layer system. It is clear on dimensional grounds that, if the orifice width or diameter D is small, the critical condition must always be expressible as $F = F_{crit}$ where the critical Froude number is defined in terms of g' some flux and vertical separation h of the sink and the interface.

For point sinks.

$$F_{crit} = Q_3 / g' \frac{1}{2} h^{\frac{5}{2}}$$

$$F_{crit} = Q_2 / g' \frac{1}{2} h^{\frac{3}{2}} \tag{1.2}$$

where Q_3 is a volume flow-rate and Q_2 the flux per unit width. This simplification is not always clear from the original papers, where the form in which the results are given puts undue emphasis on D. An explicit dependence on D/h appears in the results of Rouse (1956) shown in Fig. 1.2c because orifice diameters ranged upto D = 10 h.

Similar results hold for continuously stratified fluid, through theoretically they are approached rather differently. Yih (1965, p. 82) used the linear equation $\left(\nabla^2 \psi + \delta z \frac{d\rho}{d\psi} = \frac{dH^*}{d\psi}\right)$ to find a series solution the flow into a sink at the end of the channel, with the velocity specified upstream (uniform U in Boussinesq approximation). He showed that this solution only remains valied provided F = U/NH is sufficiently large, H being the channel depth, for slow flows, when $F < \pi^{-1}$, wave like solutions also becomes relevant upstream and it is no longer possible to satisfy the boundary conditions at $x = -\infty$ that is, to draw fluid in uniformly from all heights in the channel. The experiments of Debler (1959) have confirmed that these solution give realistic flow patterns for $F > \pi^{-1}$.

As F approaches π^{-1} from above a closed corner eddy appears in the solutions (as shown schematically in Fig. 1.3). As remarked earlier in connection with rotors this is not properly described by $\left(\nabla^2 \psi + \delta z \frac{d\rho}{d\psi} = \frac{dH^*}{d\psi}\right)$, but it is (perhaps fortuitously) correspond to what was observed in this range.

For $F < \pi^{-1}$ the fluid is divided into a flowing region and a stagnant layer extending all the way upstream. Debler's results suggests that a similar criterion to (1.2) can be used to describe the amount of fluid withdrawn. Defining

$$F_{crit} = \frac{Q_l}{d_l^2} N^{-1} = \frac{Q_l}{g \frac{1}{2} d_l^{3/2}} \tag{1.3}$$

where Q_l is the flux per unit width, d_l is the depth of flowing layer far from the source and g' is based on the density difference across d_l, the experiments correspond to the value of F_{crit} = 0.25. It turns out to be a good general rule for all kinds of slow flows that this internal Froude number, based on the properties of the flowing layer (or each of the layers, if there is more than one), lies between 1/4 and 1/3, the lower values probably being due to viscous effects which have so far from neglected here, Yih (1965) has shown how the formation of a stagnant region can be postponed to smaller F by inserting an obstacle near the sink (whose form was calculated by an indirect method, using an array of singularities and choosing a closed streamline). At even lower F blocking must inevitably occur, when a layer of fluid at the bottom of the channel cannot flow over the barrier.

1.4 SELECTIVE WITHDRAWAL OF CONDENSER COOLING WATER

"Selective withdrawal" is a term mainly pertaining to a specific (usually desirable) phenomena in buoyant flows whereby fluid, withdrawn at the boundaries of a fluid body, flows predominantly from a spatially limited selective layer (or region) of a stratified environment (Islam, 1988). This phenomenon has been practised with better performance in the intake system of condenser cooling water. The next paragraph will give a consize glimpse of essential features of this specific practical application.

A common practice for the condenser cooling system of thermal and nuclear power stations is to withdraw cold water from a neighbouring large water body, pass it through the condensers and discharge it again into the same water body with a raised temperature. Power plants are therefore conveniently located near the coast or large river. The discharged warm water forming a floating surface layer and may be transported by tidal velocity into vicinity of the cooling water intake (Fig. 1.4). A poorly designed intake system may then withdraw at least partially from the upper warm water layer, which then result in a higher than the desired temperature of the heat sink and thereby a reduction of power plant efficiency. Engineers are constantly trying to solve this problem by choosing the optimum design criterion for the intake system through proper understanding of associated flow pattern. In recent years, single or multiple round intakes have been used to selectively withdraw the cold water for condenser cooling systems from a thermally stratified water body. Furthermore, the effect of a cap or hood over the intake is still under investigation (Islam, 1988).

1.5 EFFECT OF STRATIFICATION OF WATER ON THE ENVIRONMENT OF LARGE LAKES OR IMPOUNDED POOLS

Purely homogeneous fluid is only idealization to develop classical hydrodynamic philosophy. In actual case, all fluids are stratified densimetrically or entropically to some extent. Where the effects are not serious; then it can be thought of homogeneous fluid like aerodynamics. Where the density gradient are remarkable contribution for it's flow then it must be considered as stratified flows. Seasonal variation of solar radiation and surface wind causes the water of large lake or reservoir density stratified. This has effect on the life of under water species. It has been reported (Sport Fishing USA, 1971, Government printing press) that the population of some warm-water species declines drastically after the introduction of a dam, which causes the water to be stratified and begins to release cold water from the lower layers of the reservoir.

Furthermore, well known phenomenon of survival of fishes of the polar region is possible due to stratification associated with extraordinary thermal density variation of water.

1.6 OBJECTIVE OF THE STUDY

On the context of water quality management in large reservoirs, lakes. cooling pools etc., selective withdrawal under finite amplitude motions of stratified fluid is a burning question for the engineer to make an understanding the mechanism of withdrawal that one can design efficient withdrawal system. For subcritical flow, the flow is restricted to the lower layer but for super critical flow water from both layers flows through the sink. Location and geometry of sink plays an important role in percentage drawdown from stratified system. As well as cap or hood over intake must play a vital role on drawdown. The present work will investigate the effect of cap on percentage drawdown from a stably two layered fluid body system. Hence main emphasis will be offered on cap dimension with respect to cap height.

1.7 SIMPLIFICATION OF THE PROBLEM UNDER CONSIDERATION

Classically in general all physical problems are time dependent three-dimensional, where understanding of problem makes selection of assumptions simplifies greatly for its realization. A cooling water intake from a shallow water body is introduced firstly by the spatially varying background velocity field of the water body (e.g. the main stream velocity of a river or the coastal currents) where velocity field is influenced by intake geometry in its vicinity. The main river velocity or near the coast currents also vary with time and this variation makes problem time dependent. Further time dependency is associated with the changing cycle of ambient parameters on both daily and seasonal time-scales. Finally, as mentioned above warm water discharge near intake produces a buoyant floating layer over the cold layer of water. The depth of this layer and the associated stratification may be influenced by additional mixing caused by wind shear on the free surface and by heat loss to the atmosphere.

Although all the above complexities certainly influence the real life problem, in this study it is considered appropriate to examine initially the more fundamental case of the near-field flow pattern in the withdrawal through a single intake from a stable two-layered system. Phenomena excluded from the current work an time-dependent ambient effects, all three-dimensional effects and all free surface effects such as wind shear and heat loss. In spite of all these neglected factors, the problem which is sufficient to represent the real case to provide an understanding about the phenomena which occurs in full scale.

1.8 OUTLINE OF THE THESIS

The objective of this work is to investigate the effect of cap on percentage drawdown. This thesis is divided into five chapter. Chapter-I of this thesis consists of aim of the current work and several examples of selective withdrawn. A comprehensive literature review is provided in chapter-II. In chapter-III a brief description of experimental setup and procedure is described, chapter-IV is the most important chapter of this thesis. In this chapter experimental results and discussions are summarized and all the findings are noted. Conclusions and recommendations is represented in chapter-5.

CHAPTER-2

LITERATURE REVIEW

2.1 INTRODUCTION

Inquisitiveness behind selective withdrawal from a stably stratified environment made scientists and engineers think to come into physical reality after the formulation of fluid science on the basis of Newtonian philosophy (three most remarkable conservation principles; mass-conservation, momentum conservation and energy conservation) as well as other physical problem. But other two types of modern classical formulation of Fluid Mechanics formulations (Lagrangian or Hamiltonian formulation respectively) coming to light since eve of last century, but impact of this modern science into engineering field is almostly absent. Since about half century when computer technologies had started to be familiar as well as other technology was blessed from this advanced rapidly both numerically and experimentally. So many journal since 1950 were observed on selective withdrawal phenomena.

Islam (1988) and Imberger (1980) have provided a comprehensive review on this relevant topic. Recently, Razzaque (1994) and Anawar (1995) investigated vertical axisymmetric selective withdrawal phenomena from a two layered stably stratified environment due to temperature gradient. They investigated affect of "intake geometry and intake Froude number on drawdown" and "height of intake and intake Froude number on drawdown" respectively. The following subsections contain a review of previous work on selective withdrawal from a stably stratified environment.

2.1.1 Some Familiar Parameter Concerning the Flow of Interest

Like other physical problem of continuous media, concept of stability is important for distribution of spatial density through force field for realization of stably stratified media. On this aspect Imberger and Fischer (1970) described a detailed parametric analysis of selective withdrawal problem from such a stably stratified media (Islam, 1988). If in a stratified flow field over depth and $\rho_a(y)$ is the density above ρ_o (offenly called reference density) at rest, then a vertical (direction of gravitation field) length scale for the ambient density gradient is related to

$$\gamma = -\frac{1}{\rho_o}\frac{\partial \rho_a}{\partial y} \tag{2.1}$$

Negative sign was considered in above definition in order to make the characteristics length scale positive as in stable media; $\frac{\partial \rho_a(y)}{\partial y}$ must be negative. The variable density introduces a body force which cause a major modification of flow. For case of stagnant environment, if a fluid element of volume dv is displaced vertically by an amount dy, then experience a body force equivalent to $-\rho_0 \gamma g \delta y \delta v$ in the original level or stable equillibrium position. This body force or buoyancy force plays an important role in vertical momentum balance in the flow field and impose constraint on vertical motion. For higher γ (higher degree of stratification) this buoyancy force dominates over the other prevailing forces and the flow becomes horizontally layered (why the cause of nomenclature of stratified flow).

In an unsteady flow driven or influenced by the above buoyancy for after solving a simple differential model a time scale is characterized by natural period of oscillation of an elementary volume in the gravitational field and is given by,

$$\tau = \frac{1}{N} \tag{2.2}$$

When $N = (\gamma g)^{1/2}$ is the natural frequency of osciallation and is known as the "buoyancy frequency" or "Burnt-Vaisalla" frequency.

The sudden initialization of withdrawal from a stable stratified environment through a sink induce a pressure gradient which is counter acted in the vertical direction by the buoyancy forces. As the buoyancy forces restrict the vertical motion, the flow becomes concentrated within a narrower space as fluid moves vertical downward direction. But there is a compromise between pressure, buoyancy, inertia and viscous forces to exist a dynamic equilibrium. For an inviscid buoyancy layer scaling parameter characterizing the flow is the ratio of inertia to buoyancy force and can be expressed as;

$$\frac{inertia\ forces}{buoyancy\ forces} = \frac{U^2}{N^2 l^2} = F^2 \tag{2.3}$$

where, l is a characteristic length scale for the motion and F is the densimetric Froude number in cross flow. Similarly, for creeping flow the scaling parameter is the ratio of viscous to buoyancy forces and is given by

$$\frac{viscous\ forces}{buoyancy\ forces} = \frac{\nu U}{N^2 l^3} = \frac{F^2}{\mathrm{Re}} \qquad (2.4)$$

where, Re = Ul/ν is the Reynolds number of the flow (ratio of inertia to viscous forces). For a diffusive fluid, Peclet number, p_e measure the relative strength of the convective to diffusive transport of the species and is given by,

$$\frac{convective\ transport}{diffusive\ transport} = \frac{Ul}{D} = p_e \qquad (2.5)$$

Although these three independent parameters (F, Re and Pe) are in principle required in the study of withdrawal from a stratified environment other combinations are possible and sometimes found in the literature, e.g.

Schmidt number, $S_c = \nu/D = P_e/R_e$
Rayleigh number, $R_a = (R_e.P_e)^{-1/2}.F$

2.2 WITHDRAWAL THROUGH TWO DIMENSIONAL LINE SINKS

Most of the withdrawal phenomenon may be simplified into 2D-plane flow into line sink. Buoyancy force dominant when densimetric Froude number is very small ($F \ll 1$). From the pattern of the flow, velocity increases as the fluid advances towards the sink so the Froude number will also increase as the flow advancing towards sink and on it's way flow may be characterised by there three distinct types, as subcritical, critical and super critical. Sub-critical flow is identified when buoyancy force is dominant over inertia force and opposite of this statement is known to super critical. And critical condition is identified as the contribution from both kind of force equal known as transition. Very far upstream the flow is laminar, this flow is layered due to buoyancy. As this layer approaches the sink it becomes thinner, and at some critical distance from the sink inertia is comparable to the buoyancy force. The subsequent flow in the layer will be governed by the balance of inertia, buoyancy and viscous forces.

2.2.1 Linear Stratification:

When motion is weak, density-stratified fluid in a gravitational field exhibits large departure from the motion of homogeneous fluid. Physically, a stable stratified fluid system always restricts the motion of any fluid particle in vertical direction since there exists a restoring force due to gravitational field. The cause of density stratification due to thermal gradient can be realized from molecular theory of statistical mechanics. Inter-molecular distance of fluid particle system must be function of temperature. Also temperature is the measure of kinetic energy. So at any temperature, there arise a correspond intermolecular distance which is responsible for density variation. On the other hand, Possion's gravitational field theory predicts the particles system of various density would make equipotential surfaces with same density in uniform gravitation field. That is why vertical motions are therefore inhibited in favour of horizontal motion and behaves like stratas. So according to this philosophy, pure homogeneous fluid is practically hypothetical only. Then degree of stratification must be considered and on that aspects in the example of stratified flows are in the oceans, in atmosphere, in volcanoes etc.

The problem of linearly stratified flow towards a line sink was first investigated analytically by Yih (1958). He investigated on such a line sink which was placed at bottom right corner of a channel (Fig. 2.1); the solution set in term of series for the normalized stream function was obtained which demonstrated the way in which buoyancy modifies the flow. Froude number was defined as $F = U/NH$ where U is the cross flow velocity, H is the channel depth and N is the Burnt-vaisalla frequency. At $F = 1/\pi$, it was predicted that the eddy (recirculating zone) extend to infinity and this was interpreted as the onset of a selective withdrawal layer. The infinite size of the eddy violated the upstream boundary conditions used by Yih, and the mathematical approach adopted was incapable for providing solutions for less than the critical value ($F_c = 1/\pi$). Yih assumed the velocity and density to be undisturbed far upstream, so that no solution was obtained for $F < \pi^{-1}$. An exactly analogous experimental investigation was conducted by Debler (1959), using a long finite sizes channel. He (Debler) showed by experiment that $F \sim \pi^{-1}$ is indeed a critical Froude number, above which Yih's solution is valid, and below which the flow separates into a flowing region near the level of the sink, the fluid remaining essentially stagnant elsewhere (i.e. selective withdrawal occurs). The experimental results indicated the critical Froude number, $F_c = 0.28$. The Reynolds number, $R_e = UH/\nu$ in this case sufficiently high [$0(10^4)$] and Peclet number

P_e = UH/D was of the order 10^7, so that the results might be considered to be a first approximation for the inviscid and non-diffusive case.

For flows with $F < 1/\pi$, Kao (1965, 1970) proposed an inverse trial-and-error method of solution for this problem using a fictious distributed sink on the vertical axis at the origin (Fig. 2.2) assuming that the pressure variation along the dividing streamline was hydrostatic ($dp/dx = 0$). So, the velocity above it remained constant and this fluid is therefore discharged through the fictious sinks, the fluid below the dividing streamline was discharged through the physical line sink. In this way the sum of individual Froude numbers of the fictitious sink and the physical sink was greater than $1/\pi$ and Yih's solution could be applied to the entire channel. This analysis led to a unique Froude number based on the depth of the flowing layer $Fr\delta$ ($U/N\delta$) = 0.33 for all withdrawal rates below F_c whereas the experimental results of Debler (1959) indicated $F_{r\delta}$ = 0.2 to 0.28 when the ratio of the flowing layer to the total depth (δ/H) varied from 0.3 to 1.0.

2.2.2 Effect of Viscosity and Diffusivity:

Koh (1966a), Imberger and Fischer (1970), Imberger (1972) and Pao and Kao (1970) studied the effect of viscosity and diffusivity in stratified flow towards a line sink. For fluid with Schmidt numbers, Sc, of order unity, the withdrawal layer is composed of distinct regions, in each of which a definite force balance prevails (Imberger and Fischer, 1970). If the channel depth is sufficiently larger, then at a very far upstream the flow will be slow and parallel (Fig. 2.3). This slow parallel flow then becomes layered by the action of buoyancy in the outer region where both viscous and buoyancy forces are significant. As the flow approaches the sink, the withdrawal layer becomes thinner and at critical distance, $X_c = (2F_r)^{3/2}H/R_a$ (Imberger and Fischer, 1970) [$F_r = q_o/2NH$, $R_a = (\nu D)^{1/2}/NH^2$] from the sink, inertia forces become comparable to the viscous and buoyancy forces (the inner region). Very close to the sink [$(x/x_c)^{1/3} < 0.05$; Pao and Kao, 1974], sink inertia becomes dominating and the flow becomes inviscid and buoyant.

Koh (1966a) investigated this problem with a diffusive linearly stratified fluid for an infinite medium. He obtained a solution neglecting the non-linear inertia terms, which predicted a self similar velocity profile with a peak at the level of the sink and a velocity which decays rapidly in an oscillatory manner above and below the x-axis (symmetry axis in Fig. 2.3). In addition, the thickness of the withdrawal layer, δ (Fig. 2.3) increased at a rate of $x^{1/3}$ where x is the distance from the sink and δ/H was proportional to $R_a{}^{1/3}$. Imberger and Fischer (1970) and Imberger (1972) analyzed the some problem as Koh did but with a finite depth. Using the results from Koh's method for the outer region (Fig. 2.3) on the upstream boundary condition, they obtained a integral solution for the inner region incorporating the inertia terms. This prediction also indicated a self similar velocity profile and withdrawal layer growth of order $x^{1/3}$ but added a viscous layer to the inviscid result obtained analytically by Kao (1970) (δ = 0.33 N/U) and experimentally by Debler (1959) [δ = (0.24 ± 0.04) N/U] (in Debler's experiment x_c was of order 10^5 m, confirming that all measurements belong to the inviscid core).

Koh (1966a) and Imberger (1972) also reported experimental data to support their analytical solutions. These experimental studies were carried out with very low Reynolds and Froude numbers [R_e = 0 (10) and F_r (10^{-4})]. The value of x_c was varied from 2 cm to 2 m in Imberger's experiments whereas his flume length was 13 m. Koh's experiment flume was such shorter (50 cm effective length), but x_c varied from 0.7 cm to 4 m. In both studies, the measurement locations belong to the inner and outer regions. The data for velocity profiles in both experiments showed a self similar shape in both inner and outer regions, validating the analytical solutions. However, in Imberger's experiment the reverse flow above and below the withdrawal layer increased with $(x/x_c)^{1/3}$, while his analytical solution predicted only the forward flow within the withdrawal layer. The measured growth of the thickness of the withdrawal layer, δ with x was predicted better by Imberger and Koh, since the first method considered the inertial effects in the flowing layer.

In his paper, Koh (1966a) also presented photographs showing the flow development at the level of the sink with time (measured from the moment withdrawal was begun) and these clearly indicated the presence of propagating waves. In the course of his experiments, Debler (1959) also observed some wave motions in the flow field. All these observations indicate some transitional behaviour towards the steady state. Koh (1966b) reported some calculations (for unsteady flow) for an linearised initial value problem appropriate to a sink in an infinite medium with linear stratification. His solution predicted an increase in the horizontal velocity towards the sink with time, but this increase was felt instantaneously at all distance away from the sink by an amount inversely proportional to the radial distance from the sink, which physically unrealistic

(Pao and Kao, 1974). The detailed transient behaviour of this problem was first analytical by Pao and Kao (1974) who again studied the linearised initial value problem. The sudden sink opening disturbs the fluid particles very close to the sink which due to the presence of the linear density stratification, start to oscillate at the natural frequency N. But the buoyancy force wants to restore the particles to their original positions and the oscillation and restoring process gives birth to harmonics which eventually produce an infinite number of internal waves with progressively decreasing vertical wave length. These waves propagate upstream with a speed of $C_n = NH/n\pi$, where mode number n = 1, 2, 3 .... a and are continuously attenuated by the viscous/diffusive action. The waves propagate against the induced upstream velocity $U = q/2H$ (H = half depth of fluid). If the propagation speed C_n is greater than the upstream velocity, U, then the flow field is modified by the internal waves and selective withdrawal prevails (Fig. 2.4). At (or above) a critical Froude number ($F_{rc} = 1/\pi$), the fastest wave speed is the same as (or less than) the induced upstream velocity, U, thus no waves can propagate upstream and hence no selective withdrawal occurs. Below the critical Froude number ($F_{rc} < 1/\pi$), n modes can propagate when $C_n > U$.

Pao and Kao (1974) also presented a numerical solution of the unsteady, two-dimensional non-linear partial differential equations governing the flow Kao. Pao and Wei (1974) obtained experimental data which give excellent support to their numerical results in terms of existance and speed of propagation of internal waves for a wide range of Reynolds and Froude numbers (R_e = 627 - 3380 and F_r = 0.0143 - 0.106). Their experimental data belong to the inviscid core and to the inner region [$x_c \sim 0\ (10^3$ m)]. In the numerical calculations, the experimental setup was not simulated exactly, instead a constant depth and infinite length channel was used with slip condition at all solid boundaries to avoid viscous action on the wall. The full Navier-Stokes equations were transformed into a stream function/ vorticity formulation which was discretized and solved numerically using a explicit time marching method, upwind differencing for convection terms and central difference for all other terms. By a suitable co-ordinate transformation ($x' = 1 - c^{-ax}$) the infinite length was reduced to a computational domain of unit length in which the upstream boundary condition was specified from potential flow equations and remained the same at all times. Numerical calculation were presented for various Reynolds and Schmidt numbers to account for the effect of viscosity and diffusivity on the flow development. Pao and Kao (1974) concluded that the establishment of the flow and density fields was essentially inviscid and non-diffusive for the range Fr > 0.07 and Re > 10^4 when Sc > 1. The steady state velocity profiles from the numerical and experimental studies were also compared with the analytical solutions of Koh (1966a) and Imberger (1972). Koh's self similar velocity profile agrees quite well with the results and is better than Imberger's. Computed and measured steady state withdrawal layer thickness were also compared with Koh's and Imberger's solution. For this parameter, Imberger's solution indicated experiments than Koh's.

2.2.3 End Wall Effect:

In any experimental study, there exists end wall which influences the horizontal velocity far from upstream; this can affect the whole flow field at later times if the internal waves are reflected from the end wall, before being diminished by viscous action. Silvester (1980) provided an experimental study on the evolution, propagation and reflection of the internal waves in a linearly stratified fluid and its effects on flow field. From the observational findings of this experiments, he conclude that each mode can travel a distance which proportional to n^{-3} before attenuation. For a long channel, symmetric velocity profiles were observed, even at the time of first mode reflection. For a shorter tank, however, for times when several modes has been reflected from both walls a marked asmmetry in the velocity field was always present.

2.2.4 Initial Motion

Pao and Kao (1974) have studied the dynamics of initial motion of the withdrawal of fluid from stratified container through a line sink. Immediately after the sink is turned on a nearly horizontal potential flow is created. This flow is then progressively modified by discrete spectrum of planer shear waves that travel out from the sink against the induced uniform upstream velocity. As McEwan & Baines (1974) found, each shear front travels with a speed $c_n = NH/n\pi$, where n is the modal number and it is the depth and has a frontal width $w_n = H(NT)^{1/2}/n$ where T is the time. The modification of the potential flow by these shear waves dominates the initial dynamics of flow.

2.2.5 Inflow

G.N. Ivey and S. Blake (1985) studied effect of inflow into a continuously stratified environment. While analysing the axisymmetric inflow of a homogeneous fluid into a stratified container, attention is here on the case of neutrally buoyant inflow at constant discharge Q with low momentum such that there is no mixing effects. They obtained a transition parameter denoted as "S", where $S = \left(\frac{Q^2N}{\nu^2}\right)^{1/15}$. If S is very large, viscosity is unimportant and thickness of the inflow $\delta \sim (Q/N)^{1/3}$ and spreading law;

$$l_\gamma \sim \left[\frac{Q^3N}{(\nu D)^{1/2}}\right]^{1/7} t^{3/7} \tag{2.6}$$

where l_γ is the radial extent of the spreading intrusion, D is the diffusivity of fluid, t is time. Again, when S is small the viscous forces are important throughout the flow field, the initial intrusion thickness $\delta \sim (\nu Q/N^2)^{1/3}$ and the spreading law

$$l_\gamma \sim \left[\frac{Q^4N}{\nu}\right]^{1/10} t^{1/2} \tag{2.7}$$

Chen (1980) used similarity technique to evaluate the constants of equation (2.7). Zatsepin & Shapiro (1982) conducted a number of laboratory experiments in the same flow regime and found good agreement with the predicted spreading law.

2.2.6 Computational Verification

Islam (1988) performed the computational study of the experimental works of Debler (1959), Kao, Pao and Wei (1974) and Silvester (1980). The experimental set-up for these three cases considered differ only in that in Debler's experimental studies, the sink for withdrawal was at the bottom corner of the tank while in other cases, it was it mid-depth. In all cases, salt was used as the stratifying agent and a linear vertical profile of concentration was ensured throughout the tank before the initiation of flow. Photographic techniques were employed for the quantitative measurements. To obtain the numerical predictions of these experimental studies, calculation domains were simulated using exactly the same physical dimensions as in the experiments. Calculation proceeded from time t = 0 when sink was opened. A uniform velocity profile was assumed at the sink and as a consequence of these approximations the free surface dropped at a uniform velocity as discharge continued. To adjust the calculation domain to always match the physical domain size the governing equations were transformed into a moving boundary Eulerian co-ordinate frame. A linear stratification at a gradient fixed by the experimental condition was assumed in the stagnant water prior to the start of calculation. Zero gradient conditions were applied at the free surface which was otherwise treated as a "rigid lid" in the usual way. No slip conditions were used along all solid surfaces for velocities and zero gradients for the density field.

The main experimental findings of the Debler's study was the determination of the withdrawal layer thickness as a function of Froude number, the flow visualization was used to determine this thickness by observing the motion of lines of dyed fluid introduced into the tank during the establishment of the initial linear density gradient. Fifteen layer (each approximately 40 mm thick) were used with alternate layer dyed. As time progressed after the start of withdrawal a number of layers would bend down from their originally horizontal locations towards the sink exit, on the other hand, those layers in the stagnant upper layer would remain essentially horizontal, the existance of a dividing streamline (below the critical Froude number) could therefore be noted and quantified.

This experimental technique was simulated computationally by tracking the location of a number of neutrally buoyant particles placed along originally horizontal and vertical lines within the calculation domain. As the calculation proceeded, the particles were moved to new positions as demanded by the predicted flow field and at any instant the lines obtained by joining the new particles positions represented the time lines for that instant. The withdrawal depth was then evaluated from the computation as the height of the last time-line (above the tank bottom) which curved monotonically towards the sink exit.

Ten experimental cases were considered covering a Reynolds number range from 70 to 42,200. One run provided data for the additional effects in the flow field due to waves reflected from an end wall and finally another test considered the special case of a two-layered system.

The existance of internal wave motion in the fluid could be clearly seen from the predicted time-line patterns, leading to a quite complex flow structure in the viscinity of the sink at the later times. The predicted withdrawal layer depth over the whole Froude number (instantaneous) range of Debler's experiment was compared with the experimental results. Excellent agreement but there was some deviations at higher values of Froude numbers. The measurements indicated a critical value of Froude numbers, F_c of 0.289, whereas the numerical prediction implied 0.33 in agreement with the inviscid theory of Yih (1958).

Stream line patterns for finite and semi-finite tank for an initial Froude number, F_0 = 0.112 at different time lines were predicted and the propagation of internal waves in the form of a corner eddy was found to be very much similar in both the cases. History of propagation of wave modes and reflection of internal waves were investigated in details. Velocity and concentration profiles obtained by prediction were compared with experimental results and a good agreement was found.

2.2.7 Two-Layered Stratification

For the case of two-layered stratification, Froude number is still primary governing parameter which characterizes the flow. Craya (1949) (Brooks and Koh, 1969, Islam, 1988) investigated this problem for an inviscid and non-diffusive fluid unbounded in the vertical direction with the sink placed in the vertical wall at a certain height, h away from the interface between the two fluids [Fig. 2.5(a)]. He found the critical Froude number above which both layers flow to be

$$F_{rc} = \frac{q_o}{\sqrt{g' h^3}} = 1.52 \tag{2.8}$$

Huber (1960) studied this problem but with slightly different geometry (see Fig. 2.5(b) and obtained the value of the critical Froude number to be

$$F_{rc} = \frac{q_o}{\sqrt{g' h^3}} = 1.66 \tag{2.9}$$

The differences in the value of the critical Froude numbers for these two configurations are presumably due to the different boundary conditions. Kao (1976) analyzed this problem with two homogeneous fluid with the aid of wave theory. The disturbance experienced at the interface by the intake flow is also influenced by the boundary conditions and thus provides different results. He extended his analysis to the thermocline type of stratification with the line sink located at the middle of the thermocline. The critical Froude number , he obtained for this case is:

$$F_{Ic} = \frac{q_o}{\sqrt{g'\beta b}} = \frac{1}{\sqrt{2}} \qquad (2.10)$$

Where, $\beta = \Delta\rho/(\rho_1 + \rho_2)$, b is the half of the thickness of thermocline.

2.2.8 Interface Shape: Analytical and Experimental Work

During drawdown, the shape of interface plays important role in water quality management. The interface during the flow of two-layered fluid body into line sink was investigated by Ingber and Munson (1986) both analytically and experimentally. They pointed out that three essential distincts, steady state flow topologies exists (Fig. 2.6). In the first flow topology, a stagnation point exists in the interface directly above (below) the sink. In this case, the layer with the sink is flowing while the other is essentially stagnant outside a thin shear layer. In the second flow topology, the interface between two fluids cusps down toward sink but does not enter into it. Again, one layer flows and other is essentially stagnant. In third flow topology, the interface is drawdown into sink and both layers are flowing.

Over each flow topology to exist, the range of Froude number was determined experimentally. According to Fig. 2.7, experimental results were taken under considering viscous effects. Froude number was defined as $F_i = [q^2/2g'h^3]^{1/2}$. For flows with $F \leq 0.36$, the stagnation point of interface was obtained. The horizontal extent of deflected surface was approximately one and a half times of the depth of lower fluid layer irrespective of Froude number. For flows is $F_i \geq 0.38$, the interface was drawndown into the sink. With very intensive care it was impossible to adjust the flow rate to originate the interfacial position shown in Fig. 2.7 with Froude numbers, F_i = 0.37. This condition is necessarily like cusp the flow where the interface cusp down toward the sink-down of interface towards sink but does not enter into it. The region above the sink ($\theta < x/h_c < 0.4$; dashed portion of the curve) was observed to be quite unsteady with apparently considerable viscous and surface tension effects. However, a slight change on flow rate changed this type of flow into either a drawdown or a stagnant point flow.

In the case of withdrawing water though a line sink from a region containing two distinct homogeneous layers of different densities separated by a very sharp interface. Tuck and Vanden-Broeck (1984) showed that only two types of solution are possible beneath the critical Froude number, i.e., when only a single layer is flowing out through the sink. The first solution type involves a stagnation point on the interface directly above the sink. Peregrine (1972), Vanden-Broeck, Schwartz and Tuck (1978) and Vanden-Broeck (1984) all computed solutions of this type for the case of a line sink but had limited success as the Froude Number $F_r = (q^2/g'h^3)^{1/2}$, was increased (Here, h is the depth of lower layer). Hocking and Forbes (1991) computed solution with a stagnation point for the case of a layer of infinite depth for values of Froude number, $F_r = (q^2/g'h^3)^{1/2}$, upto 1.4 where h is the depth of the sink beneath the level of the interface.

The second solution higher than critical Froude number permits water above the interface begins to be drawn out through the sink. In this flow, a downward cusp forms in the interface directly above the sink, as the interface is drawn down to enter the sink vertically.

In case of infinite depth, Hocking and Forbes (1991) and Tuck and Vanden Broeck (1984) observed the range $1.4 < F_r < 3.54$. Hocking derived and solved an integral equation for this case which verified all results of Vanden-Broeck and Keller (1987) and extended to the branch of solution in which the interface contained a hump above the sink as the sink depth approached zero, even upto the reion where the sink rises above the level of the interface in the far field. He attempted but failed to compute solutions with a cusp for values of Froude number less than unity.

2.2.9 Effect of Sink Location

When withdrawn is taken from a fluid consisting of two or more homogeneous layers of different densities separated by interfaces, the withdrawn water will come from the layer adjacent to the point of removal until threshold in flowrate is reached after which other two layers will begin to flow out through the sink. This threshold can be described most easily in terms of dimensionless parameter Froude number $F = (q^2/g'h_b)^{1/2}$, where h_b is the depth of lower layer of the fluid. Hocking (1991) studied effect of location of on the rate of withdrawal from both layers. He found that interface between two layers rises up and then enters the sink vertically from above even when the sink is located above the undisturbed level of the interface. He redefined Froude number as $F = (q^2/g'h_s)^{1/2}$, where h_s is the depth of the sink beneath the level of the interface. He developed a mathematical model and solved the problem numerically. In his solution he found that the interface contained a hump above the sink as the sink depth approaches zero. His numerical method was capable of producing solution in the region where the sink rises above the interface level in the far field (Fig. 2.8).

2.2.10 Drawdown History

Hocking (1991), in a technical note presented the results of a series of experiments in which the critical value of densimetric Froude number was obtained for the case of a line sink in the bottom corner of a rectangular tank containing two layers of fluid of different densities over a range of different interface thickness. The experiments were performed in a double glazed glass tank, 5.5 m long, 0.5 m wide and 0.6 m deep. A two-electrode conductivity probe was used to continuously monitor the density of the out flowing water. A four electrode conductivity probe mounted on a step motor traversing gear mechanism was used to determine the density profile and the interface thickness, l, defined as the distance between 10% and 90% of the density difference between the layers. Sodium Chloride solution beneath a layer of fresh water was used and $\Delta\rho/\rho$ was of the order of 0.001. Interface thickness was measured before the initiation of the sink flow. The time of the drawdown was computed from the plot of conductivity against time measured behind the sink (Fig. 2.9). The moment at which drawdown occurred was identified by a drop in conductivity indicating the initiation of the flow from the fresh water layer.

A best fit curve was drawn through data, the equation of which is given by, $\log F = -0.71 - 0.51 \log F_l^{-1}$, where $F = [q^2/g'h^3]^{1/2}$ (Froude number based on the lower layer depth) and $F_l = [q^2/g'h^3]^{1/2}$ (Froude number based on interface thickness). Given relationship indicates that $F \propto F_l^{1/2}$ which is in contrast with the linear relationship obtained by Jirka and Katavola (1979) for a point sink. A lower bound for the critical value of Froude number F was determined approximately to be 0.46 which is closed to the theoretical value of $F_c = (2/3)^{3/2} = 0.54$ given by Jirka and Katavola (1979). The finding that it is a lower bound suggests that the actual critical value of Froude number with an infinetesimal interface may be larger.

2.3 AXISYMMETRIC WITHDRAWAL THROUGH POINT SINKS

Works on vertical withdrawal through round hole (point sink) are described in this subsections. Vertical withdrawal are widely applicable to cooling water intake problem.

Davidian and Glover (1956), Harleman, Morgan and Purple (1959), Hino and Onishi (1969), Ho (1973), Lawrence and Imberger (1979), Goldring (1981), Onishi et al. (1982). Ivey and Blake (1983), Islam (1988) Zhou and Greabel (1990), Razzaque (1991) and Anwar (1995) have studied the vertical axisymmetric withdrawal. These works include both two-layered fluid system and continuous linear stratification.

2.3.1 Linear Stratification

Analytical and experimental data for axisymmetric withdrawal from linearly stratified fluid were provided by Ho (1973). His work yielded a self similar velocity profile and a withdrawal layer thickness growth at rate of $r^{1/3}$ where r is the radial distance from sink. Hino and Onishi (1969) studied this problem analytically for the performance of the location of the point sink in a linearly stratified fluid and obtained the critical Froude number, $F_{rc} = Q_o/(g'h^3)^{1/3} = 1.42$, where h is the half depth of the fluid, (sink at mid-depth). Onishi et al (1982) extended Hino and Onishi (1969) work to study the performance of the sink dimensions and reported that for sink radius less than h, no significant difference in the values of critical Froude number were observed; as the radius increased to 6h, however, so did the critical Froude number to approximately 7 times.

Lawrence and Imberger (1979) and Lawrence (1980) have demonstrated that for the case of axisymmetric withdrawal the flow field is modified and withdrawal layer is established by the passage of internal waves in an exactly anologous manner to 2-D line sink flow. However, in this case the waves are cylindrical with amplitude inversely proportional to the radius.

As in withdrawal through a line sink Raleigh number, R_a which is a combination of R_e, P_e and F_r, (section 2.1.1) describes the relative importance between viscous, inertia and buoyancy forces in the flow field. For a linear stratification and for $F.R_a^{-2/3} > 1$ (F and Ra based on L, the distance between the sink and the upstream wall) the flow in most of the tank is governed by inertia and buoyancy forces and the withdrawal layer thickness, δ is of order $(Q_o/N)^{1/3}$. Lawrence and Imberger (1979) suggested $\delta = 0.66\ (Q_o/N)^{1/3}$, Imberger (1980) quoted $\delta = 0.71\ (Q_o/N)^{1/3}$ from the works of Bohan and Grace (1973); finally Ivey and Blake (1985) reported $\delta = 0.71\ (Q_o/N)^{1/3}$. For $F.R_a^{-2/3} < 1$, when most of the fluid is governed by viscous and buoyancy forces, Ivey and Blake (1985) suggested that the withdrawal layer thickness, δ should be of the order of $(\nu Q_o/N^2)^{1/3}$ and quoted $\delta = 2.1\ (\nu Q_o/N^2)^{1/3}$ from their experimental observations.

2.3.2 Effect of Rotation on Selective Withdrawal

Monismith, Mcdonal and J. Imberger (1993) have worked on the axisymmetric flow of a rotating linearly stratified fluid into a point sink. Linear analysis of the initial value problem of flow of a linearly stratified fluid into a point sink that is suddenly switched on shows that a spatially variable selective withdrawal layer is established through the outwards propagation of inertial shear wave. The amplitude of this shear waves decays with distance from the sink. The flow reaches an asymtotic state, dependent on viscosity and species diffusion, in which the withdrawal layer structure only exists for distances less than the Rossby radius R = Nh/£, based on the wave speed of the lowest mode, where N is the buoyancy frequency, £ is the coriolis parameter and h is half depth of fluid (here N > £). Since there is no fluid azimuthal pressure gradient to balance the coriolis force associated with the radial, sinkward flow, a strong swirling flow develops. This swirl causes the withdrawal layer thickness to grow like $(£t)^{1/3}$ (t = time), such that eventually there is no withdrawal layer anywhere in the flow domain.

Robertson & Ivey (1983) who considered the possibility of selective withdrawing 4°C bottom water from Lake Ontario for use as cooling water to air conditioning Toronto in summer. But the so-called "FREECOOL" scheme would not work because rotation effects would greatly increase the vertical extent of withdrawal layer. The authors considered the analysis of Whitehead (1980), to simplify the analysis considering deceptively simple case of finite depth, infinite horizontal extent fluid domain. They start looking at the inviscid, linear initial value problem associated with impulsively initiating the sink flow. The resulting solution obtained by model expansions and Laplace transforms, shows the establish long inertial-internal waves, which can be dubbed inertial shear waves, by analogy with their non-rotating counterparts. The asymptotic solution form taken by the transient solution is not entirely expected in that it shows that the withdrawal layer vanishes at a distance of order Nh/£.

From their analysis they observed that "Rossby radii" is very important for selective withdrawal. In order to maintain any selectivity, the withdraw structure must be placed within one or two Rossby Radii of the lowest internal wave mode of the shore. In general, in order to have the ability to produce as narrow a layer as possible and so gain the maximum degree of control of the outflow, the structure should be positioned so as to prevent the development of swirl around the structure.

2.3.3 Effect of Location of Sink

Hino and Onishi (1969) studied this problem analytically for the performance of the location of the point sink in a linearly stratified fluid (Fig. 2.10) and defined densimetric Froude number as

$$G = \frac{Q}{2\pi\sqrt{g\beta d^3}}, \qquad \text{when} \quad \beta = \frac{\rho_o - \rho_l}{\rho_o d}$$

where ρ_o and ρ_l are the densities at the bottom and top of the pool respectively. They developed a mathematical model and predicted that the critical value of G_{cr} varies according to the location of the sink. To study the range of the value of G under which selective withdrawal of the stratified fluid is possible, they considered the point sink is located near by the mid depth of water. There may exist three different conditions of flow for different ranges of G.

i. If the rate of inflow is large enough or the stratification is enough, the whole portion of sink flows into the sink.

ii. When the rate of inflow is so small and or the stratification is so strong that the value of G is less than G_{cr}, the theoretical solution shows that stagnation zone begins to appear in the region of fluid above the sink in the case of $b < 0.5$ (below the sink in the case of $b > 0.5$). According to the inviscid fluid flow theory, the region of stagnant layer grows in the upper portion of fluid when the sink is located below the mid depth of water (in the lower portion of fluid for sink located above the mid depth of water) when the stagnant layer exists in the fluid, the depth flowing portion d, can be obtained from relation $G' = \frac{Q}{2\pi\sqrt{g\beta d'^3}}$ and G' is equal to G_{cr}.

iii. With further decrease in the value of G, the stagnant layer increases more and more in the depth, and a second critical condition at which the value $b' = bd/d'$ (or 1-b), becomes to be 0.5. Let denote the value of G at the second critical condition by a symbol of G_{cr}. Under the flow condition with the value of G less than G_{cr} these layers can exist in both the upper and lower portions of fluid. At the second critical condition the value of G was calculated taking $d' = 2db$ for the case $b < 1/2$ (or with $d' = 2\,(1-b)\,d$ for case $b > 1/2$) is equal to the value of G_{cr} for $b = 0.05$. This relation is described by

$$G_{cr(atb=0.05)} = \frac{Q}{2\pi\sqrt{g\beta\{2(1-b)d\}^3}} \qquad \text{for } b < 0.5 \qquad (2.11)$$

$$= \frac{Q}{2\pi\sqrt{g\beta\{2bd\}^3}} \qquad \text{for } b > 0.5 \qquad (2.12)$$

The numerical solution that they have got is shown in Fig. 2.11, it shows the relation between G_{cr} and location of sink. When a point fixed by G and b drops in the area numbered as 1 in Fig. 2.11, the stagnation layer exists in the upper portion of fluid and it is possible to withdrawn only from the lower portion of the stratified fluid. When the point said above in the area 2, the withdrawal of water only in the upper layer of stratified fluid is possible. If the value of G and the point sink location is selected so that the above mentioned point falls in the area 3, then only the water in the mid layer of fluid can be taken in, leaving both upper and lower stagnant layers.

2.3.4 Two-Layered Stratification

Harleman, Morgan and Purple (1959) investigated experimentally a two-layered system for the configuration as shown in Fig. 2.12(a). The main objective of this study was to investigate the performance of different types (sharp edge and rounded edge) of intake pipes and the results yielded a unique critical Froude number irrespective of size and shape of intake pipe when the intake diameter d varied from 0.3h to 1.5h. But for drawup case as shown in Fig. 2.12(b), Davidian and Glover (1956) reported a critical Froude number which is dependent on the size of the intake pipe when the intake pipe diameter vaired from 0.3h to 14h. These two experimental studies revealed that the size of the intake pipe will not affect the critical condition so long as the pipe diameter is small compared to the characteristic length, h.

For two-layered stratification, Ivey and Blake (1985) reported a drawdown height, (i.e. the height at which upper layer fluid is withdrawn) (Fig. 2.12) for the inertial regime ($F.R_a^{-2/3} > 1$) as $h = C_1 (Q_o^2/g')^{1/5}$ and for the viscous regime ($F.R_a^{-2/3} > 1$) as $h = C_2 (\theta_o/g')^{1/4}$. The analytical solution of Craya (1949) suggested $C_1 = 0.69$, Harleman, Morgan and Purple (1959) gave $C_1 = 0.826$ from their experimental results and Goldring 1981) reported $C_1 = 0.64$ from experimental studies with fresh and salt water. For the viscous dominated regime Blake and Ivey (1985) (quoted from Ivey and Blake (1985) obtained $C_2 = 2.1$ from their experimental results.

2.3.5 Effect of Intake Shape

Razzaque (1994) investigated the effect of shape on the percentage drawdown. He worked with three types of intake they are plain, rounded and portruded intakes. The results that he has got is that for the same intake Froude number, rounded intakes reduces the percentage drawdown based on critical height of the mean interface measure from the intake level. Sharp protrusion reduces this height further.

2.3.6 Effect of Sink Level

Anwar (1995) investigated the effect of sink level on the percentage of drawdown. He worked with four different intake height levels and got the condition that for $EX/H \geq 0.2$ the value F_d and F_l has less significant effect on drawdown history of fluid, rather in such state the effect of densimetric Froude number becomes notable.

2.3.7 Effect of a Cap

The effect on a bottom withdrawal through a circular pipe has received much less attention for the case of two-layered fluid system under slack water conditions, Goldring (1981) has provided the single set of experiments available in the literature which served to dimensions the beneficial effect of the cap on the critical withdrawal situation.

The presence of the cap does exert an influence on the internal waves and acts to produce significant local distortions in the flow above the cap (Islam, 1988). The experimental data by Goldring (1981) and the numerical predictions by Islam (1988) were found to be in good accord with the semi-empirical equation by Goldring.

$$\frac{h_c}{S} = 0.26\left(\frac{S}{R_c}\frac{Q}{\sqrt{g' s^5}}\right)^{2/3} \tag{2.14}$$

where S and R_C represent the cap height and cap radius respectively. According to equation (2.10), h_C in independent of S but varies inversely with two third power of R_C. But numerical prediction by Islam showed this statement to be invalied except for some limited conditions.

2.3.8 Computational Verification: Miscible Two Layers:

The experimental program of Goldring (1981) consisted of 4 runs for the plain hole case and 17 runs in 5 series for the capped hole case. The diameter of the cylindrical vessel containing the initially stratified fluid was 236 mm and the withdrawal hole diameter (centrally located) was 18.8 mm in both cases. For the capped hole runs, the cap radius, $R_C = (d_C/2)$ varied from 9.4 mm to 20 mm whereas the cap height, S varied from 4 mm to 6.2 mm. In computational work of Islam (1988), all the experimental runs were simulated in the calculations initiated at time t = 0 when the intake hole at the bottom was opened. Uniform exit velocity and approximately 2 mm thick pyonocline were assumed. All the tests surface mode and hence the solution domain was also adjusted continuously match the physical domain size.

The critical interface height was identified by observing the motion of neutrally buoyant dye spots placed at the initial interface height, when the first of these entered the intakes the experiment was terminated and the lower layer depth at the cylinder was taken as critical interface height. Islam (1988) simulated this by tracking the locus of an originally horizontal line of neutrally buoyant particles placed at the interface height (x at $\theta = 0.5$) until one particle left the solution domain; the height of the particles far away from the intake was then taken as the predicted critical height. All the predicted and experimental data were shown to be in good agreement with Goldring's (1981) correlation,

$$\frac{h_c}{d} = 0.64\left(\frac{Q^2}{g' d}\right)^{1/5} \tag{2.13}$$

This equation reveals that the critical height is independent of hole diameter and varies linearly with the one fifth power of (Q^2/g') as was also obtained by Ivey and Blake (1985) for the inertia dominated regime. But this findings is in contrast with the Davidian and Glover's (1956) experimental correlation for the range $0.3 < d/h < 14$ showing the dependence of critical interface height on intake diameter. About 30% higher value for the constant of proportionality of equation 2.9 was reported by Harleman et al. (1959) from there experimental studies. In Harleman's experiment the interface height was kept constant by recirculating the lower layer fluid and the critical intake flowrate corresponding to the given interface height was recorded by increasing the flow rate until the interface was pulled down to the hole (Fig. 2-13).

Numerical prediction of withdrawal ratio indicated that a smaller amount of mixed fluid is withdrawn (i.e. lower λ) as the critical height and hole diameter increases. This is due to the sharper drawdown cone for higher h_c and d.

2.3.9 Computational Verification: Immiscible two-layers:

The axisymmetric withdrawal of both one and two-layered fluids from a circular tank has been studied analytically and experimentally by Lubin and Springer (1967), who found a relation between the critical height, the drain rate and the density ratio. They observed that the drain rate is nearly constant throughtout the draining process until a dip is formed. The formation of the dip was so quick that it appeared to extend into the sink almost instantly. The analytic formula obtained by Lubin and Springer is in excellent agreement with their experimental data, in spite of the fact that only the Froude number based on the drain rate (assumed to be constant) and the density ratio are included.

Zhou (1989) studied this problem numerically and found for the one layer fluid case that when a dip forms, the computed critical heights agree with Lubin and Springer's analytic solution only for moderate values of the Froude number. For large Froude number the computed values are consideration smaller than their analytic values. The discrepancies increased with the Froude numbers and varied with sink sizes and initial depth of the free surface. For the two-layered fluid case the differences are even larger. It was also found that there are strong free surface oscillations as predicted theoretically by Saad and Oliver (1964) and Zhou and Graebel (1989).

For both one and two-layered fluid cases, Zhou and Graebel (1989) investigated numerically the axisymmetric evolution of a free surface and an interface in a circular tank under a constant draining rate through a concentric hole at the bottom. Froude number was defined as $F_R = (Q^2/gR^5)^{1/2}$, where R stands for the tank radius and is the normalizing parameter. In case of one layer fluid the effect of dimensionless parameters controlling the flow, i.e. Froude number, F_R, normalized initial depth of free surface, Ho and the normalized sink radius, **a** was analyzed. It was found that the free surface configuration was nearly independent of initial free surface height, Ho for same F_R and a, until Ho $\geq$ 1. For same a and Ho, a sufficiently large value of F_R (say larger than 1.0) can suppress the drainage initiated free surface oscillations. In the case of a small mean level of the free surface, similar final surface configurations may be occurred despite different motion histories; because of the quick damping out of the existing oscillation by the dominating sink influence. For same Ho and small F_R (say = 0.1), a smaller a results in a greater drawdown of the free surface. Equivalently, one can say that a more concentrated drawdown force overcomes the squeezing of the near-centre surface points by the off-centre surface points and a pulling down of the centre of the free surface. Thus a sufficiently small **a** can give rise to a dip (Fig. 2.10) whereas if **a** is not sufficiently small, the squeezing together of the near-centre surface points decelerates the centre and consequently a reverse jet is formed (Fig. 2.15) when a dip is about to form, the surface velocities near the centre are dominant while those away from the centre are small (Fig. 2.16). This is the kinematic reason why the dip develops so rapidly. But when a reverse jet appears, the maximum surface velocity occurs at the trough of the free surface. If the trough velocity is sufficiently large, the centre must be pushed upward owing to the strong compression, hence a reverse jet will form. The effect of Ho on whether a dip or a jet forms is similar to that of **a**. A weak jet occurs when the initial depth Ho is large and the drainage initiated free surface oscillations occurs in the early stage of the motion.

For the two-layer fluid case, where only slight stratification exists, (say density ratio = 0.9) the free surface undergoes severe oscillations when a dip forms on the interface (Fig. 2.17). But for a large stratification (say density ratio = 0.5), the free surface shows the sign of travelling waves when a reverse jet forms on the interface (Fig. 2.18). The physical mechanism as to why different values of stratification cause quite different surface motion, was explained by the interfacial vorticity when a dip develops on the interface, the vortex strength near the centre is negative, which aids in pulling the centre of the interface into sink. The negative vortex strength indicate, that the inward (pointing toward the centreline) tangential velocity of the upper fluid on the interface is greater than that of the lower fluid on the interface. When a jet forms, the vortex strength is positive everywhere, indicating that particles of the lower fluid on the interface move towards the centreline faster than do upper fluid particles on the interface. It has been assumed in simple analytic analysis (e.g. Lubin and Springer (1967) and Harleman et al. (1959)) that the pressure on an interface is approximately hydrostatic. But numerical results showed that this assumption is no longer correct after an appreciable depression occurs on the interface.

2.3.10 Drawdown History

In case of two-layered fluid systems, Jirka and Katavola (1979), studied the supercritical withdrawal behaviour including the effect of finite size intakes and finite ambient pycnocline widths. By defining pycnocline width l as the distance between the 10% and 90% value of the density difference and the interface position h as the distance between the intake centreline and 50% value of the density difference, three independent Froude numbers were defined as,

$$F_r = \frac{Q}{\sqrt{g' h^5}}; \qquad F_D = \frac{Q}{\sqrt{g' d^5}}\left(\frac{4}{\pi}\right) \text{ and } F_l = \frac{Q}{\sqrt{g' l^5}}$$

For the supercritical flow, a withdrawal ratio λ is defined as, $\lambda = (Q_l/Q)$, where Q = total flow and Q_l is the flow from upper layer. The tests were conducted in a temperature insulated tank 1.52 m long 1.32 m wide and 0.91 m deep. The intake opening was located 0.30 m above the tank bottom on the centreline of one of the tank walls. Variable intake openings from 5.3 mm to 37.2 mm wide were used. The intake flowrate was measured with precision rotameters and varied between 3.6 lpm to 27 lpm. The density stratification was produced with heated water. Temperature differences between upper and lower layer ranged from 14.3°C to 23.3°C which represents values of $\Delta\rho/\rho$ from 0.0032 to 0.0063. The thickness of the thermocouple region, l, varied between 8.6 cm and 16.3 cm. The temperature distribution within the tank and the intake was measured by 66 thermistor probes with ± 0.05°C accuracy and 7 sec time constant. The entire probe set was connected to a first-scanning digital recording system with a scanning rate of above 0.7 sec per probe.

All experiments were in falling interface mode while the total water depth stayed constant by an inflow of warm water at the same rate of discharge. Temperatures were monitored continuously throughout the experiment to determine the instantaneous withdrawal ratio $\lambda(t) = (T_i - T_2)/(T_1 - T_2)$, where T_1 and T_2 are the average upper and lower layer temperatures respectively and T_i being the instantaneous temperature at the intake.

Sixteen withdrawal experiments were carried out with the ranges $F_D \sim 1$ to 437 and $F_I \sim 0.05 - 0.33$. In all experiments it was found that a small degree of withdrawal ($\Lambda > 3\%$) consistently occured even at values of F_r well below the incipient condition. Interfacial viscous effects and ambient diffused interface were suspected to be responsible for it. The withdrawal curves (λ vs. F_r) provided the value of critical Froude number Fr and these curves are approximately symmetrical about the $\lambda = 0.50$ axis (Fig. 2.19). It was found that increasing values of either F_I and F_D increases the value of Fr_c. The observed values of F_{rc} ranged from 0.05 to 0.27 which are much less than Craya's theoretical limiting ($F_D \rightarrow \infty$, $F_I \rightarrow \infty$) value of $F_{rc} = 2.54$. This deviation was perhaps due to the lower value of F_I (i.e. the diffused interface) in the order of 10^{-1}, which was in the order of 10^3 in Grariel's experiments. A best fit expression for approximation of Frc values in the experimental range was determined to be $F_{rc} = 0.06 \log F_D + 0.64 F_I - 0.05$ which was in moderate agreement with the experimental data. $\lambda = f(Fr/Fr_c)$ plot of all experimental data having a moderate amount of scatter suggested that the withdrawal characteristics in the supercritical range can be represented by a unique empirical curve independent of geometric effects. The equation of this curve is given by,

$$\lambda = 0.142 \log (F_r/F_{rc}) \qquad \text{for } F_r/F_{rc} < 300 \qquad (2.15)$$

$$\lambda \doteq 0.50 \log (1 - F_r/F_{rc})^{-0.22} \qquad \text{for } F_r/F_{rc} < 300 \qquad (2.16)$$

Wood [1978] presented an elegant theory giving the relationship between F_r and λ. Lawrence [1980] extended Wood's theory to the case of two-layered fluid with a linearity stratified lower layer withdrawn through a special type of point sink. Experimental verification provided the drawdown history data without giving any satisfactory proof to the proposed specific demarcation of the flowing zones as a function of Froude number.

2.4 AXISYMMETRIC WITHDRAWAL FROM A TWO-LAYERED SYSTEM WITH CROSS-FLOW

A 3-D version of a real life cooling water intake system was simulated experimentally by Islam (1988) for withdrawal from a thermally stratified two-layered fluid in a unidirectional cross-flow without any wind shear on the free surface. Goldring (1984) has however provided only data on critical heights and drawdown behaviour under these conditions. The Reynolds number of cross flow was high [O(1000)] so that it become turbulent and drawdown behaviour was observed to be dependent also on the inlet (cross-flow) Froude number defined as $F = U/(g'H^5)^{1/2}$, where U is the cross-flow velocity and H is the total depth of flow. Computational predictions and their verifications are available in Islam (1988).

CHAPTER-3

EXPERIMENTAL SET-UP AND PROCEDURE

3.1 INTRODUCTION

The objective of this experimental work is to investigate the effect of cap over a sink on the drawdown of water from two-layered stable hot and cold water body. Recently, Razzaque (1994) and Anawar (1995) has worked on a similar field. They investigated the effect of intake geometry and sink location respectively on the drawdown. The experimental set-up used by Anawar is taken with slightly changed condition. The procedure of calculation was same to both of them. In the following subsections, a brief description of experimental set-up and procedure is provided.

3.2 THE TEST RIG

The test rig consists of experimental tank, feeder tank, mechanism for hot water supply, provision for withdrawal of water, temperature measuring device, traverse mechanism. A brief description of these items are given below.

3.2.1 Experimental Tank

All experiments are conducted in a square tank made of perspex sheet of 6.0 mm thickness and of inside dimension is 1210 x 1210 x 530 mm (Fig. 3.1 and 3.2). The sheet were joined by silicon glue. The tank are further reinforced by double steel frame. The tank is placed 1700 mm above the ground on a rigid steel frame. The middle point is chosen to avoid the effect of the side walls and the tank is made so large square that it may be assumed to be round. Then the flow may be considered axisymmetric. The round hole at the ground level of the tank, where intake is placed as encirled by cast iron ring, so that the base is free from all possible cracks. The intakes those are used for experiments are inserted into this intake (attached with tank) with some special attachment, discussed later. A measuring scale is attached on one vertical side of the wall to measure the vertical height of the water in the tank. Water is drained out through 42 mm dia pipe and out of water from tank is controlled by a globe valve placed on this draining pipe. This draining pipe also contains the three thermocouple sets, placed at a distance of 400 mm from the bottom of the tank.

3.2.2 Feeder Tank:

To ensure uniform and turbulence free flow of hot water into the experimental tank, a feeder tank (Fig. 3.1 and Fig. 3.2) of size 1115 mm x 38 mm x 64 mm is used. It is placed into the experimental tank (adjacent to one of vertical wall) at a desired height from a steel bar placed on the main tank. A number of spherical glass balls kept into the feeder tank, so that any turbulence in the water from hot water flow is damped out. Water is fed into the feeder tank from a hot water tank placed at a height of 600 mm from bottom of the experimental tank, through four flexible pipes. These four pipes are equally spaced so that uniform flow of water prevails along the feeder tank.

3.2.3 Hot and Cold Water Supply:

Hot and cold water supply are required to make two layered fluid system. Cold water is supplied from the "Supply Water" line, i.e. cold water is at ambient temperature. For hot water, water heaters are used to heat the water. The heaters are of three 2 kW immersion heaters placed at the bottom of heater tank. The heater raises the water temperature by 8^oC to 15^oC above ambient. Water is then stirred by a rod manually for mixing properly as a uniform temperature water body and then the water is pumped into hot water reservoir at a height of 2300 mm from the ground.

3.2.4 Selection of Sink:

During the entire experimental work; point sinks are placed at the bottom of the main tank with the cast iron ring with slight pressure that permits no leakage. There are four different sinks are used: one is plain intake for verification of experiment with previous work and other three intakes are of capped. The cap is inserted by equally spaced three metal legs on conical rubber holder and the intake pipe of 18.8 mm passed through the rubber holder. The typical intake system of sink are shown in Fig. 3.3. The diameters of the caps have three different ratios (1.5, 2.5 and 3.5) with intake pipe diameter. All three cases, the gap between cap and the intake pipe is kept constant i.e. equals to diameter of the intake pipe throughout this investigation.

3.2.5 Formation of Two-Layered System:

Formation of two-layer is one of the most important work of this investigation. In all the experiments two layer is developed by using hot and cold water. Hot and cold water have a difference of temperature of about 8°C to 15°C and thus these two fluids have density differences as a result they form a two-layer. Initially, cold water is pumped into the experimental tank up to the height of the feeder tank, the heaters are turned on and they take several hours for heating to attain the desired temperature and during this long time water in the experimental tank becomes free from all sorts of circulations, vibrations or rather in short, from all sorts of disturbances. When hot water temperature rises to a desired temperature is delivered to the feeder tank and is allowed to overflow slowly to form two-layers with minimum interface thickness between them. Warm water from the hot water reservoir is discharged at four locations into marble layers of the feeder tank by means of four flexible PVC Pipes and as a result the disturbances are damped out. Flow rate of hot water is kept low to achieve minimum mixing with cold water.

3.3 MEASURING DEVICES AND MEASUREMENT PROCEDURE

3.3.1 Water Flow Measurement:

In all calculations, flow rate through sink is based on falling height method. This is done by measuring time of fall of water column from the tank of constant cross-section. One might argue that water flow rate might vary due to fall of the height of water. But here the tank is located at sufficiently high elevation and gravitational force is the driving force for the water fall. Water in all the experiments is about 200 mm only and such little fall in water column, the variation of water flow rate with respect to the average flow rate is not so much significant for such kind of experimental work.

3.3.2 Temperature Measurements:

Water temperature is measured by means of Alumel-Chromel (K-type) thermocouple through "Omega" digital output thermometer with accuracy of 0.1°C. This thermometer is calibrated with highly accurate mercury thermometer (Fig. 3.4).

a. Measurement of Interface Thickness:

Most of the recent works (Jirka and Katavola, 1979) suggests that pycnocline region of width l is the height difference between 10% and 90% value of the density difference and interface position "h" is defined as the height difference between intake center and 50% value of the density difference. Depending on that principle, the instantaneous interface position calculation will be represented next. This density difference can be measured on different ways like conductivity measurement, temperature, measurement etc. For this work temperature measurement technique is used for density measurement of water at different location of the tank. The reason for selecting temperature measurement technique is that temperature measurement is very easy, and the temperature of the fluid has linear relationship within the maximum and minimum temperature of this work (temperature range of this work is 18°C to 47°C). Density of water is related to the temperature via. the following polynomial.

$$\rho = 266.5 + 6.466\,(T+273) - 0.01788\,(77273 + 0.0000148\,(T+273)^3 \qquad (3.1)$$

Where, T is the temperature in celcious and ρ is the density in kg/m^3. Equation 3.1 is a curve fit to $\rho(T)$ data given in Batchelor (1980) and Islam (1988). This is plotted in Fig. 3.5 and from the figure it is clear that within the working range of temperature of this work, the density profile is linear with temperature.

A digital Omega thermometer used to record the temperature measured by K-type thermocouple. The thermocouple is mounted on a traversing unit with precision $\pm$ 0.1 inches and temperature profile is measure by recording direct temperature reading of the thermocouple at different vertical locations. The normalized temperature ratio, Q is plotted against vertical location and it is defined by following equation,

$$\theta = \frac{T - T_2}{T_1 - T_2} \qquad (3.2)$$

where subscript 1 and 2 corresponds to upper and lower layers respectively and T denotes the local temperature, Fig. 3.6 shows a typical temperature profile. The height corresponding to $\theta = 0.5$ was taken as mean interface height (h) and the interface thickness (l) is determined by taking the difference between the elevations corresponding to $\theta = 0.1$ and 0.9.

b. Measurement of Drawdown Fraction (λ) and percentage Drawdown (Λ):

Drawdown fraction is defined as the ratio of fluid volume drawn from the upper layer to the total volume flow and as represented by λ, i.e.

$$\lambda = (Q_l / Q) = Q_l / (Q_l + Q_2) \tag{3.3}$$

Where Q_l and Q_2 are the inflow from the upper and lower layer respectively. If the discharged fluid can be mixed sufficiently so that it may be considered as a homogeneous fluid, its density would be in between the densities of both layers. It is obvious that this density will be an indication of the proportion of the fluid volume drawn from the upper layer. If the density of the mixed fluid past the intake is ρ_m then

$$\lambda = (\rho_m - \rho_2) / (\rho_1 - \rho_2) \tag{3.4}$$

Now for the small temperature range (18°C - 47°C) of the present experiment the relationship between density and temperature may be assumed approximately linear (Fig. 3.5) and the equation (3.5) takes the following form,

$$\lambda = \frac{T_m - T_2}{T_1 - T_2} \quad and\ \Lambda = 100\lambda \tag{3.5}$$

where T_m is the temperature of mixture, T_1 and T_2 are average temperature of fluid of top and bottom layer respectively.

Three K-type thermocouples are placed at approximately 400 mm below the intake. The middle one is used while recording the actual reading and the rest two are used only for checking if mixing of the outgoing fluid is adequate or not. To ensure proper mixing the discharge is passed through two inclined filter nets and then through a funnel before the temperature is sensed by thermocouple (Fig. 3.7). The inclined net on both sides of filter and funnel helps in creating disturbances for proper mixing of the fluid. Comparison of the thermocouple readings confirms the attainment of adequate homogenity in temperature of the fluid at the location of measurement. Measurement of temperature of outgoing water is done by Omega digital thermometer. Output temperature versus time at any time interval can be recorded on a paper sheet. From the experience of few runs, the data is recorded on 20 seconds of interval with accuracy of 0.1°C. Then this data is inserted into computer with other data format sheet for calculation with fortran program. For temperature recording in current work the maximum possible time, which the water requires to reach the thermocouple is around 2.5 seconds, but selected time interval is kept 20 seconds.

3.4 EXPERIMENTAL PROCEDURE

Initially a sink is inserted to the experimental tank (procedure described earlier) and the tank is filled with isothermal water at temperature T_2 and hot water is introduced at T_1 in the tank as mentioned in section 3.2.5 to form two layers. After formation of two layers, the interface thickness and the height of interface are measured according to the procedure described in section 3.3.2(a). Next the sink and Omega thermometer are turned on simultaneously to record the temperatures of the water at outflow. Then data format sheet is prepared on computer. The required fluid dynamic variable described in section 3.6 and also from value of λ, instantaneous mean height, h_i is measured by calculation procedure followed in FORTRAN77 program is represented in section 3.5.

3.5 INSTANTANEOUS HEIGHT FROM DRAWDOWN

Applying conservation of mass for incompressible fluid makes problem of volume conservation.

From figure 3.9a

$$q_i - q_o = C\frac{dh(t)}{dt}$$

(oftenly used in control engineering)

Here $q_i = 0$, $q_o = q(t)$ $C = A$

$$A\frac{dh(t)}{dt} + q(t) = 0$$

Next applying the similar principle on different control volume in case of hot part of two-layer body.

From figure 3.9b

$$C\frac{dh'(t)}{dt} = q_{i1} - q_{o1}$$

Here C = A (cross section area of experimental tank)

$h'(t) = h(t) - h_i(t)$

$q_{i1} = 0$

$q_{o1} = q_1(t)$

So, $A\frac{d}{dt}\{h(t) - h_i(t)\} = -q_1(t)$

$$=> A\frac{dh(t)}{dt} - A\frac{dh_i(t)}{dt} = -q_1(t) \qquad (3.7)$$

Now from definition of drawdown

$$\lambda(t) = \frac{q_1(t)}{q(t)} \qquad (3.8)$$

From equation (3.7) and (3.8) we have

$$A\frac{dh(t)}{dt} - A\frac{dh(t)}{dt} = -\lambda(t)\,q(t) \qquad (3.9)$$

Now from equation (3.6) and (3.9) we have

$$-q(t) - A\frac{dh(t)}{dt} = -\lambda(t)\,q(t) \qquad (3.10)$$

Then the equation (3.10) is discretized by finite difference method considering it as initial value problem, at t = 0, $h_i(o)$ = H (inface height measured just before the experiment start). And we have,

$$A\left\{\frac{(h)_{i+1} - (h)_i}{\Delta t}\right\} = -\{1 - \lambda_i(t)\}q_i(t)$$

$$=> (h)_{i+1} = \frac{-\{1 - \lambda_i(t)\}q_i(t)\Delta t}{A} + (h)_i \qquad (3.11)$$

where $$q_i(t) = q = \frac{Ah}{t}$$

$$\lambda_i(t) = \frac{T_m(i) - T_2}{T_l - T_2}$$

3.6 CALCULATION OF F_r, F_d, F_l

The literature review follows that the Froude number emerges as the primary similitude parameter for this type of flow. Three types of Froude number are used in calculation and they are defined as,

densimetric Froude number, $$F_r = \frac{Q}{\sqrt{g' h^5}} \tag{3.12}$$

intake Froude number, $$F_d = \frac{Q}{\sqrt{g' d^5}} \tag{3.13}$$

and interface Froude number, $$F_l = \frac{Q}{\sqrt{g' l^5}} \tag{3.14}$$

where

Q = average flow rate

h = instantaneous interface height from the intake level

d = intake diameter

l = interface thickness measured just before the onset of the withdrawal

The value of g' indicates the effect of gravity. A heavier fluid flowing beneath a lighter fluid will be subjected to gravitational effects which depend upon the difference between the two specific weight rather than upon the absolute magnitude of the specific weight of the heavier fluid. The less dense fluid may then be regarded as if it were weightless and the more dense as if it were subjected to a reduced gravitational acceleration of magnitude

$$g' = \frac{\rho_2 - \rho_1}{\rho_2} g = \frac{\Delta\rho}{\rho_2} \tag{3.15}$$

This effective gravitational acceleration is used in all calculations and the value of ρ is determined from equation (3.1). The magnitude of g was assumed to be 9810 mm/sec^2.

CHAPTER-4

EXPERIMENTAL RESULTS AND DISCUSSIONS

4.1 INTRODUCTION

The aim of this experimental investigation is to investigate the effect of cap on the consequence of effect of the ratio of cap diameter to it's separation height from intake on percentage of drawdown. Most recently, Anawer [1995] and Razzaque [1994] had worked on similar field and studied the effect of sink location and intake shape on drawdown respectively. They found that drawdown is effected greatly by location and shape of the sink respectively. In the present experimental work, the sink diameter is kept nearly constant throughout the investigation. The ratio of cap diameter to its separation is varied for three different cases (but for every case separation height is kept constant). For each case nine different flow conditions are imposed as twenty seven experimental runs were made for drawdown effected by cap.

4.2 VERIFICATION OF DATA WITH SOME OF THE PREVIOUS WORK

In the present experiment first nine runs (except twenty seven runs described earlier) is taken as plain intake condition described by Razzaque [1994] for verification. The Table 4.1 and corresponding plotting (Fig. 4.2b) from Razzaque's and present work is compared. From this observation it is clear that two experimental results have excellent agreement with each other.

Jirka and Katavola [1979] worked on similar field. From their work it was clear that at $\Lambda = 50\%$, F_r increases rapidly which is also observed in the current experiment shows an agreement with previous work (Fig. 4.2a).

Also first nine data sets have excellently agreed with equation

$$\frac{h_c}{d} = [(0.784 - 1.33\lambda)/F_l + 0.3766\lambda^{-0.295}]F_d^{\,0.4} \tag{4.1}$$

which is a correlation as outcome of Razzaque's [1994] work (Fig. 4.2b).
Although through equation (4.1) it is told that h_c/d is proportion to $F_d^{0.4}$ as other parameter remains silent. This verification is furtherly verified through Fig. 4.2c and Fig. 4.2d as Harleman [1959] and Goldring [1981] also recommended.

4.3 EFFECT OF INTAKE FROUDE NUMBER (F_d) ON PERCENTAGE OF DRAWDOWN

Intake Froude number must play a vital role on the percentage of drawdown. Harleman [1959], Goldring [1981], Razzaque [1994], Anawer [1995] studied the effect of intake Froude number on drawdown. All of them reported that F_d is a vital parameter for the prediction of drawdown. Fig. 4.3a, 4.3b and 4.3c clearly portrays the sharp distinction of the critical heights on Intake Froude number in three different capped cases d_c/S = 1.5, d_c/S = 2.5 and d_c/S = 3.5 respectively. From the figures higher intake Froude number remarks higher non-dimensional critical heights (h_c/d). This phenomenon are analogous to both Razzaque [1994] and Anawer [1995]. Hence non-dimensional critical heights are also proportional to two-fifths power of intake Froude number as other fluid dynamic parameters remain constant.

Also higher critical height is analogous to the lower of drawdown. This phenomena can be explained with a little consideration. As $F_d = Q\sqrt{g'd^5}$; hence Q is the parameter that govern the flow (more accurately measures velocity of flow), g´ is the parameter that govern the stratification (more accurately acts as strainer for hotter fluid of upper region) and d is the intake parameter that measures amount of passage for fluid flow. If one does not consider about Q and g´ as those effects are common for varied Froude number specified in this experiments; only considering d, lower value of d means higher value of F_d. Also lower value d means narrower passage for the flow. So less amount of higher temperature fluid will get permission to cross through interface layer and as a result less drawdown will be observed. That means higher F_d dominates to lower percentage of drawdown. In this experiment, critical heights are defined in correspondence with drawdown as denoting mean interface height. That means every drawdown (percentage of drawdown) has it's characteristic critical heights. From the definition of critical heights, it could be easily realized that higher drawdown would be observed for the response of lower critical heights. So on this aspect a general comment is higher critical heights (non dimensional) means lower drawdown.

As a result from the above discussion; two relations can be observed; one is - critical heights increase as increase of intake Froude number and other is - critical height increases as drawdown decreases. So the summary is less amount of drawdown will be observed for higher intake Froude number.

4.4 EFFECT OF d_c/S ON DRAWDOWN

The main cause of drawdown is the overcome of buoyant force by inertia. Certain amount of kinetic energy is required to overcome the certain amount of buoyant potential barrier due to stratification on the consequence of classical energy conservation principle. That is why higher flow means higher drawdown if other governing parameters remain unchanged in case of cap free intake.

In the cases of capped intake similar ideology must be adapted but extra consideration must have to be taken. Cap works in favour of higher stratification in different way causing a barrier on free flow. As diameter of the cap measures the amount of barrier, indicates lower amount of drawdown. If one wants to measure critical height keeping same drawdown, one will observe lower critical height with respect to cap-free condition. So to reduce critical heights, the cap size or cap diameter with respect to separation height or intake diameter must be increased (which can be a tool for water quality management for selective withdrawal). The observed Fig. 4.4a to 4.4c verifies the above intrusion. Also it is possible to express a relationship quantitatively through keen observation and iteration. This relation is -

$$h_c \backslash d = \left\{(0.784 - 1.33\lambda) / F_l + 0.3766\lambda^{-0.295}\right\} F_d^{\,0.4} \times \exp\{-1.07(d_c / S)\}.\{1 + (d_c / S)^{2.5}\} \qquad (4.2)$$

4.5 DEPENDENCE OF THE DENSIMETRIC FROUDE NUMBER WITH d_c/S

Densimetric Froude number is the function of flow rate, instantaneous interface height from intake and nature of density stratification. Hence Fig. 4.5 consisting of four curves of similar F_d and F_l are compared. It is observed that there is no regular occurrence with d_c/S and all four curves are nearly similar. So there exist less effect of d_c/S on F_r. Values of F_r in relation with drawdown is irrelevant in all four cases.

4.6 EFFECT ON INTERFACE FROUDE NUMBER WITH DRAWDOWN

Interface Froude number describes nature of stratification more significantly than any other Froude number. Considering flow rate to be constant, the interface Froude number describes nature of stratification only. Nature of stratification indicates two different meanings. One is density gradient that is always present in any other Froude number and other is interface thickness which is only contained by this Froude number.

For firstly, density gradient - higher density gradient dominates to higher buoyant acceleration results lower Froude number.

So higher inertia or flow rate will be required to be withdrawn from less denser fluid region, which consequently reduces the percentage of drawdown (described different way earlier) of the same flow rate. So higher density gradient dominates lower draw down. This means, reduced intake Froude number causes less drawdown.

For secondly, in case of interface thickness; higher interface thickness offers lower interface Froude number. As interface thickness shows higher means higher amount of stratified potential barrier permits less hotter fluid through interface. So less drawdown will be observed. Higher interface height is responsible for lower drawdown. That is reduced intake Froude number causes reduced drawdown.

So both way less interface height dominates to lower drawdown. But the effect of F_l is not so significant over F_d. Increased F_d means increased drawdown discussed section 4.3. For this Figure 4.6a to 4.6d are agreement with in vapor with F_d. As F_d increased higher drawdown observed in less F_r.

But the effect of F_l is not so significant over F_d. Increased F_d means increased drawdown discussed section-4.3. From the figures 4.6a to 4.6d are agreement with in favour with F_d. As F_d increased higher drawdown observed in less F_r.

CHAPTER - 5
CONCLUSIONS AND RECOMMENDATIONS

5.1 INTRODUCTION

The objective of this work is **"AN EXPERIMENTAL INVESTIGATION OF SELECTIVE WITHDRAWAL FROM A TWO LAYER FLUID BODY"**. The results and discussions are presented in previous chapter. But focusing the memorable points and concluding remarks here to be refreshed only on the following sub-sections as well as future extension of this work.

5.2 CONCLUSIONS

Twenty seven **"experimental run"** are carried out at three different cap size with nine different flow condition in each case. From this experimental data it is evident that cap size on sink plays an significant role on the drawdown history. Except twenty seven run, more nine experimental runs were taken for verification with previous as plain intake of Razzaque's works. This data gives more idea for comparison of hood free or cap free condition except verification. In different cap size, effect of F_l or F_d are significantly observable with a natural harmony on drawdown history; whereas densimetric Froude number F_r becomes the governing parameter in controlling the drawdown history. A brief summary of concluding remarks of this work are followed as-

1. The percentage of drawdown is decreased with increase in intake Froude number if other deciding parameter remains fixed.
2. The percentage of drawdown is decreased with increase of the ratio (d_c/S).
3. Densimetric Froude number is independent on (d_c/S).
4. Less interface Froude number dominates to lower percentage of drawdown.
5. A generalized correlation
   $h_c \setminus d = \left\{(0.784 - 1.33\lambda) / F_1 + 0.3766\lambda^{-0.295}\right\} F_d^{0.4} \times \exp\{-1.07(d_c / S)\}.\{1 + (d_c / S)^{2.5}\}$
   is established.

5.3 RECOMMENDATIONS

Following recommendations are made for future work:

1. The present work may be extended by varying the ratio of hood or cap diameter to it's height from sink (d_c/S), diameter of intake, height of bottom layer, thickness of stratified layer etc. to investigate the effect on drawdown history.

2. A more generalized correlation is found among percentage of drawdown and intake Froude number. Interface Froude number, densimetric Froude number and ratio of cap size to it's separation from intake may be established.

3. The parameter involved in the real flow such as topographical effect, wind shear and heat loss at the free surface, steady and unsteady cross flow, multiple intake system etc. can be included in the experiments.

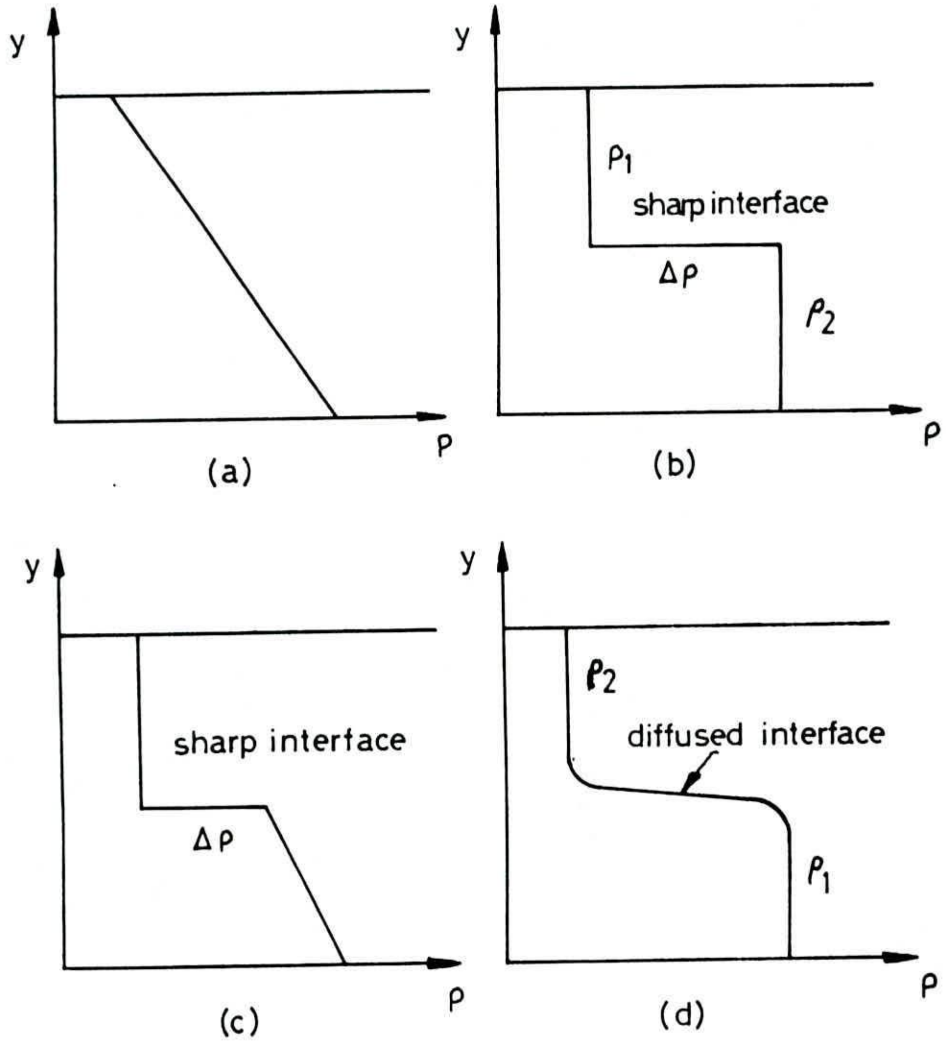


Figure 1.1: Typical stratification, (a) linear (b) two homogeneous layers with a sharp interface, (c) upper layer homogeneous and lower layer linearly stratified with a sharp interface, and (d) two homogeneous layers with a diffused interface.

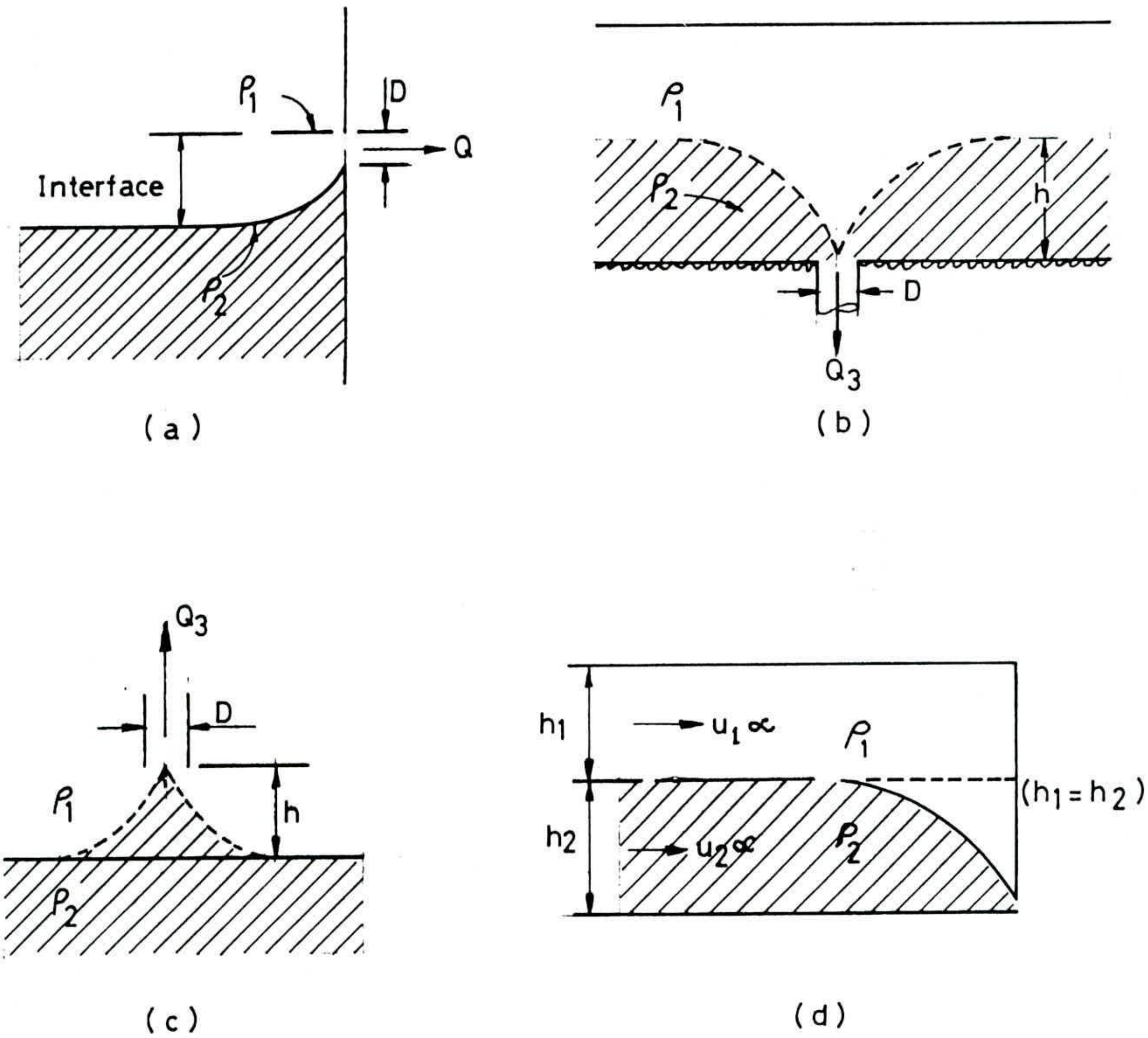


Figure 1.2: Selective withdrawal of fluid from a two-layer system: Critical Froude numbers (as defined) for various boundary conditions, (a) Orifice or slot in end wall, $F_{crit} = 2.6$ (orifice), 1.5 (slot) (b) Orifice in bottom $F_{crit} = 1.6$, (c) Large above interface $F_{crit} = 4.5\ (D/h)^{1/2}$, (d) Slot in corner (Huber, theoretical) $F_{crit} = 1.66$.

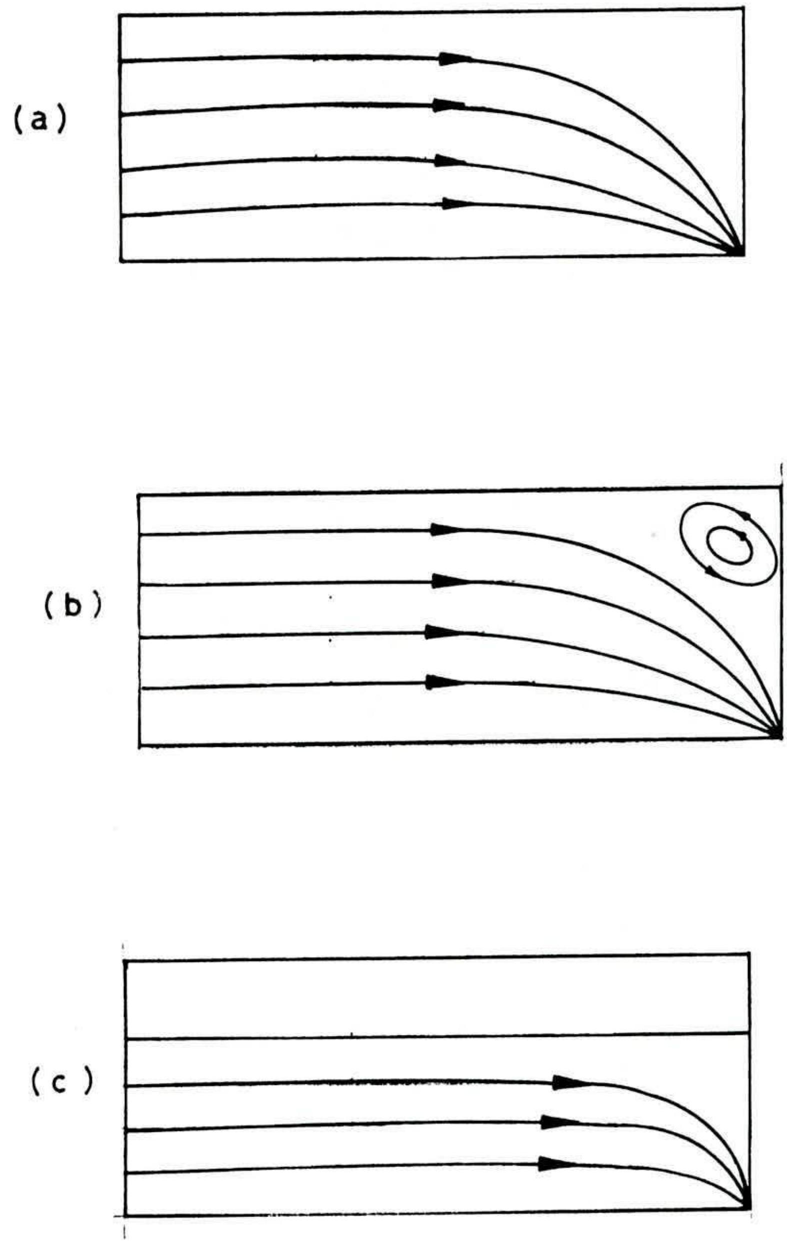


Figure 1.3: Selective withdrawal from a continuously stratified fluid (a) Complete withdrawal, (b) the formation of corner eddy, (c) a stagnant upper region.

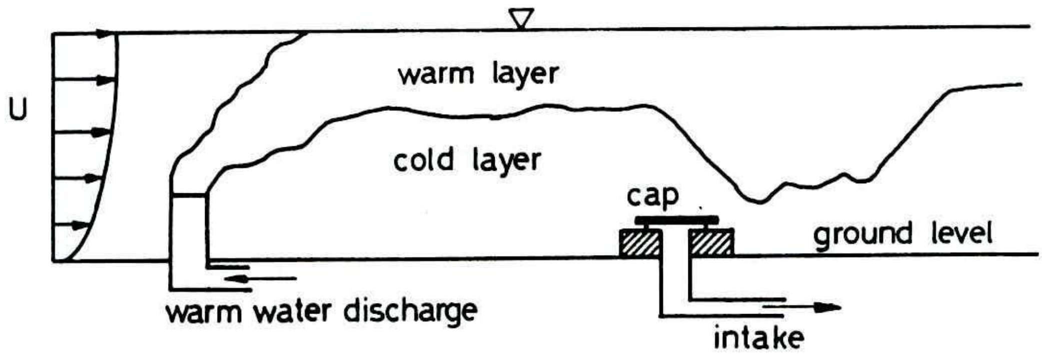


Figure 1.4: Typical cooling water intake in cross flowing stream.

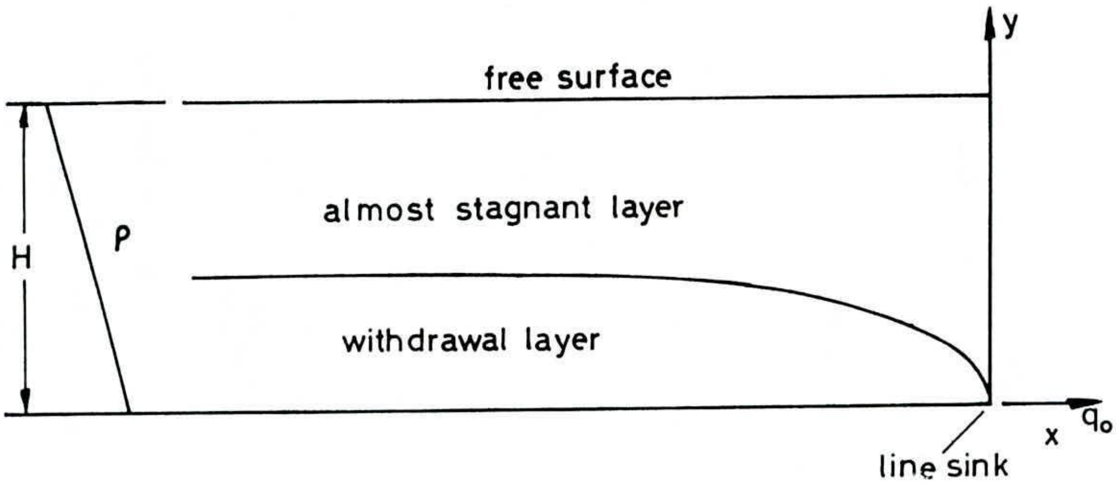


Figure 2.1: Two-dimensional flow into a line sink.

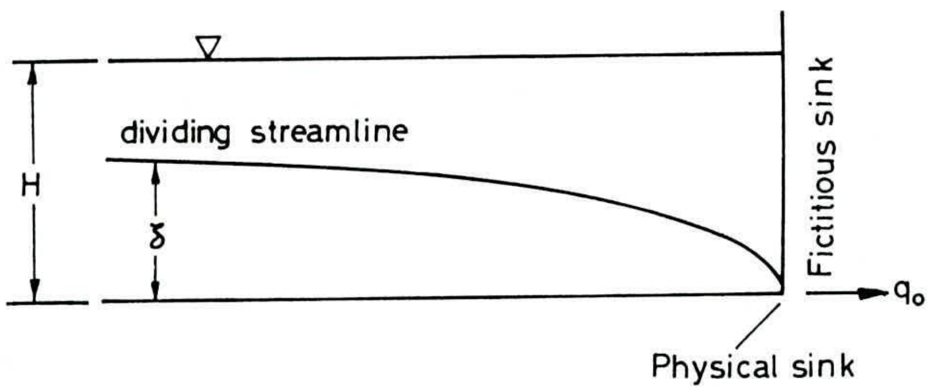
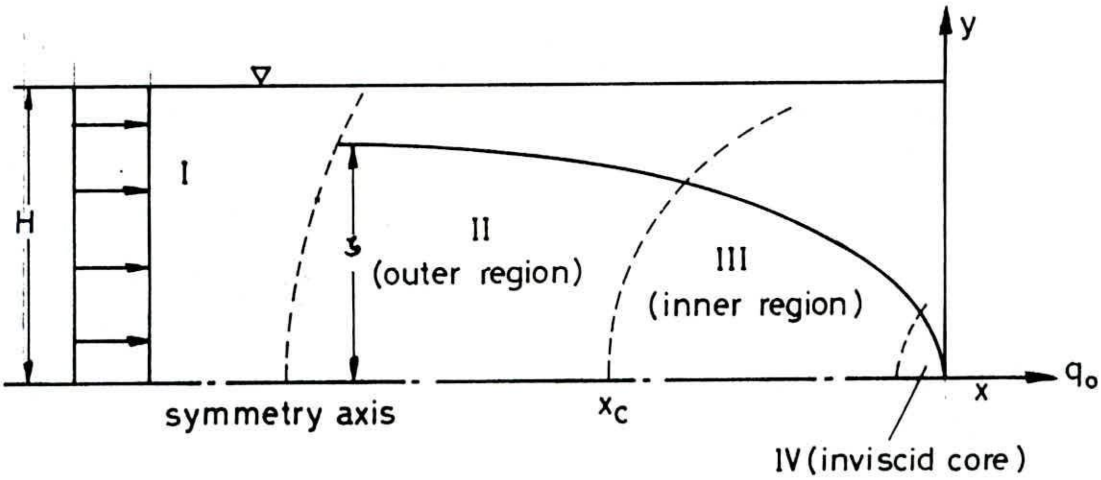


Figure 2.2: Definition sketch of Kao's (1970) analytical solution for 2-D line sink flow.



Region:	I	uniform upstream flow (inviscid and non-buoyant).
	II	outer region (negligible inertia but viscous and buoyancy important)
	III	inner region (inertia, viscous and buoyancy important)
	IV	inviscid core (inertia and buoyancy important)

Figure 2.3: Different regions of flow towards a 2-D line sink (after Imberger and Fischer, 1970).

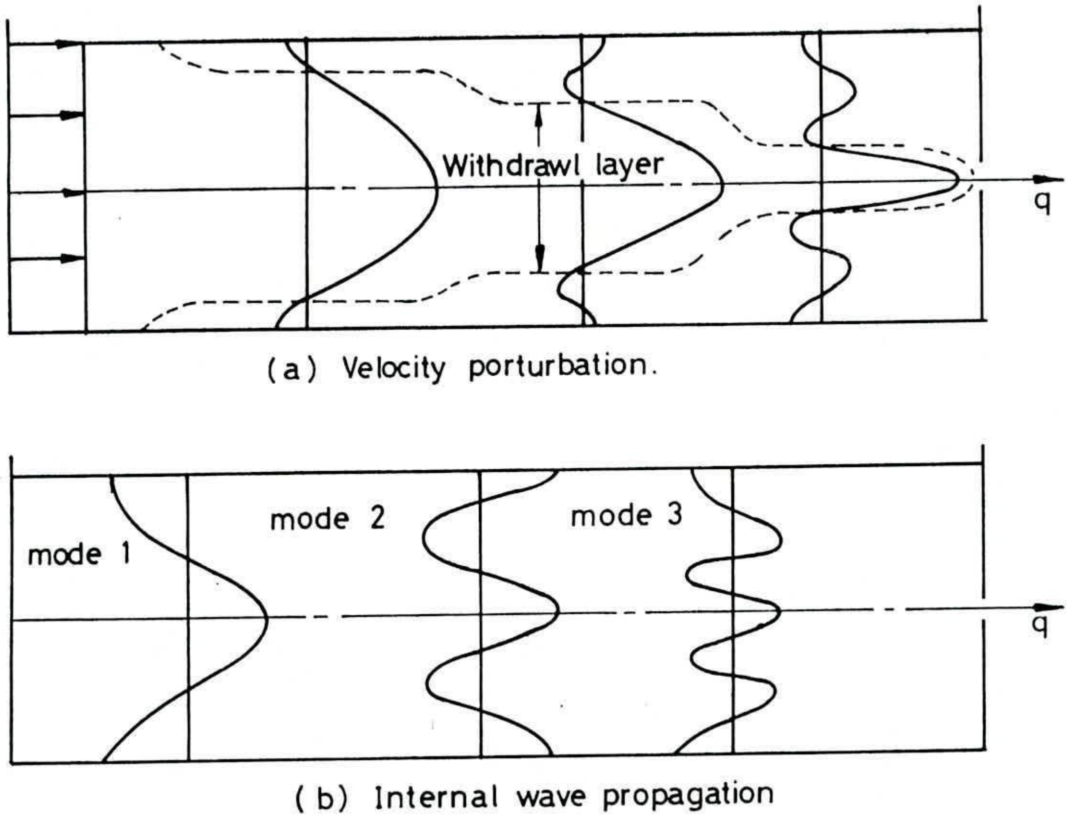


Figure 2.4: Schematic diagram showing the effect of internal wave propagation on the velocity field (Islam, 1988).

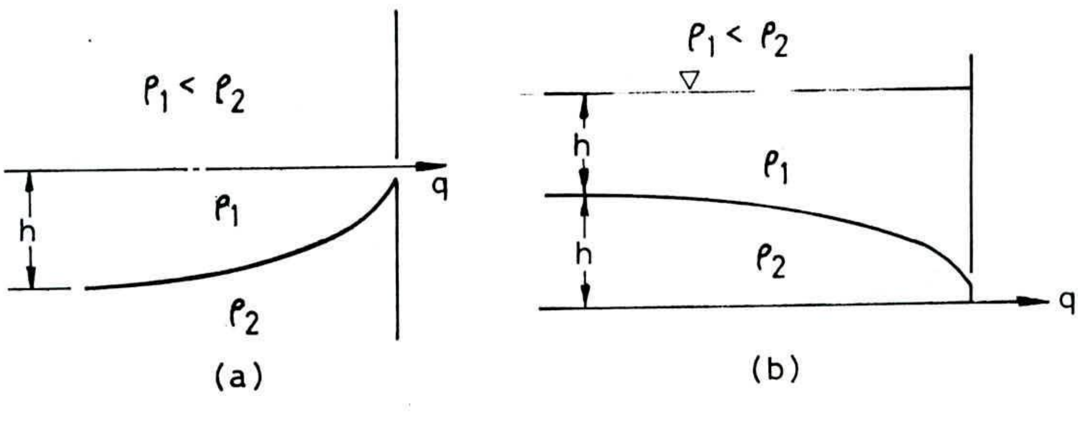


Figure 2.5: Critical flows from two layer fluid system into a line sink (a) after Craya (1949) and (b) after Huber (1960).

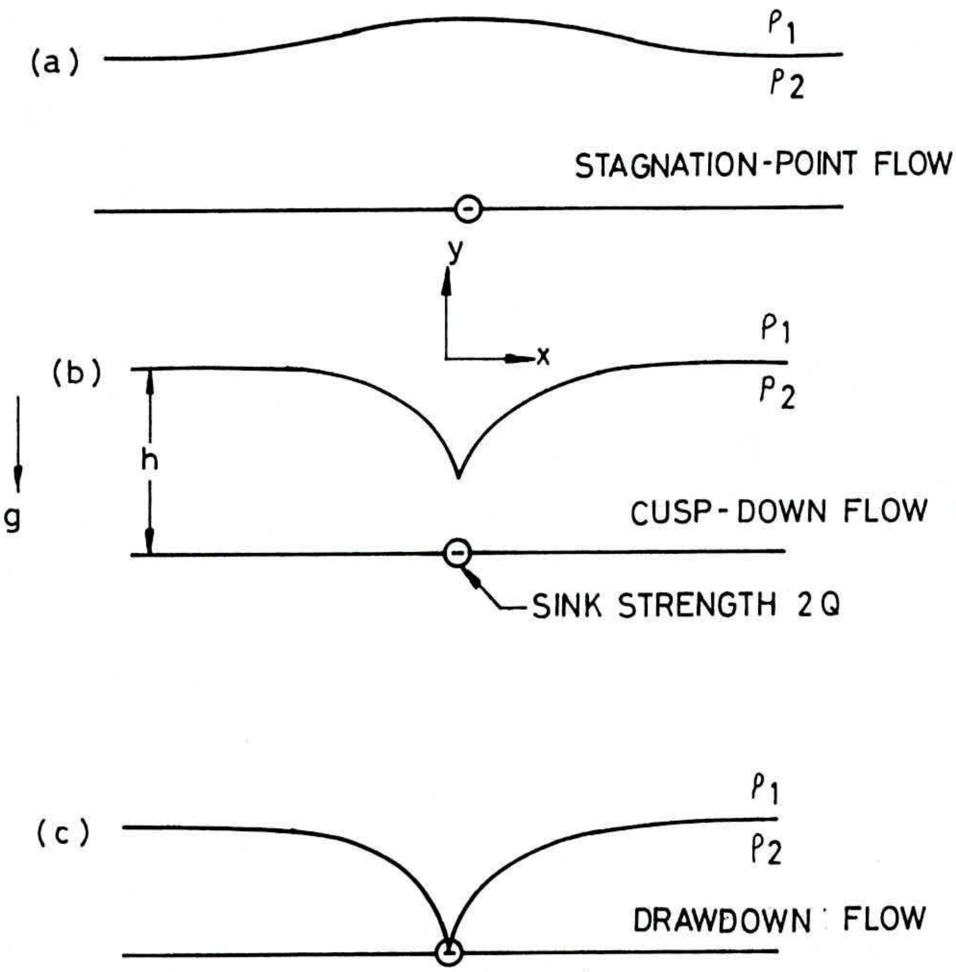


Figure 2.6: Possible steady-state flow configuration (Imgber and Munson, 1986).

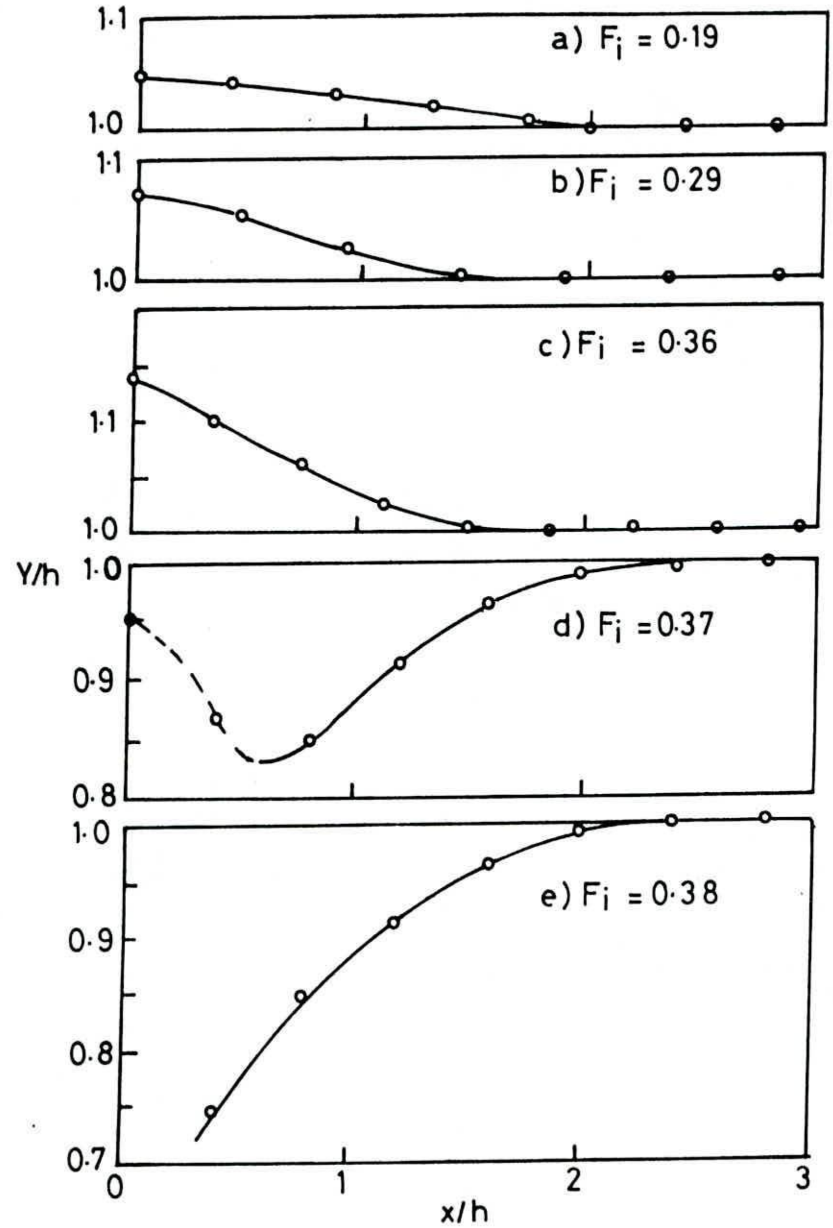


Figure 2.7: Interface shape as a function of Froude number when isolated of viscous effects (Imgber and Munson, 1986).

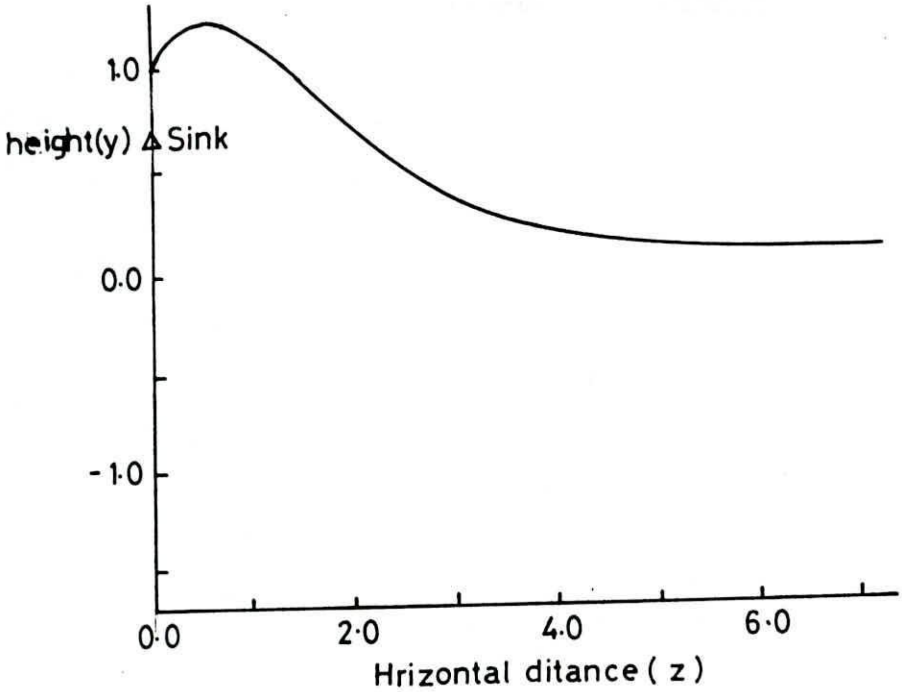


Figure 2.8: Diagram showing the interface shape for a situation in which the sink is above the level of the interface away from the sink (Hocking, 1990).

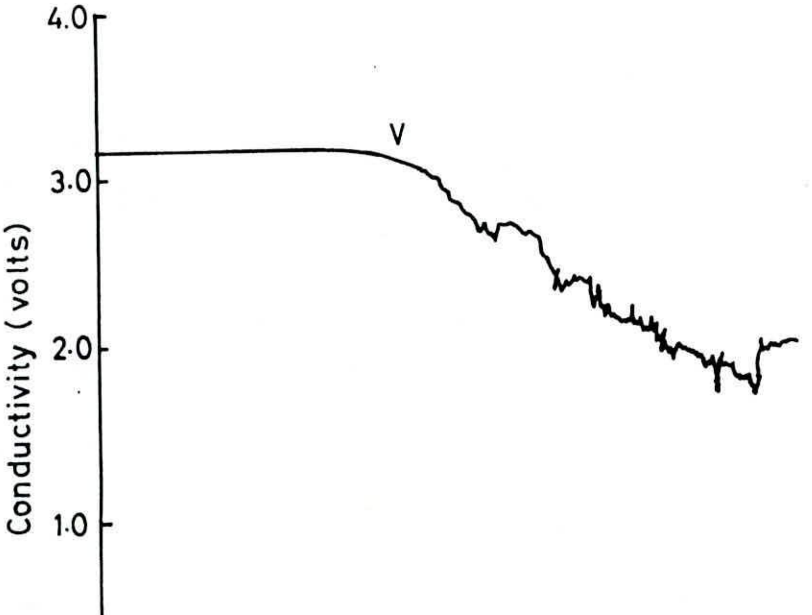


Figure 2.9: Hocking's (1991) technique to identify the initiations of withdrawal.

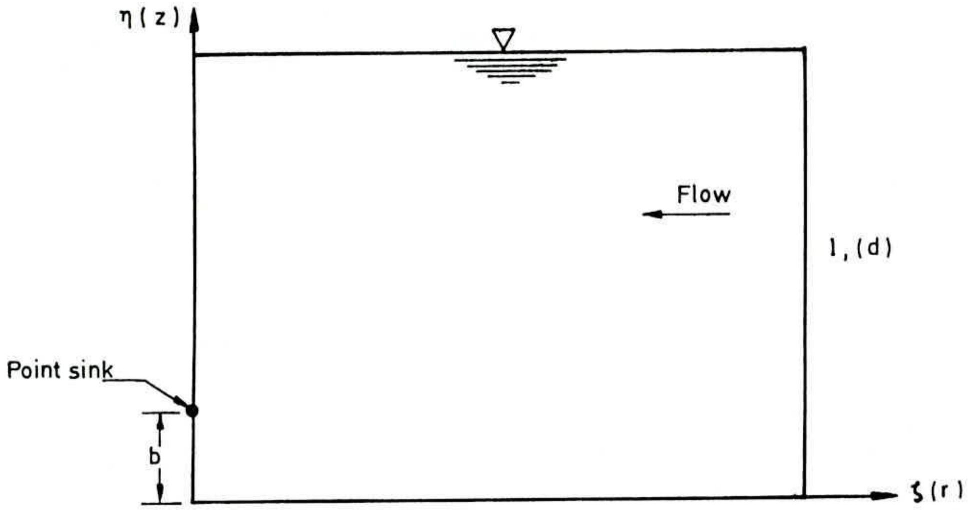


Figure 2.10: Cylindrical coordinate for flow system (Hino and Onishi, 1969).

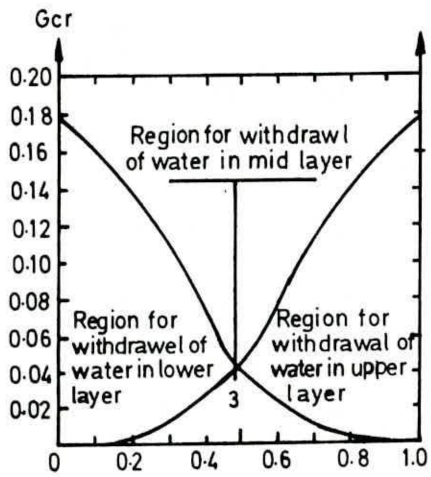


Figure 2.11: Relation of G_{cr} to the location of sink and the conditions of selective withdrawal (Hino and Onishi, 1969).

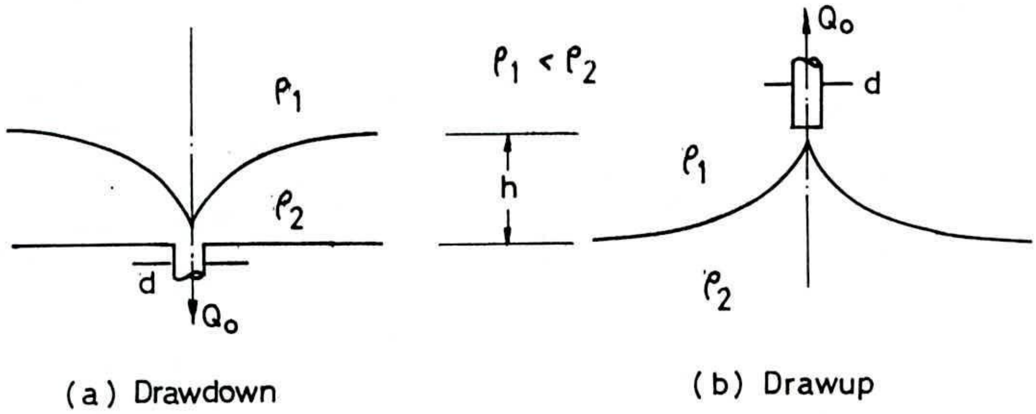


Figure 2.12: Vertical axisymmetric withdrawal through a round hole from a two layer fluid system.

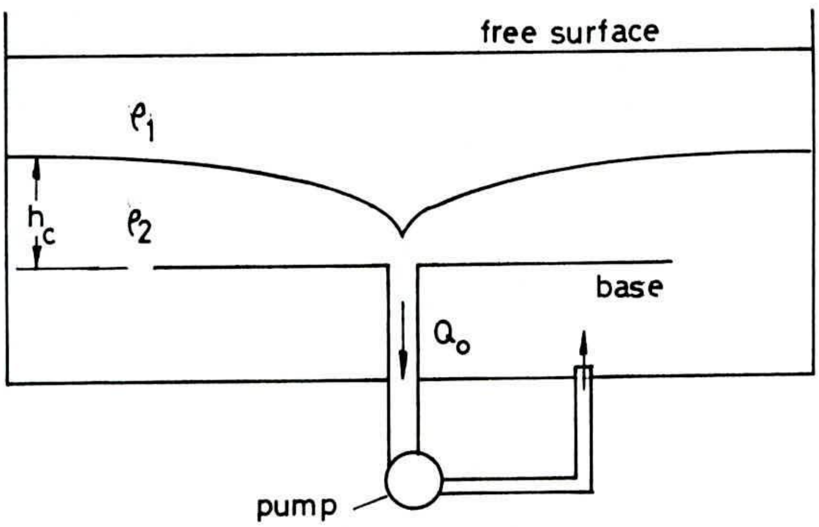


Figure 2.13: Flow configuration of Harleman et al's (1959) experiment.

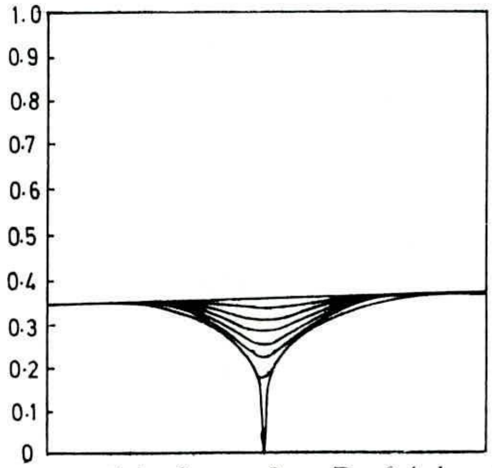


Figure 2.14: Time development of the free surface; F = 0.1, h_o= 0.35, a = 0.05 at t = 0.01, 0.02, 0.03, 0.04, 0.05, 0.06, 0.065, 0.06625, (Zhou, 1990).

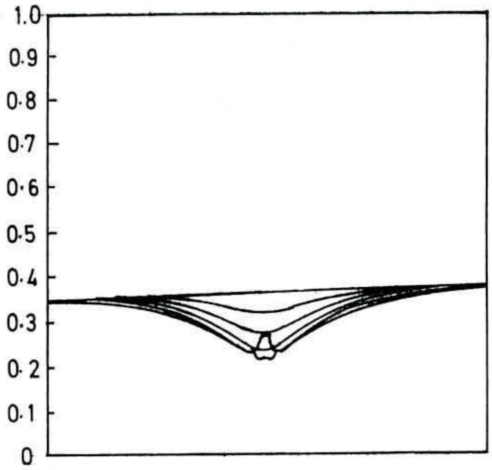


Figure 2.15: Time development of the free surface; F = 0.1, h_0 = 0.35, a = 0.02 at t = 0.02, 0.04, 0.06, 0.08, 0.1, 0.102, 0.104, 0.106, (Zhou, 1990).

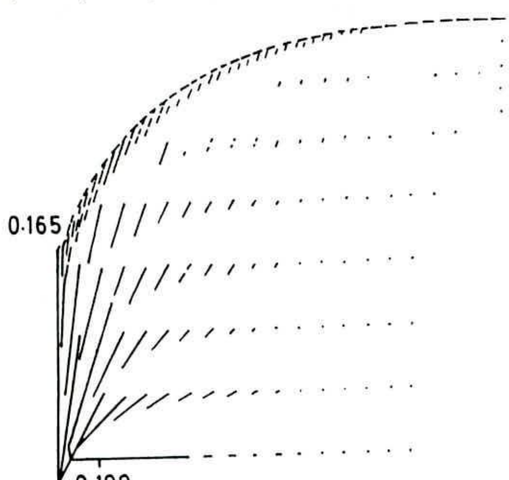


Figure 2.16: Velocity field when a dip forms; F = 0.1, h_0 = 0.35, a = 0.1 at t = 0.064, (Zhou, 1990).

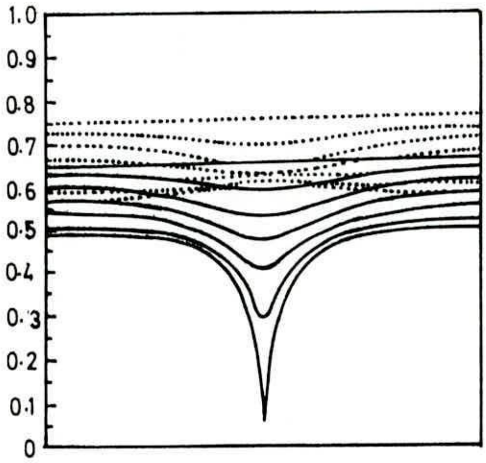


Figure 2.17: Time development of - the free surface and - the interface: F = 0.25, a = 0.1, β = 0.5, h_l = 0.65, and h_o = 0.1 at time t = 0.1, 0.2, 0.3, 0.4, 0.5, 0.553 (Zhou, 1990).

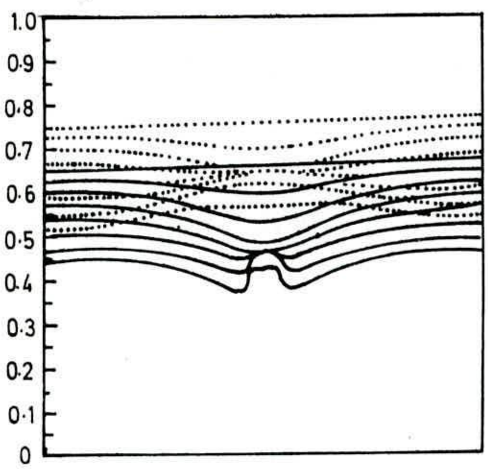


Figure 2.18: Time development of - the free surface and - the interface: F = 0.25, a = 0.1, β = 0.5, h_l = 0.65, and h_o = 0.1 at time t = 0.3, 0.5, 0.69 (Zhou, 1990).

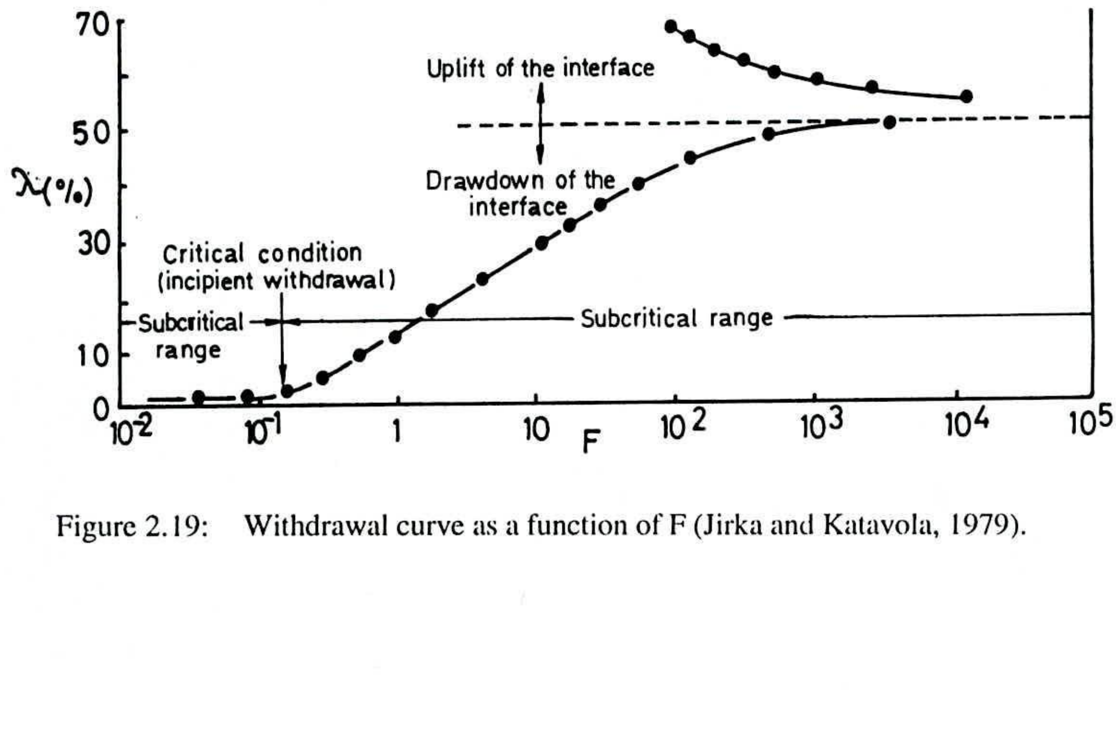


Figure 2.19: Withdrawal curve as a function of F (Jirka and Katavola, 1979).

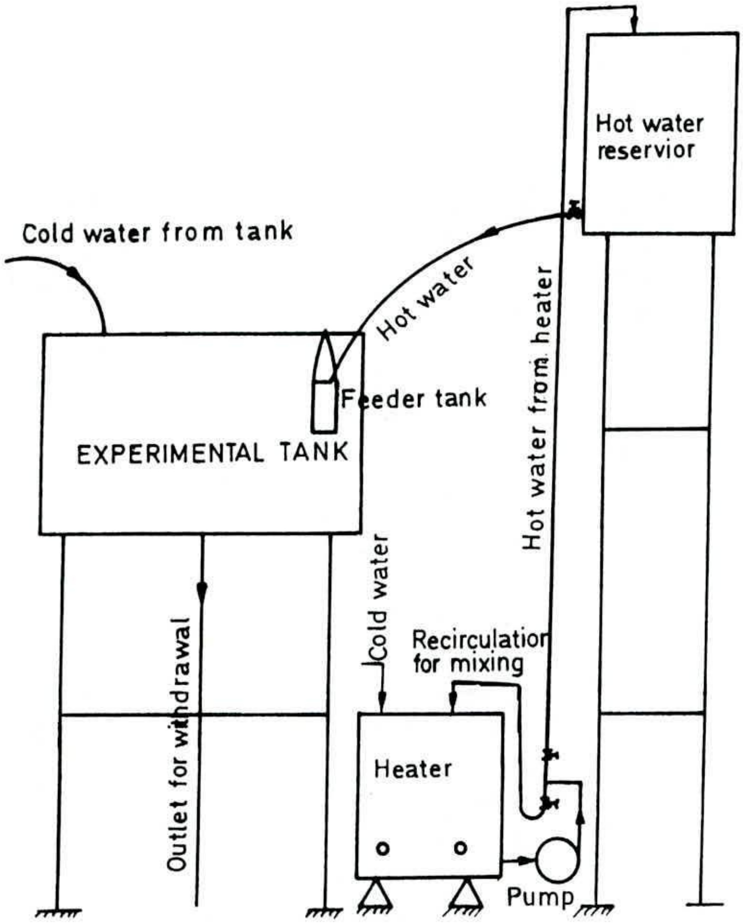


Figure 3.1: Schematic diagram of experimental setup.

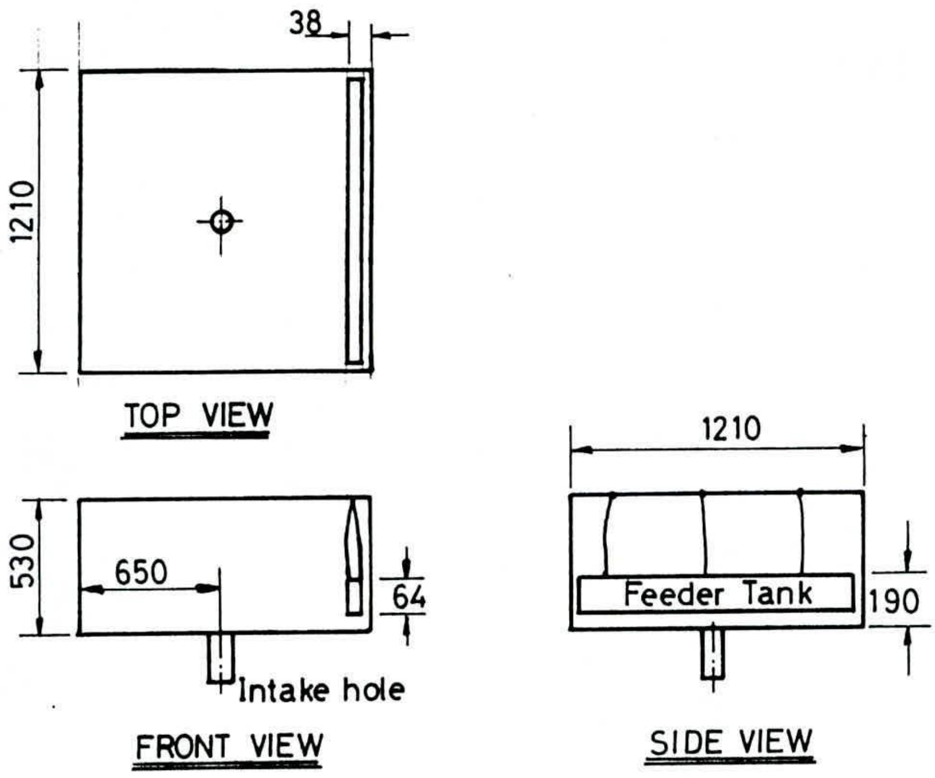


Figure 3.2: Experimental Tank (Dim-mm).

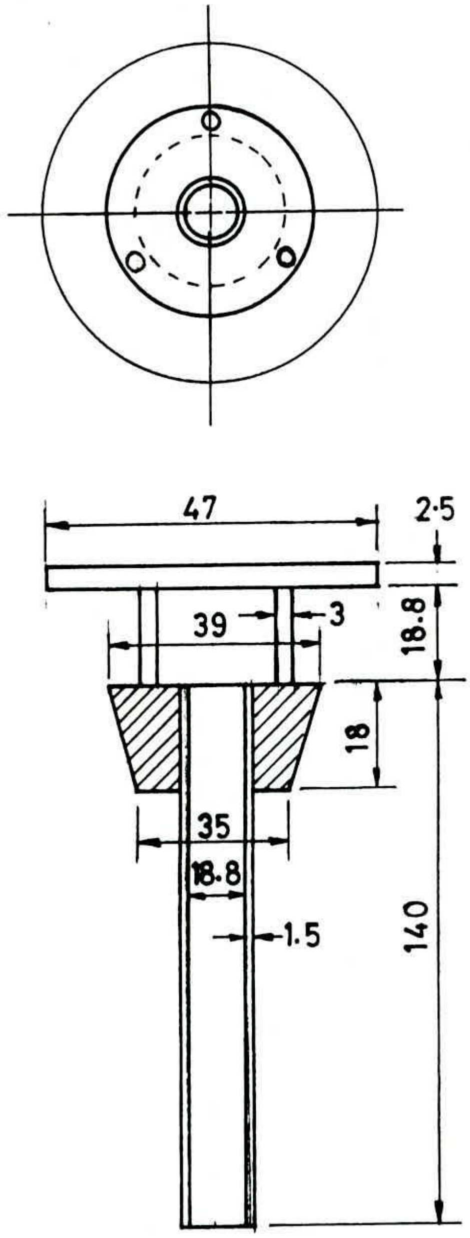


Figure 3.3: Cap intake system.

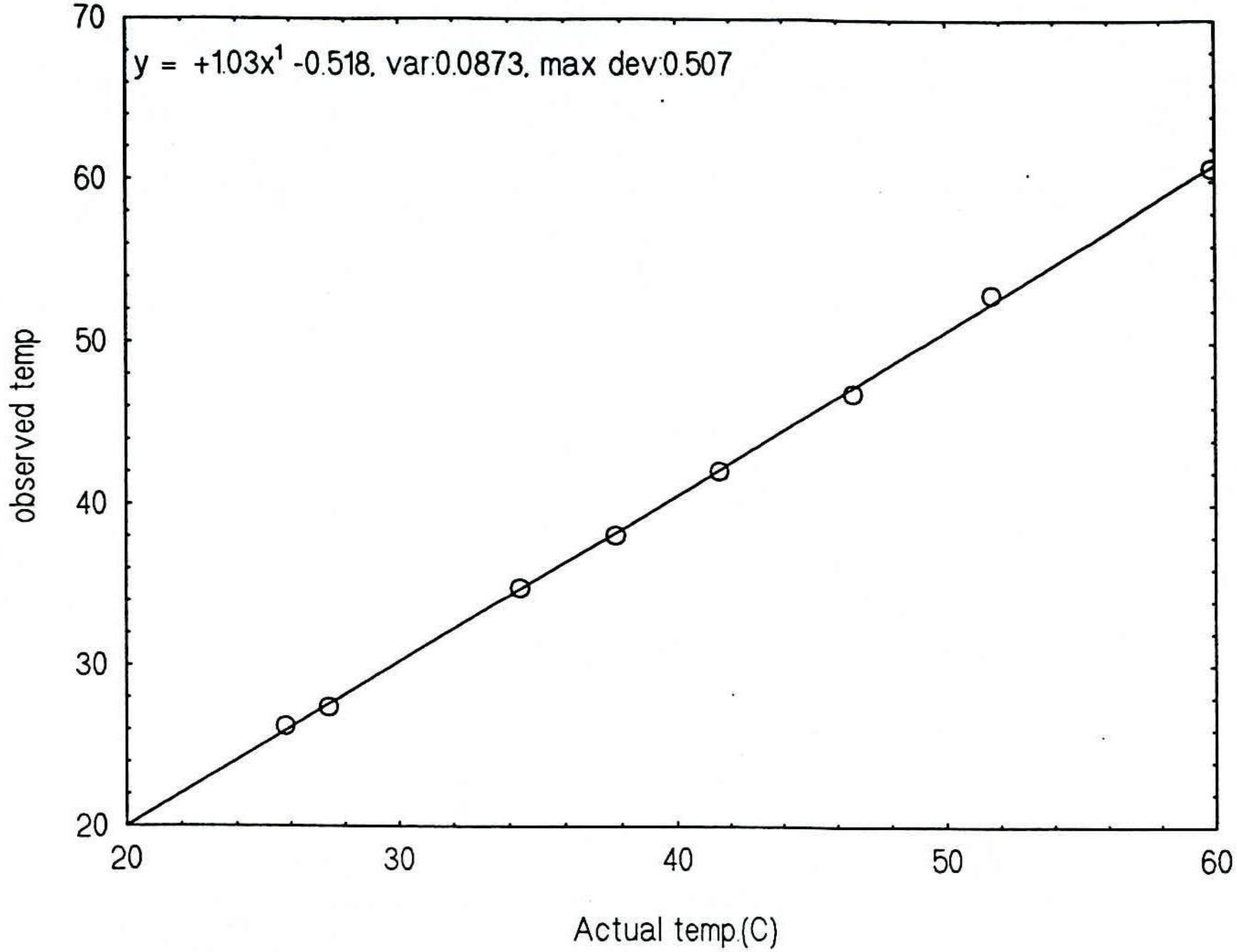


Figure 3.4: Omega thermometer calibration.

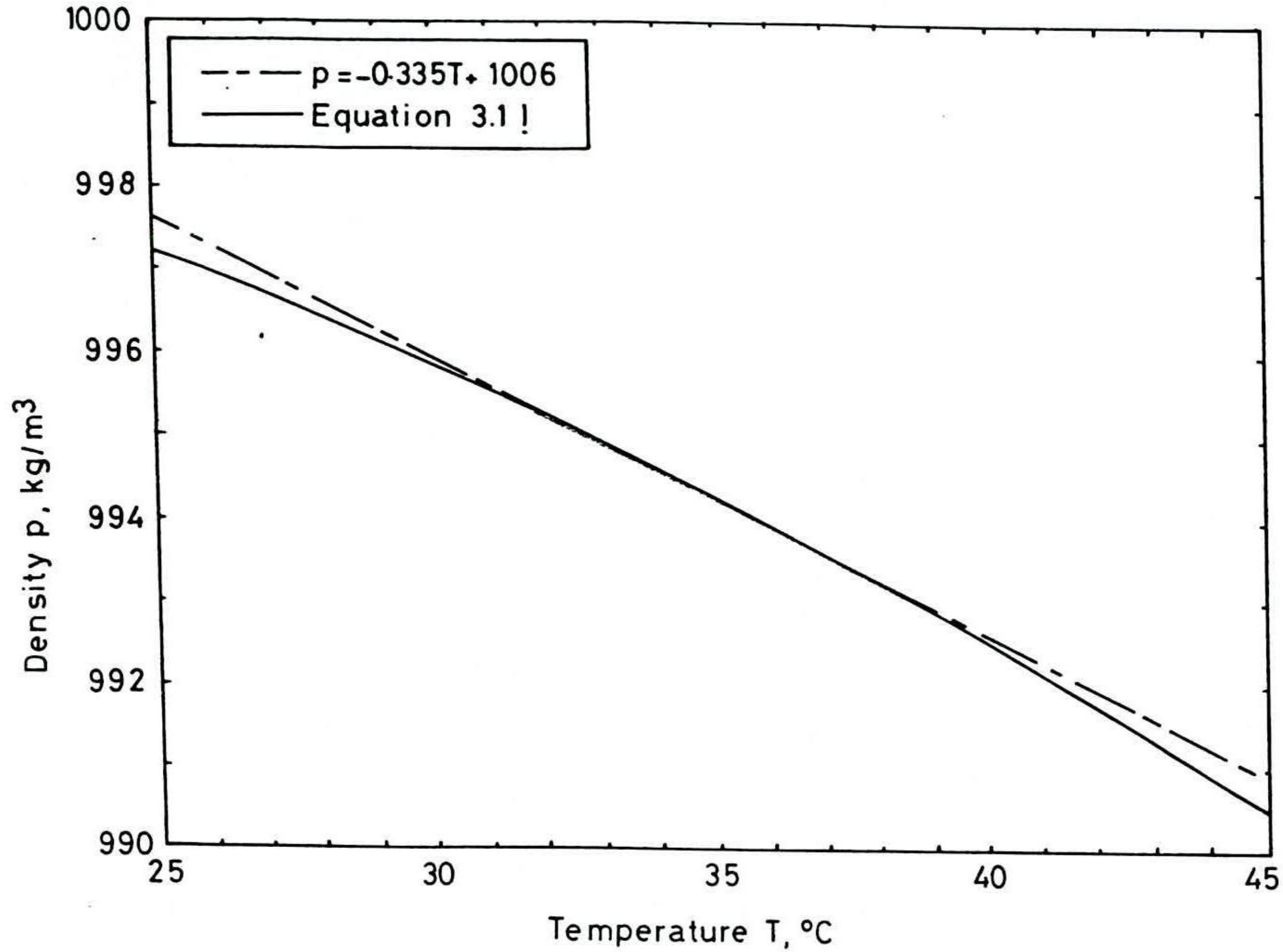


Figure 3.5: Variation of water density with temperature.

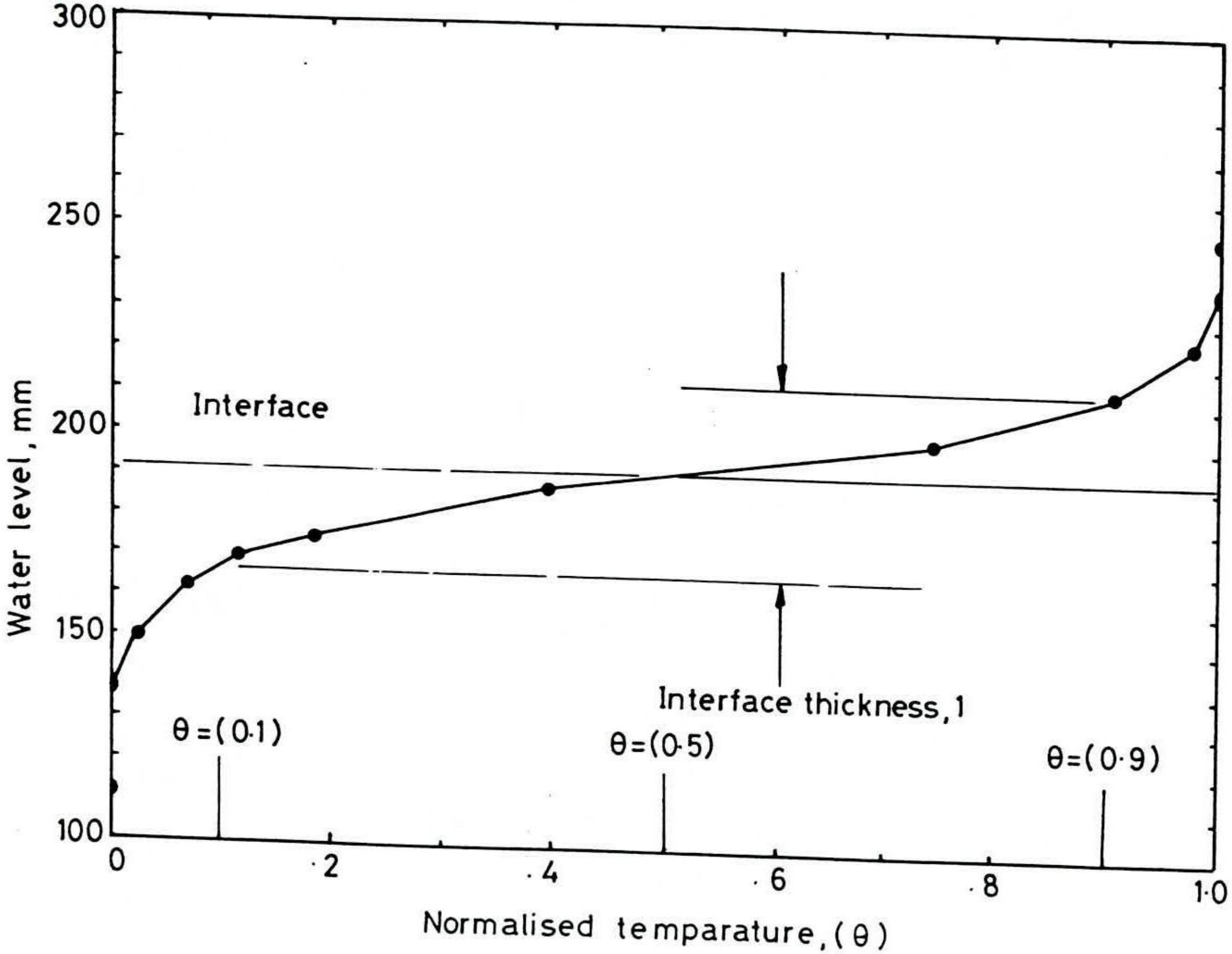


Figure 3.6: A typical temperature (density) profile.

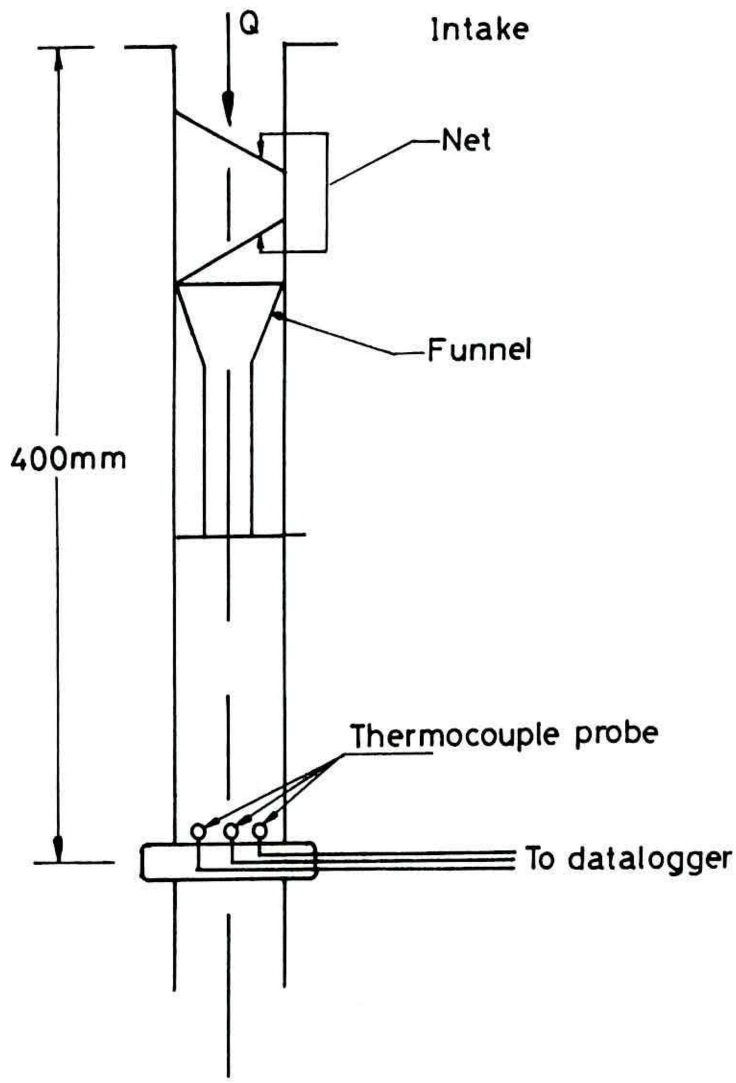


Figure 3.7: Arrangement of filter, funnel and thermocouple probe in the discharge pipe.

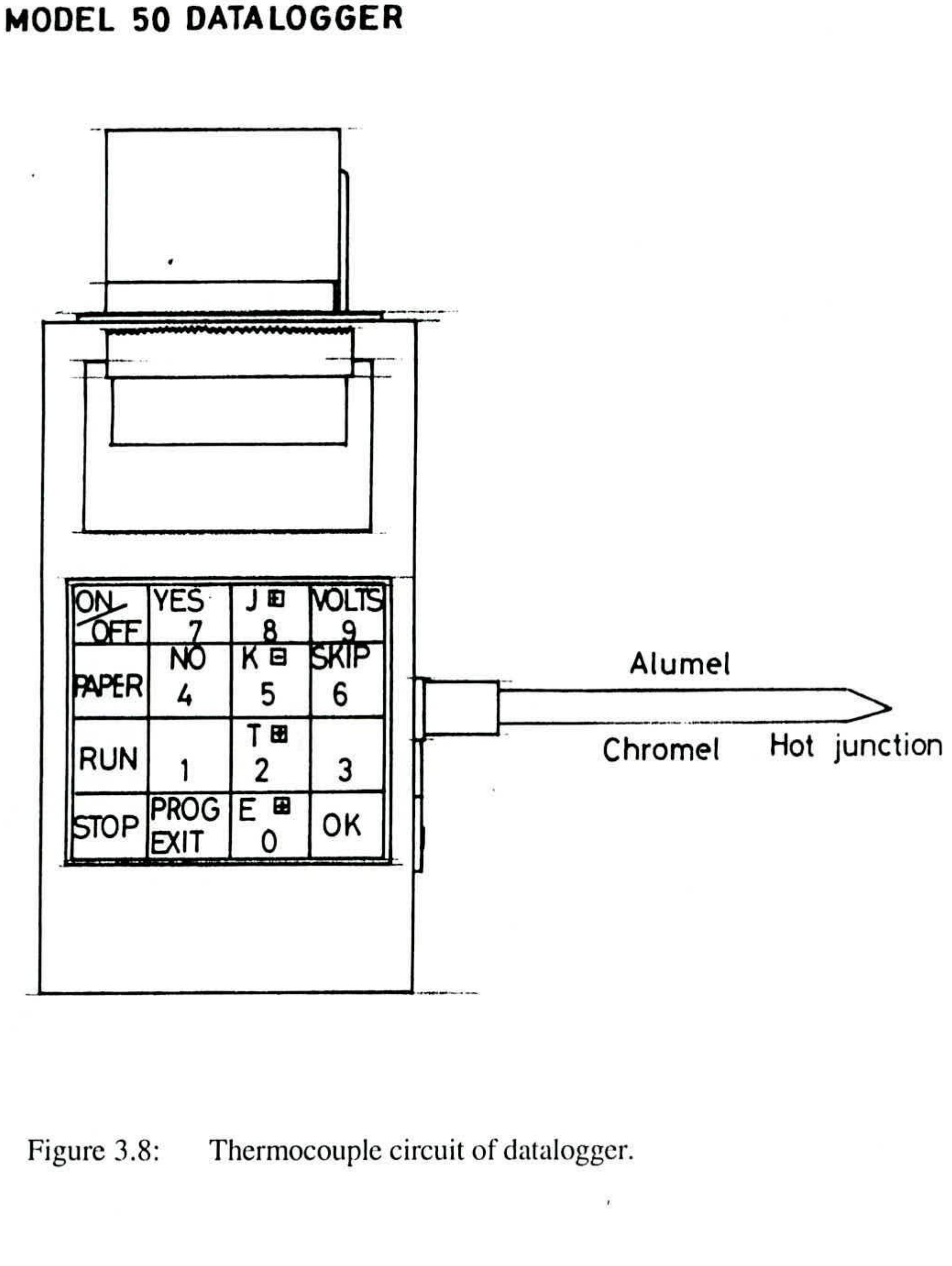


Figure 3.8: Thermocouple circuit of datalogger.

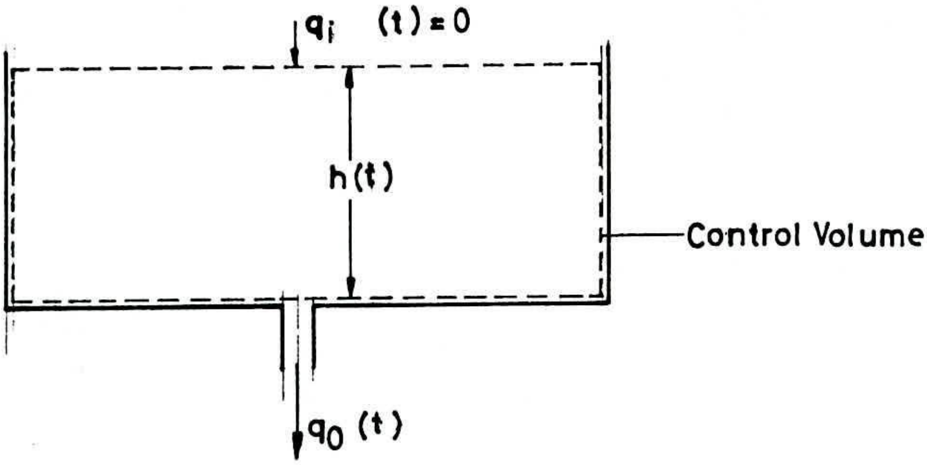


Figure 3.9(a): Inflow-outflow for total water.

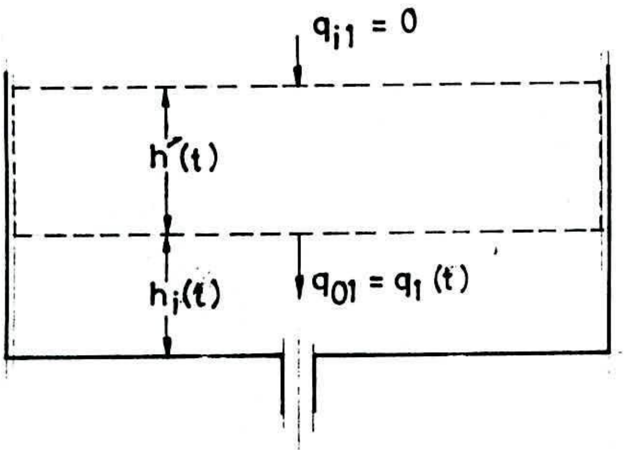


Figure 3.9(b): Inflow-outflow for hot water.

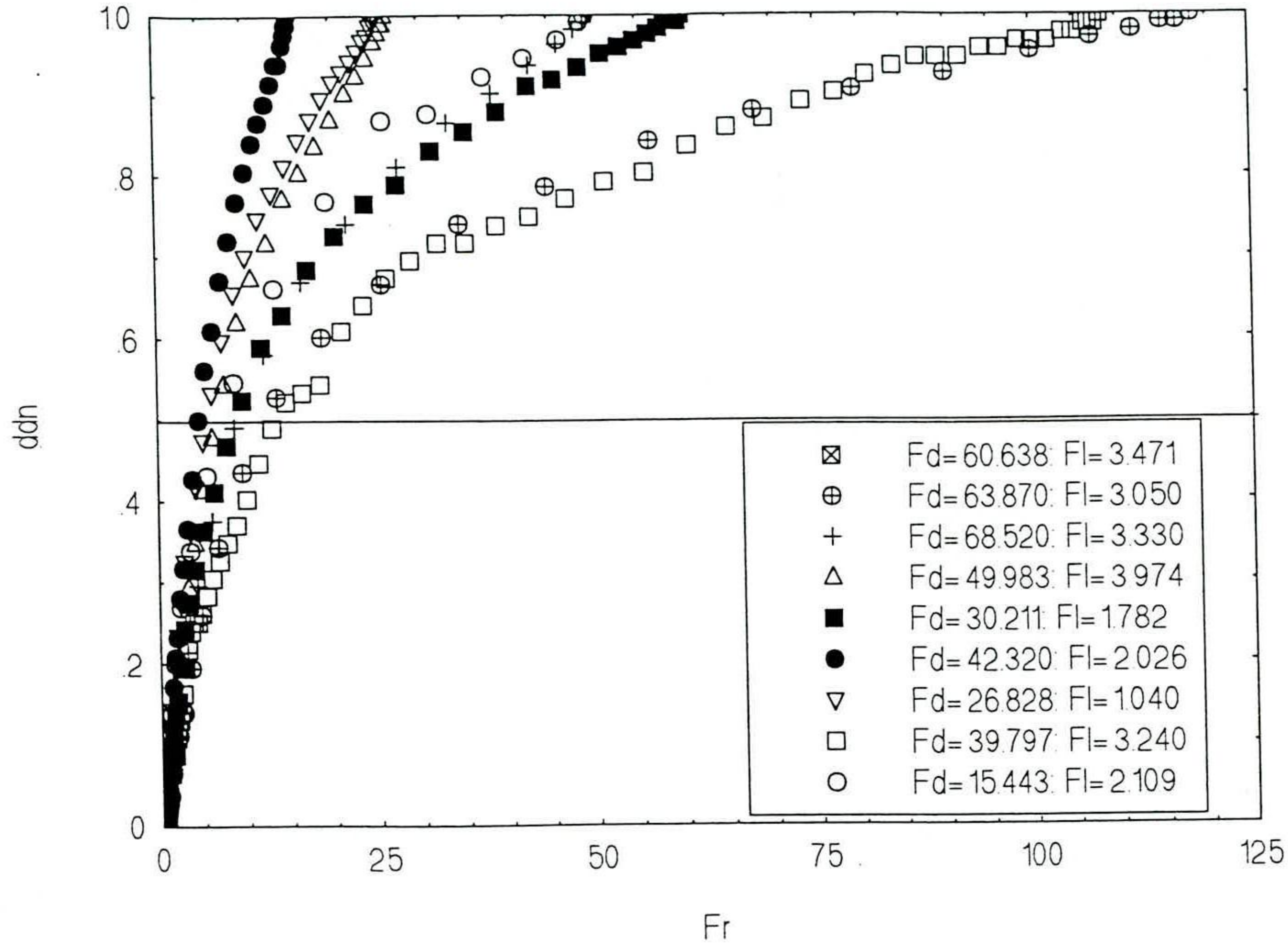


Figure.4.2a: Densimetric Froude number increases rapidly at 50% drawdown

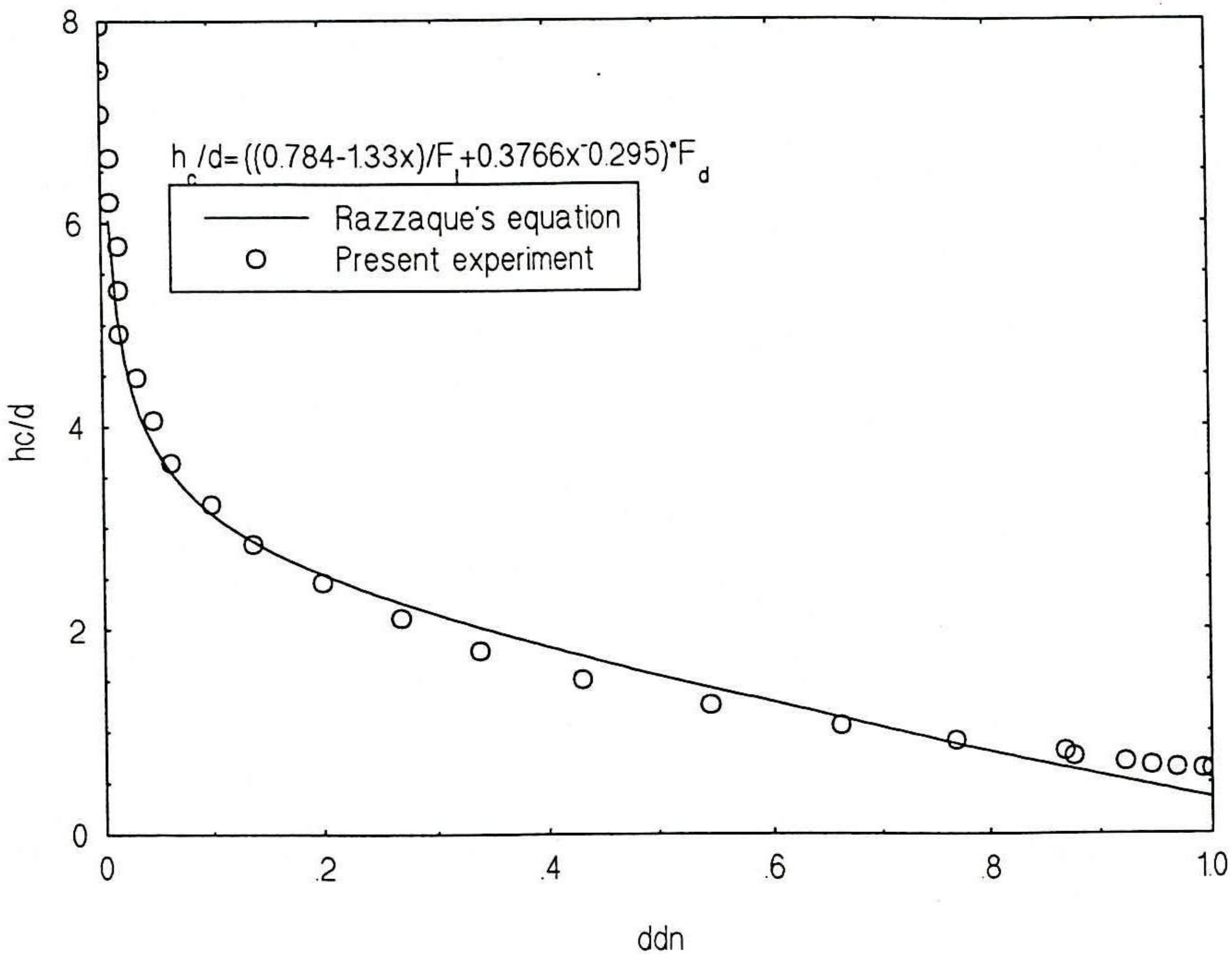


Figure.4.2b: Verification of Razzaque's equation.

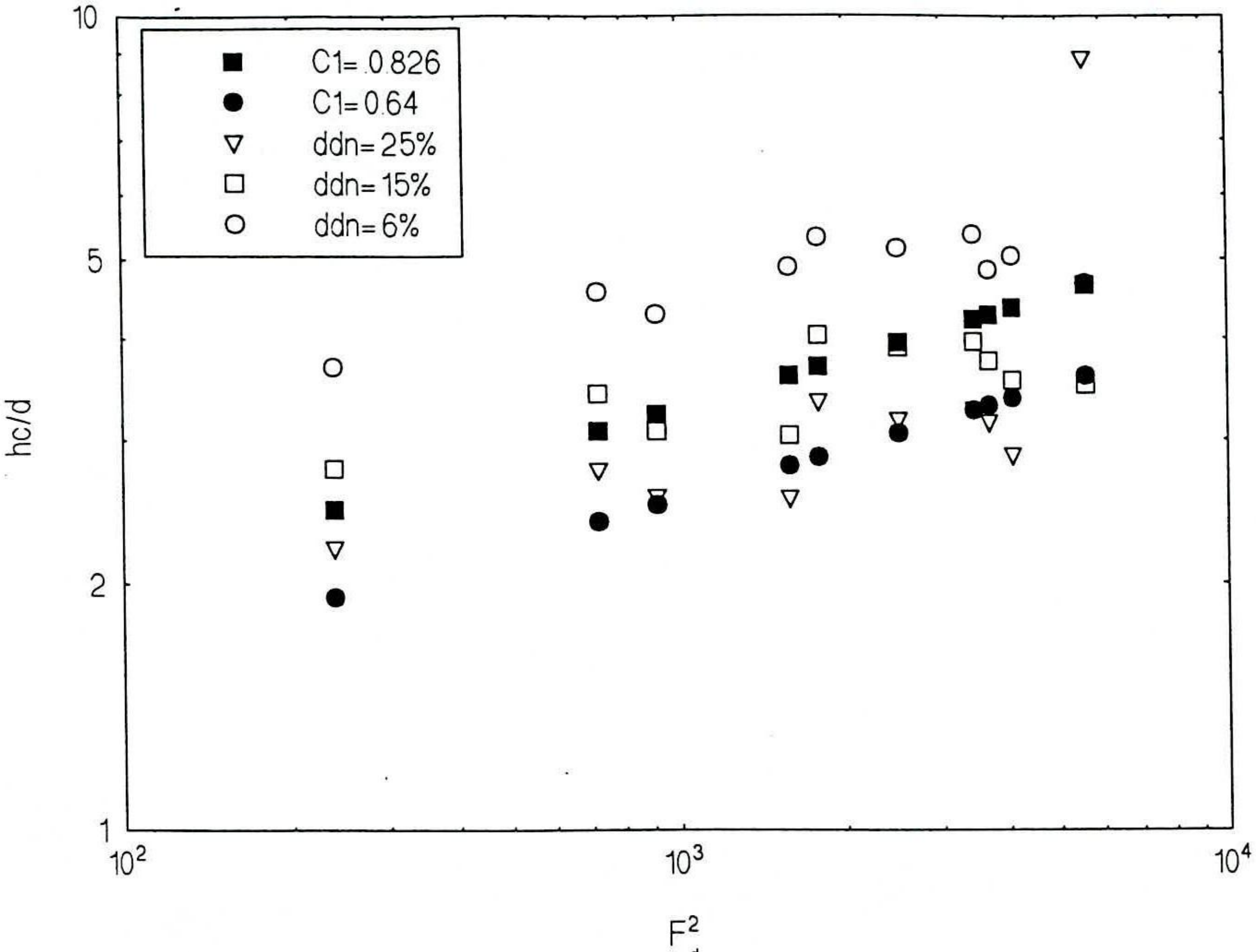


Figure:4.2c: At capfree condition hc/d is more or less proportional to two-fifths power of intake Froude number.

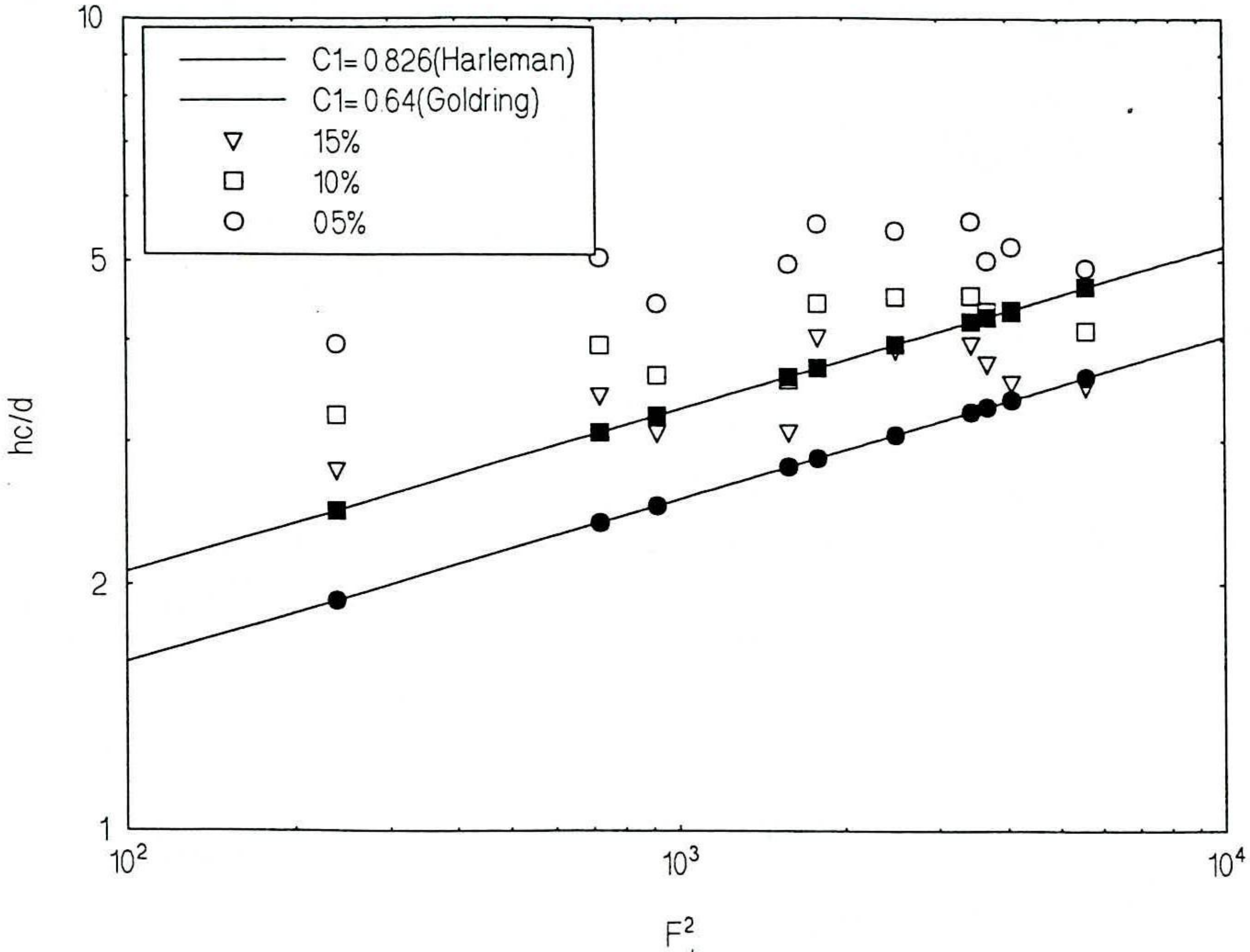


Figure:4.2d: Verification of $h_c/d = c_1 F_d^{0.4}$ with first nine dataset.

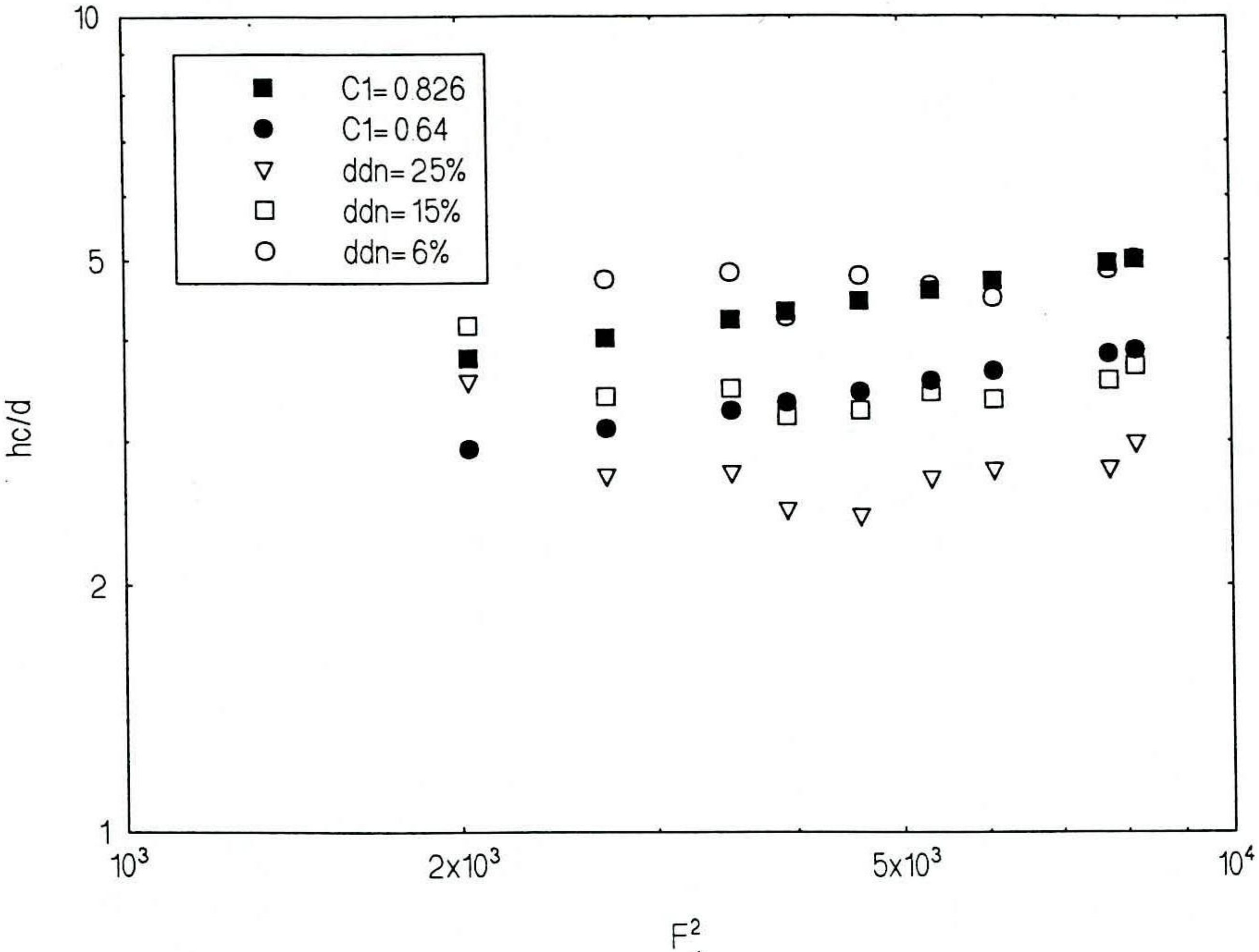


Figure:4.3a: At d /S= 1.5, h /d is proportional to two-fifths power of intake Froude number.

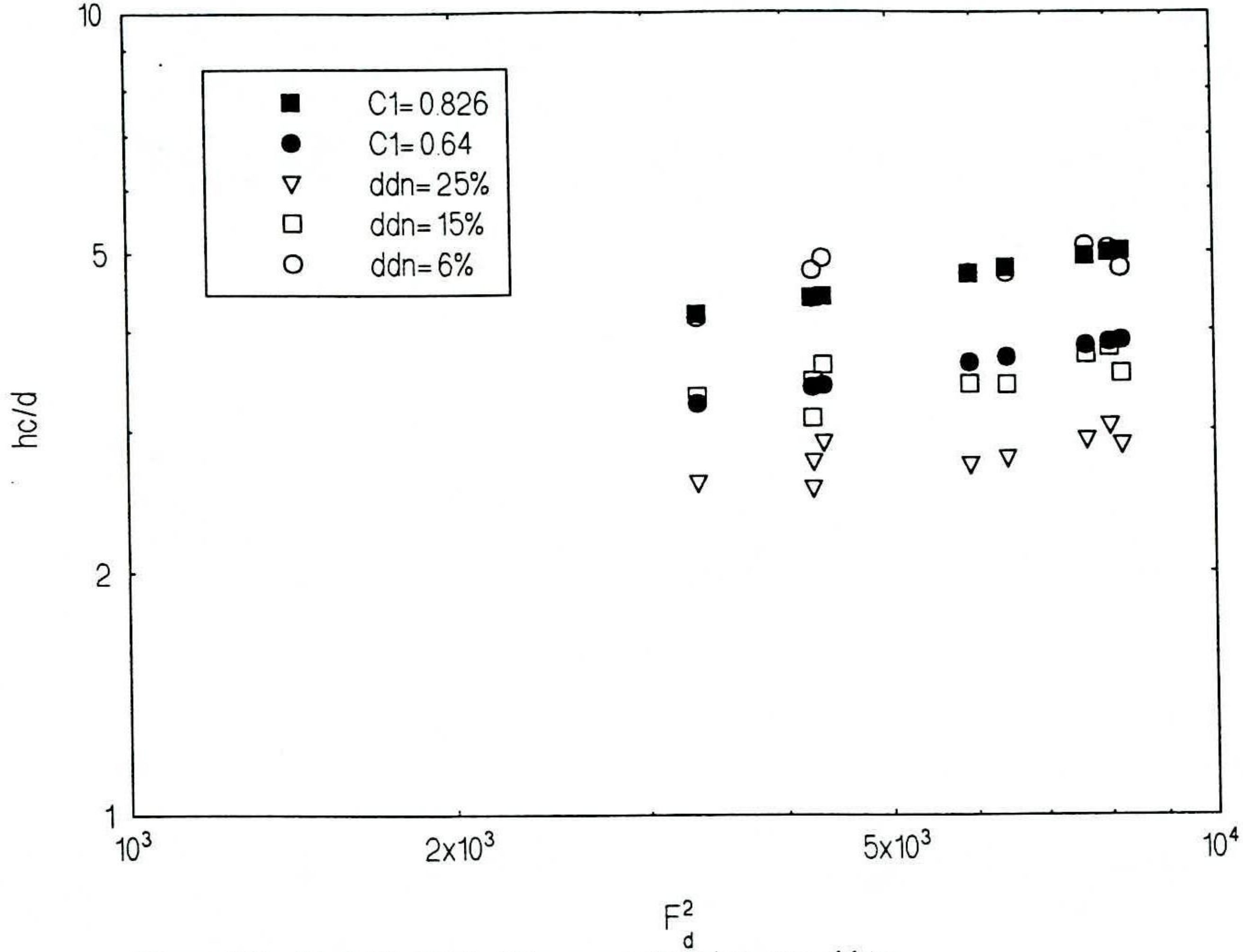


Figure:4.3b: At d /S=2.5, h /d is proportional to two-fifths power of intake Froude number.

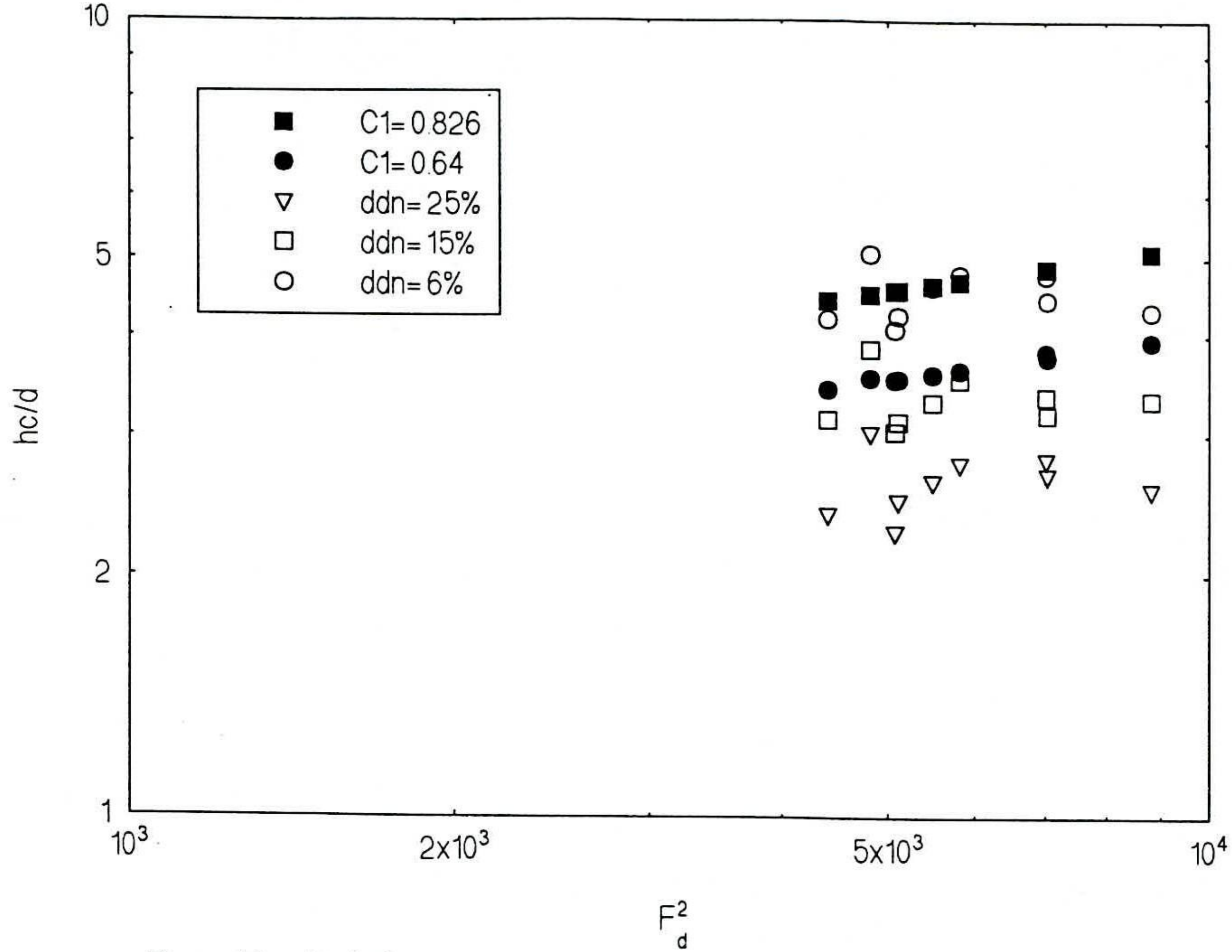


Figure:4.3c: At d /S= 3.5,h /d is proportional to two-fifths power of intake Froude number.

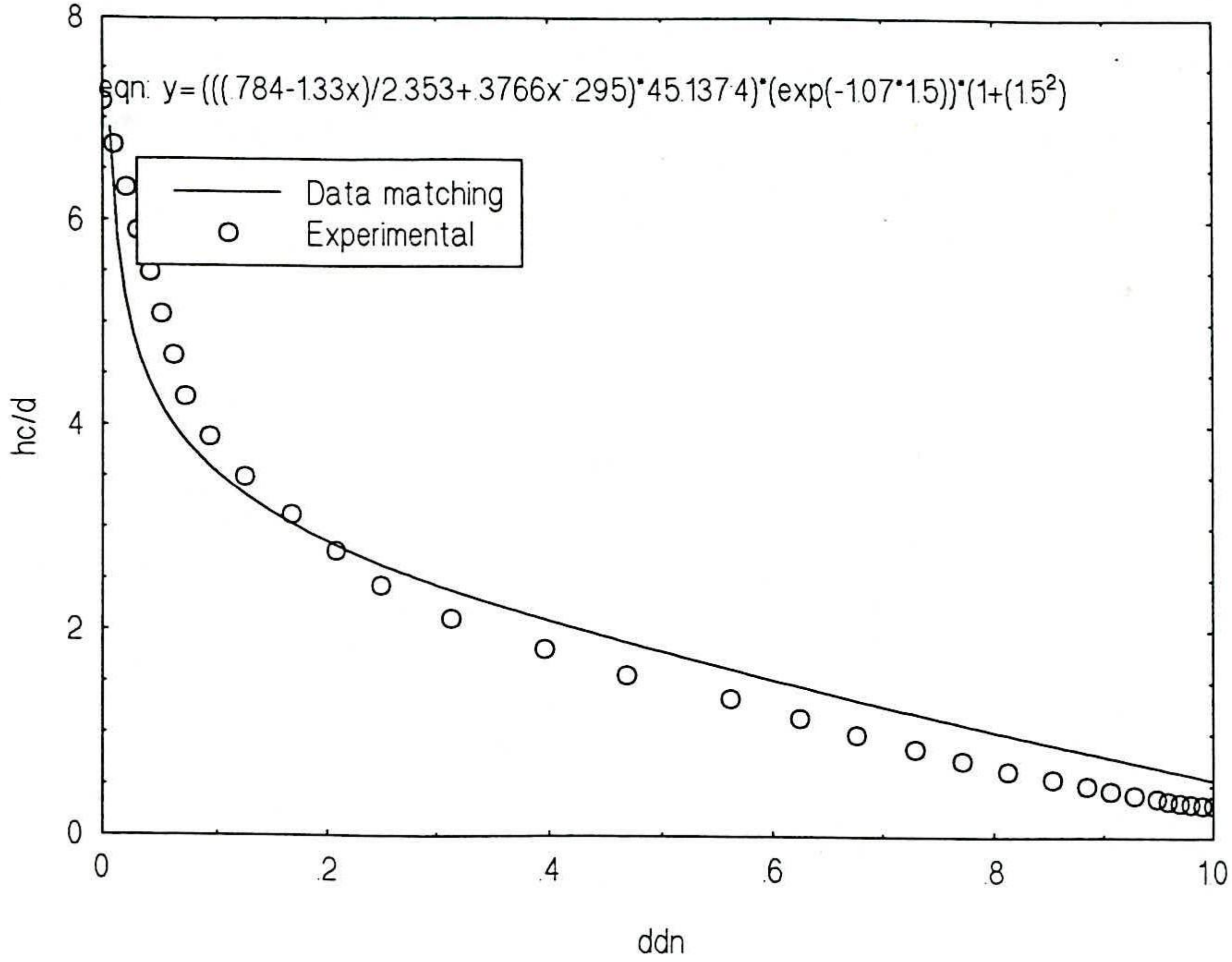


Figure 4.4a: Effect of d_c/S on drawdown showing a sample for $d_c/S=1.5$

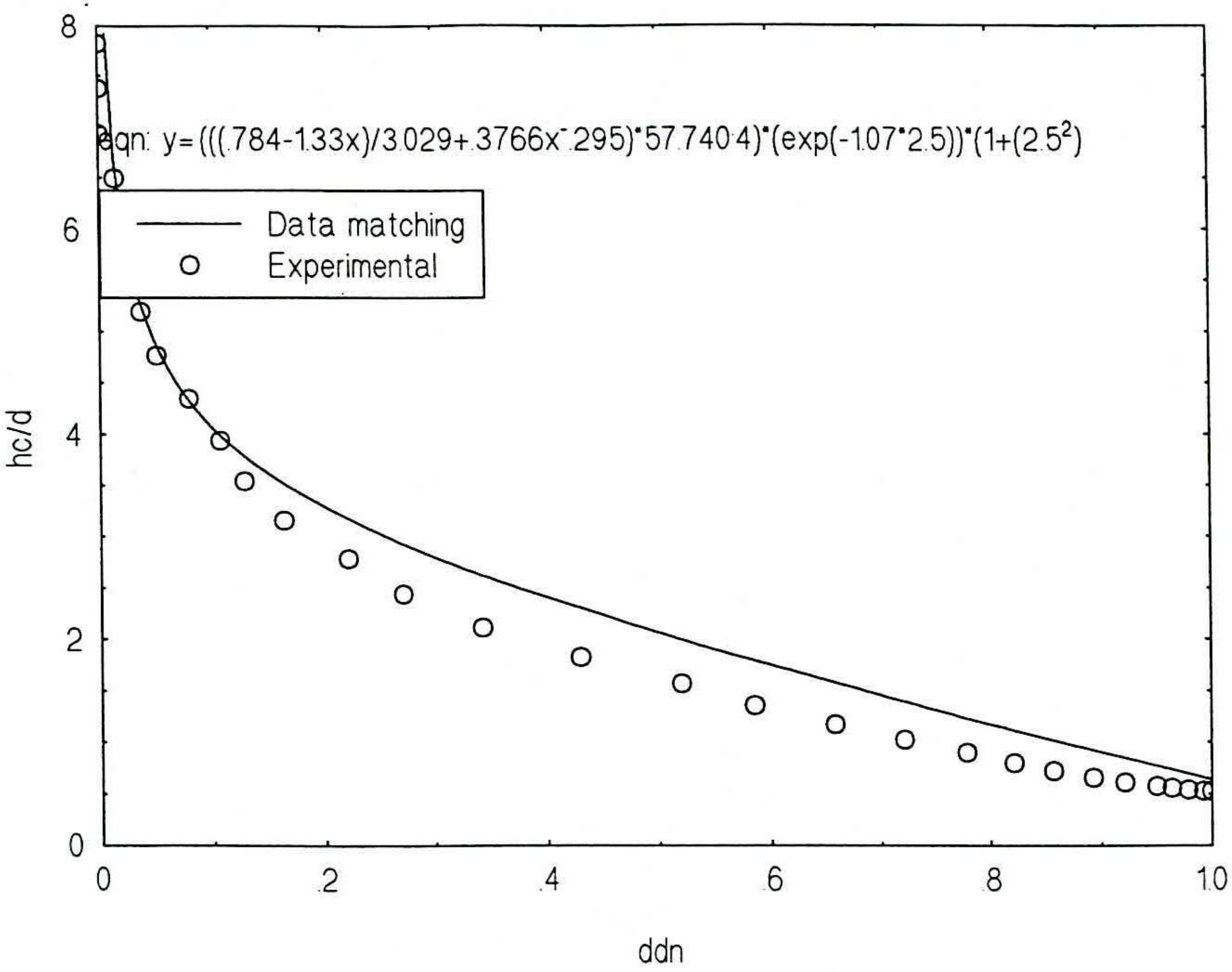


Figure:4.4b: Effect of d_c/S on drawdown as a sample for d_c/S=2.5

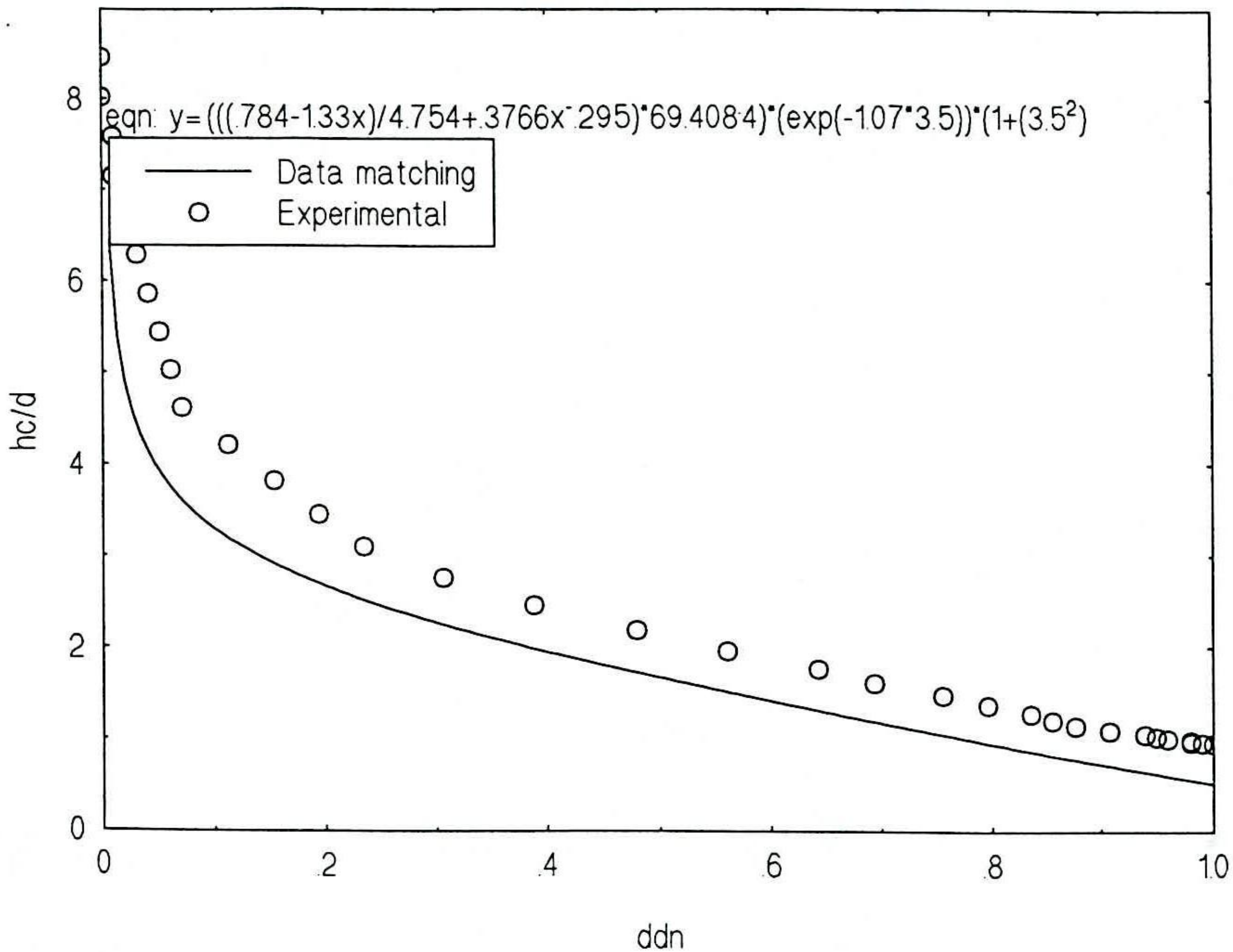


Figure 4.4c: Effect of d_c/S on drawdown as a sample for $d_c/S=3.5$

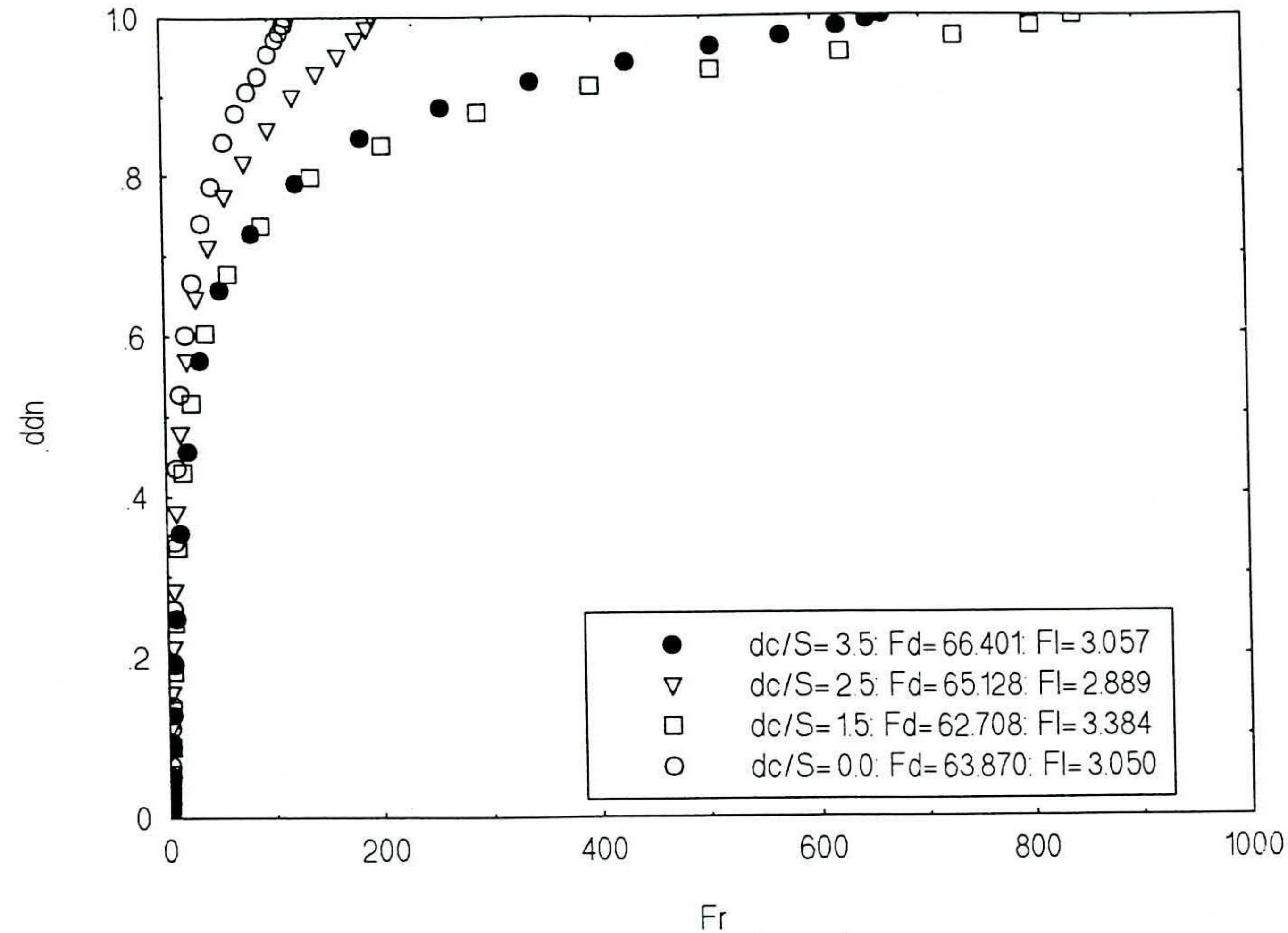


Figure 4.5 Effect of $d_{c/}S$ on densimetric Froude number

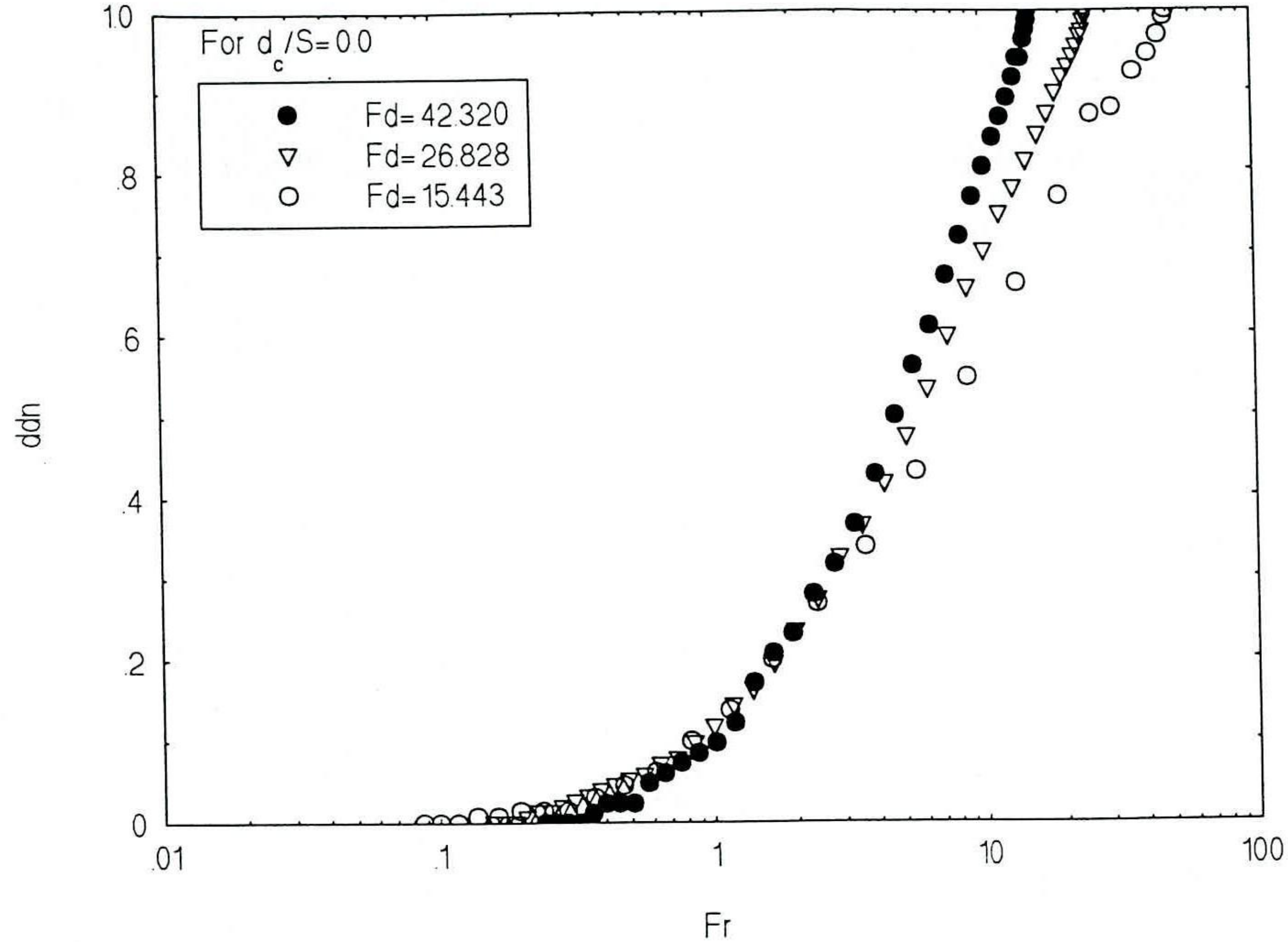


Figure 4.6a: Effect of intake Froude number on drawdown.

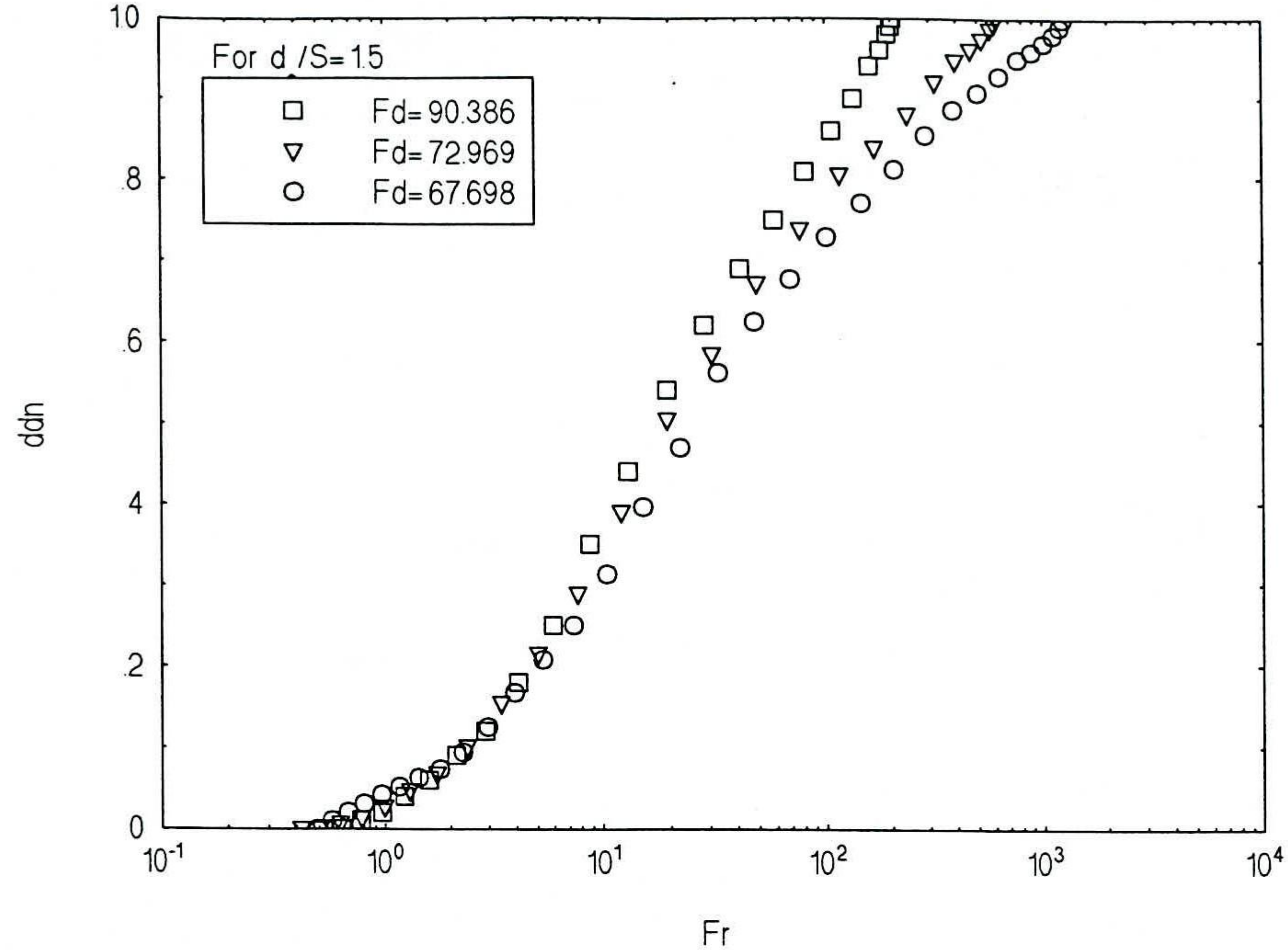


Figure:4.6b: Effect of intake Froude number on drawdown.

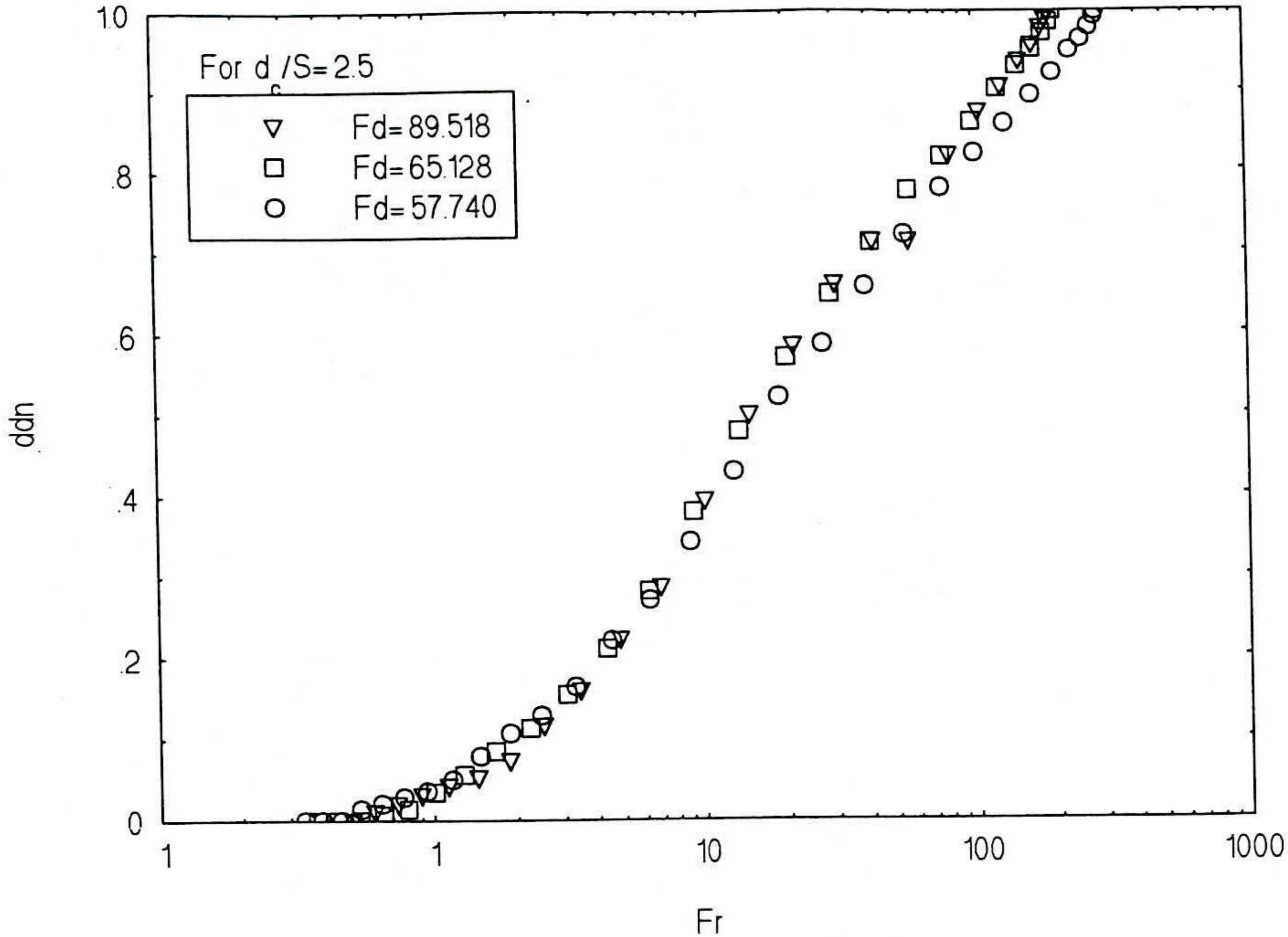


Figure:4.6c: Effect of intake Froude number on drawdown.

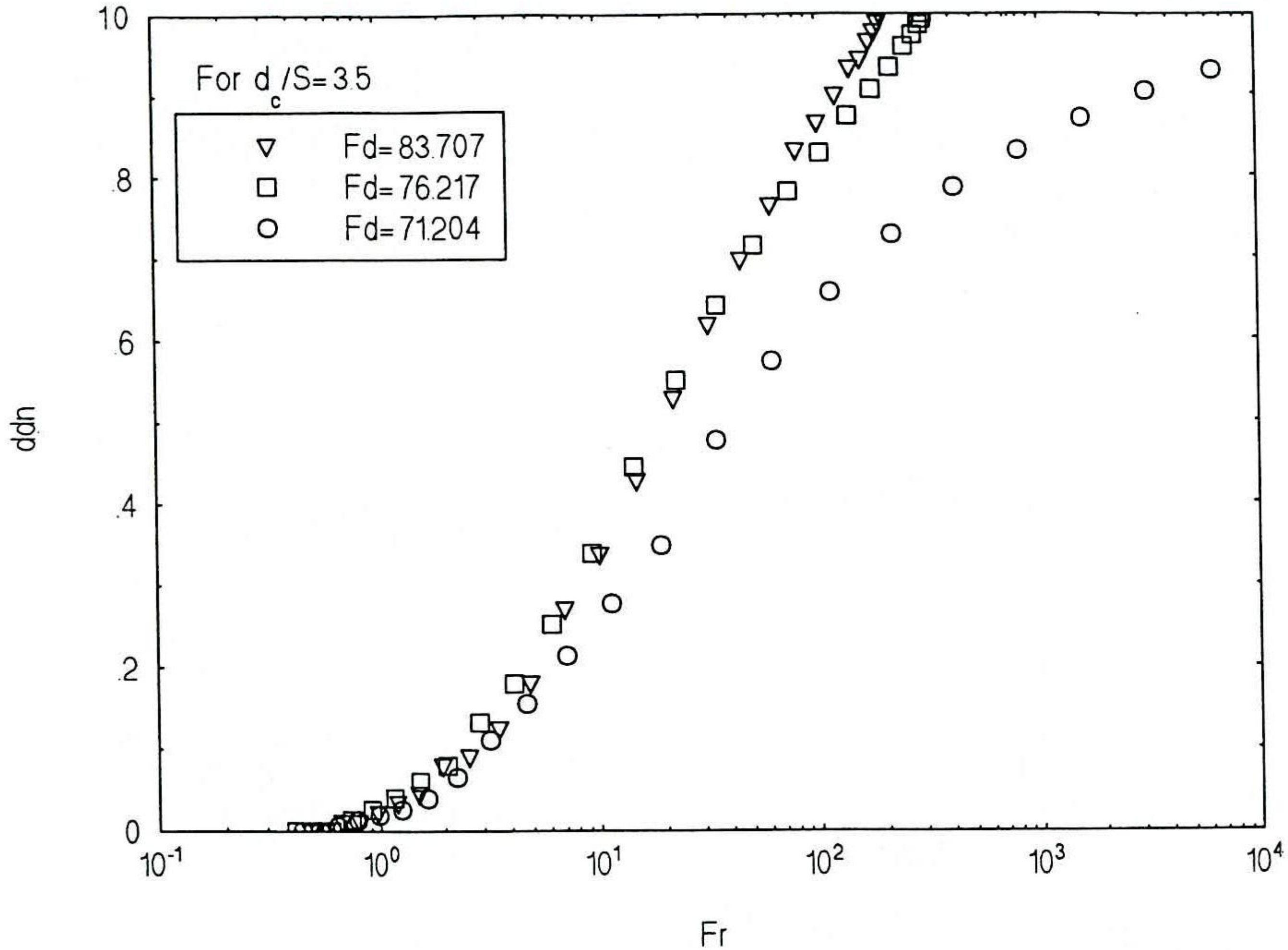


Figure:4.6d: Effect of intake Froude number on Drawdown.

TABLE:4.1

FILE:TAB.DAT

CODE	RUN	dc/S	d(mm)	Q(L/sec)	L(mm)	H(mm)	T1(*C)	T2(*C)	G'(mm/s2
D1H01.DAT	01	0.0	19.9	0.212040	44.13	158.22	44.80	26.78	60.412
D1H02.DAT	02	0.0	19.9	0.422453	54.27	147.98	39.96	28.84	36.016
D1H03.DAT	03	0.0	19.9	0.387386	73.03	156.18	46.04	26.26	66.808
D1H04.DAT	04	0.0	19.9	0.437892	67.11	158.40	38.93	28.12	34.307
D1H05.DAT	05	0.0	19.9	0.379581	61.74	149.98	42.74	27.40	50.584
D1H06.DAT	06	0.0	19.9	0.495010	54.79	159.20	35.84	25.03	31.428
D1H07.DAT	07	0.0	19.9	0.811510	66.71	152.68	40.78	26.67	44.946
D1H08.DAT	08	0.0	19.9	0.707648	67.18	146.05	38.62	25.75	39.335
D1H09.DAT	09	0.0	19.9	0.683246	62.48	150.37	39.14	25.95	40.682
D2H01.DAT	10	1.5	18.8	0.334651	61.28	151.77	34.50	26.47	23.406
D2H02.DAT	11	1.5	18.8	0.586006	70.40	134.69	35.33	24.10	31.910
D2H03.DAT	12	1.5	18.8	0.609387	75.08	145.17	42.43	23.79	58.270
D2H04.DAT	13	1.5	18.8	0.793054	58.72	147.92	35.02	23.27	32.780
D2H05.DAT	14	1.5	18.8	0.605974	65.02	146.05	39.45	24.82	44.584
D2H06.DAT	15	1.5	18.8	0.707648	60.44	148.27	41.51	24.00	60.440
D2H07.DAT	16	1.5	18.8	0.795494	63.78	148.12	39.55	22.35	50.607
D2H08.DAT	17	1.5	18.8	0.800374	63.62	147.15	37.90	26.36	35.213
D2H09.DAT	18	1.5	18.8	0.795494	65.73	146.22	37.80	22.35	44.317
D3H01.DAT	19	2.5	18.8	0.610041	61.13	147.08	38.21	21.52	47.531
D3H02.DAT	20	2.5	18.8	0.707648	65.37	147.99	39.03	21.63	50.271
D3H03.DAT	21	2.5	18.8	0.707648	35.37	147.99	39.03	21.63	50.271
D3H04.DAT	22	2.5	18.8	0.780853	72.53	150.36	38.42	23.58	43.756
D3H05.DAT	23	2.5	18.8	0.766212	64.72	149.49	34.60	23.38	31.196
D3H06.DAT	24	2.5	18.8	0.788987	74.46	146.84	35.74	23.48	34.712
D3H07.DAT	25	2.5	18.8	0.780853	56.56	148.80	35.02	23.79	31.604
D3H08.DAT	26	2.5	18.8	0.744250	63.87	147.89	34.91	21.32	36.682
D3H09.DAT	27	2.5	18.8	0.748317	62.22	147.52	40.17	20.70	56.330
D4H01.DAT	28	3.5	18.8	0.603069	54.94	159.07	34.19	22.35	32.146
D4H02.DAT	29	3.5	18.8	0.695447	54.49	149.77	33.47	22.55	29.391
D4H03.DAT	30	3.5	18.8	0.744250	63.25	148.30	33.37	20.39	33.586
D4H04.DAT	31	3.5	18.8	0.805255	68.33	147.89	32.85	20.70	31.352
D4H05.DAT	32	3.5	18.8	0.748317	70.67	145.16	37.18	19.98	47.030
D4H06.DAT	33	3.5	18.8	0.784920	66.94	153.28	35.84	18.54	45.161
D4H07.DAT	34	3.5	18.8	0.739021	66.45	151.13	35.53	19.46	42.409
D4H08.DAT	35	3.5	18.8	0.747855	64.41	152.12	39.65	20.91	54.013
D4H09.DAT	36	3.5	18.8	0.784920	61.60	151.56	38.93	20.91	51.388
D3H01.DAT	19	2.5	18.8	0.610041	61.13	147.08	38.21	21.52	47.531
D3H02.DAT	20	2.5	18.8	0.707648	65.37	147.99	39.03	21.63	50.271
D3H03.DAT	21	2.5	18.8	0.707648	35.37	147.99	39.03	21.63	50.271
D3H04.DAT	22	2.5	18.8	0.780853	72.53	150.36	38.42	23.58	43.756
D3H05.DAT	23	2.5	18.8	0.766212	64.72	149.49	34.60	23.38	31.196
D3H06.DAT	24	2.5	18.8	0.788987	74.46	146.84	35.74	23.48	34.712
D3H07.DAT	25	2.5	18.8	0.780853	56.56	148.80	35.02	23.79	31.604
D3H08.DAT	26	2.5	18.8	0.744250	63.87	147.89	34.91	21.32	36.682
D3H09.DAT	27	2.5	18.8	0.748317	62.22	147.52	40.17	20.70	56.330
D4H01.DAT	28	3.5	18.8	0.603069	54.94	159.07	34.19	22.35	32.146
D4H02.DAT	29	3.5	18.8	0.695447	54.49	149.77	33.47	22.55	29.391
D4H03.DAT	30	3.5	18.8	0.744250	63.25	148.30	33.37	20.39	33.586
D4H04.DAT	31	3.5	18.8	0.805255	68.33	147.89	32.85	20.70	31.352
D4H05.DAT	32	3.5	18.8	0.748317	70.67	145.16	37.18	19.98	47.030
D4H06.DAT	33	3.5	18.8	0.784920	66.94	153.28	35.84	18.54	45.161
D4H07.DAT	34	3.5	18.8	0.739021	66.45	151.13	35.53	19.46	42.409
D4H08.DAT	35	3.5	18.8	0.747855	64.41	152.12	39.65	20.91	54.013
D4H09.DAT	36	3.5	18.8	0.784920	61.60	151.56	38.93	20.91	51.388

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