ANALYSIS OF FLUID FLOW THROUGH SQUARE-EDGED ORIFICES AND ITS APPLICATION TO LIQUID DISTRIBUTORS

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PREFACE

An experimental apparatus with a recirculating loop was designed, constructed and tested for the analysis of fluid flow through square-edged orifices. This information is to be used in the design of liquid distributors for packed columns. It has been observed that the flow pattern is influenced by parameters such as the hole diameter, plate thickness, effect of deburring, hysteresis and the punch direction relative to the flow direction. Though the relative effect of the individual parameters is small, the cumulative effect of all the parameters may be substantial. Certain phenomena such as vortex formation have also been observed; these have not been analyzed but are found to affect the flow pattern. Further research is underway.

I wish to express my profound gratitude to all the individuals who have helped me in this project and during all thick and thin of my studies at Oklahoma State University. Especially, a lot of thanks are due to my academic advisor Dr. Kenneth J. Bell who has provided me with incomparable guidance, inspiration, moral support and a sense of you-can-do feeling which I think was so important for my success. I sincerely believe that without him, the project and I would not have been successful. I am also sure that the project will be continued in the best professional manner under him. I also am grateful to the other faculty members of my committee and the faculty of School of Chemical Engineering in whole for their invaluable support in my educational pursuits. A special thanks is due to Dr. Arland H. Johannes, who I sincerely believe has been extremely helpful, friendly and most importantly 'approachable' to me and many students of this department. Also, thanks is due to Dr. K. A. M. Gasem for his views while serving on my committee.

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Lastly, I would like to thank Fractionation Research, Inc., the Oklahoma Center for the Advancement of Science and Technology and the Department of Energy for providing financial support for this project. A special thanks is due to Dr. John G. Kunesh of FRI for his suggestions.

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NOMENCLATURE

A	Cross sectional area of orifice, ft^2, m^2
C_c	Contraction coefficient (Eq. 5.15)
C_D	Discharge coefficient (same as C_o)
C_o	Orifice coefficient (Eq. 5.9)
D	Channel diameter, ft, m
d	Orifice diameter, ft, m
l	Plate thickness, ft, m
La	Laplace number, $=\mu/(\sigma\rho d)^{1/2}$
Re	Reynolds number (Eq. 5.1)
V	Approach velocity of liquid, ft/sec, m/sec
We	Weber number, $=\rho v^2 d/\sigma$
Z	Ohnesorge number, $= \eta/(\rho d\sigma)^{1/2}$
β	Diameter ratio of the orifice and the pipe.
δ	Initial disturbance level in the Weber equation (Eq.2.4)
μ	Liquid absolute viscosity, lb/ft·sec, kg/m.·sec
ρ	Liquid density, lb/ft^3, kg/m^3
υ	Liquid dynamic viscosity, ft^2/sec, m^2/sec
σ	Surface tension of liquid, lb/sec^2, kg/sec^2

CHAPTER I

INTRODUCTION

Fractionation is a very important and expensive unit operation in most chemical plants and refineries. Much effort is devoted to obtain higher efficiency in the fractionation columns. The efficiency of a fractionation column is a function of the degree of mixing between the liquid and vapor passing through the column. If the vapor and liquid streams are not in proper contact, the mass transfer between the streams is greatly reduced. This results in low column efficiency and higher operational costs.

Two types of fractionation columns are used. One is the conventional tray column where the liquid passes down the column and over each tray sequentially and the vapor is bubbled upwards through the trays. This method is efficient but suffers from certain drawbacks such as high pressure drop, high initial investment and reduced efficiencies at operating limits due to phenomena such as flooding, weeping and entrainment. The other type is the packed column filled with various types of packing materials. Due to the lower cost, relatively lower weight of the packing material (except ceramic packing) and low pressure drop involved with these columns, they have attracted recent attention. The packing material is of two types as shown in Figure 1. The first is structured packing, formed in a particular geometrical pattern to maximize contact area and minimize pressure drop and weight. Though this packing is relatively expensive, it involves the lowest pressure drop in any contacting equipment. The other type of packing is random packing such as Raschig rings, pall-rings, Lessing rings, etc. These packing materials are randomly dumped into the tower and require substantially higher pressure drop and generally

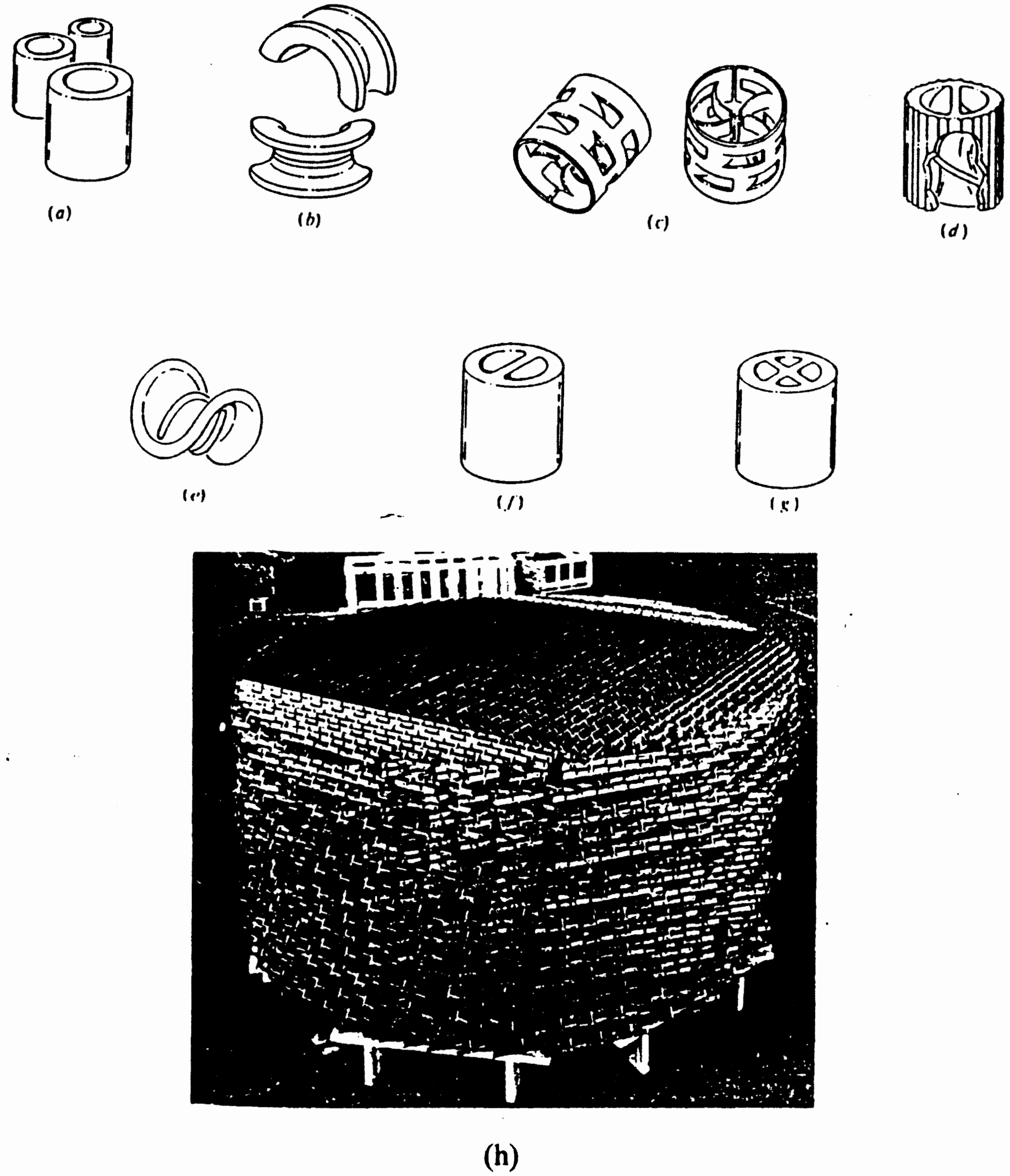

Figure 1. Different types of commercial packing (King J. C., *Separation Processes*, McGraw Hill, 2nd edition, 1980, p-153). (a) Raschig rings, (b) Intalox Saddle, (c) Pall rings, (d) Cyclohelix spiral ring, (e) Berl saddle, (f) Lessing ring, (g) Cross-partition ring, and (h) Structured packing

greater weight than the structured packing. The random packing are less expensive and very easy to install. The relative advantages and disadvantages of the different types of contacting devices are given in Table 1.

TABLE 1

COMPARISON OF DIFFERENT CONTACTING DEVICES

Contacting Device	Cost	Weight	Pressure Drop	Performance
Trays	Expensive	Medium	High	Excellent
Random Packing	Cheap to medium	Medium to Heavy	Medium to High	Medium
Structured Packing	Expensive	Low to Medium	Low	Excellent

The benefits of using structured packing, such as low pressure drop and excellent performance are often reduced by the poor contacting efficiency. Earlier, the poor performance of these packed columns was usually attributed to the inefficiency of the packing material used. After considerable research in this field, especially by Fractionation Research, Inc., maldistribution of the liquid across the cross section of the column has been found to be a major reason for improper contacting between the vapor and liquid streams.

In industrial packed columns, liquid distributors are used for distributing liquid across the cross section of the columns. These distributors are a cluster of channels with orifices punched into the bottom surface or sides of the channels as shown in Figure 2.

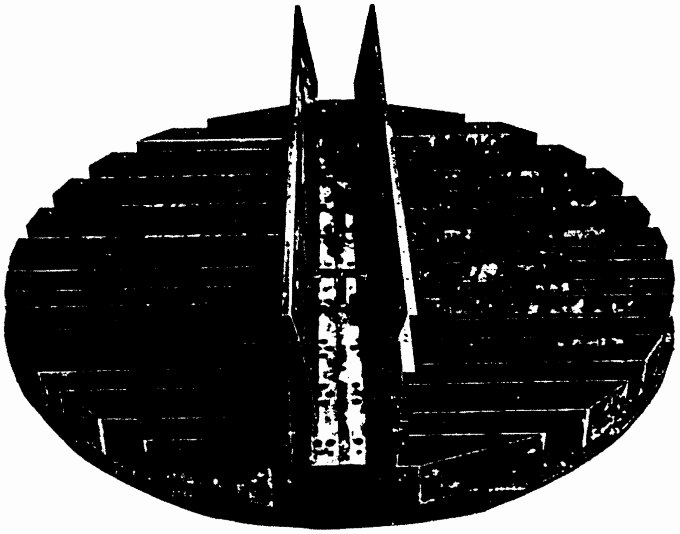

Figure 2. An industrial distributor.
(Nutter Engineering, Bulletin T1-1).

Some have Borda entrances (short tubes) attached to the bottom. Regardless of the geometry, the aim of these distributors is to uniformly distribute the incoming liquid. The problem associated with the functioning of the distributor is that the flow of liquid through orifices and small tubes is not entirely predictable. Liquid flow in an open channel is influenced by various parameters such as the ratio of the horizontal velocity component to the vertical velocity component and the geometrical parameters of the channel. The orifice flow rate is a function of the liquid head, hole diameter, plate thickness, punch direction, whether or not the surface is deburred, etc. To achieve uniform flow distribution, the flow conditions in the distributor and the flow out of the orifice need to be analyzed.

In this study the effect of several parameters of flow through square-edged orifices has been experimentally studied. Also vortex formation, which may occur with such flows, has also been qualitatively observed and studied. Vortex formation is very significant at low liquid heads and appears to be a major reason for the variation in orifice flow rates. Vortex formation can increase the head 2-3 times giving a much lower orifice coefficient at the same flow rate.

The two main purposes of this study were:

A) To design, construct and test a recirculating pilot plant scale experimental facility to be used for measuring the flow behavior of liquid through distributors with multiple orifices. The recirculating facility was designed to provide an input flow rate of around 50 gpm to the distributor to simulate typical industrial conditions, providing the liquid at a constant head to the distributor to minimize flow fluctuations.

B) To measure and evaluate the effect of the various parameters controlling the flow of liquid through a single orifice. The parameters considered to be of concern are:

1] Hole diameter.
2] Plate thickness.
3] Liquid head.
4] Increasing vs. decreasing head (hysteresis).
5] Effect of punching vs. machine drilling
6] Deburred surface at the entrance/exit of the orifice.
7] Direction of punching relative to flow direction.
8] Effects due to variation in punch condition and punching technique among commercial distributor manufacturers.

These data are to be used later in connection with the flow of fluid through multiple orifices.

CHAPTER II

LITERATURE REVIEW

The flow of liquid through orifices is a very common phenomenon and has been closely studied over the years. Orifice meters are frequently applied to measure the flow rate in a pipeline. Especially in custody transfer, accurate flow measurements are important. Hence, the flow characteristics of orifices are widely available in the literature. Though these studies were conducted for orifice flow meters, the data obtained can be used for comparison to our application. For distributors, the liquid flow is in open channels with orifices at the bottom or sides of the troughs, whereas in pipeline flow the flow is in a closed channel and the discharge jet is surrounded by an eddy region of the same fluid.

The literature can be classified into the following sections.

- Orifice coefficient : Available data and analysis
- Flow through an orifice from a transverse stream
- Contraction coefficient
- Jet behavior
- Hysteresis effect
- Available correlations

Orifice Coefficient : Available Data and Analysis

Considerable research has been done to determine orifice coefficients (Eq. 5.9) for fluid flowing through square-edged orifices. Judd and King (1906) experimentally measured the relation between the flow rate and the liquid head for the orifice flow meter application. They predicted the average value of the discharge coefficient to be 0.6066 for high values of liquid head. This value was considered accurate enough, taking into account the uncertainties involved with this kind of flow. Furthermore they analyzed the shapes and diameter of the jets that they obtained in these runs. They also estimated the average contraction coefficient, the ratio of the jet diameter and the orifice diameter, to be 0.6117 and the coefficient of velocity, the ratio of the discharge coefficient to the contraction coefficient, to be $0.9993 \cong 1.0$. They concluded that the discharge coefficient, the contraction coefficient and the unbroken jet length decrease with the increase in orifice diameter. They also ruled out the effect of static pressure on the contraction of the jet diameter when the velocity of approach is neglected. Though these data were for pipe flow rate measurement, the results are generally applicable to any orifice flow application. Later, Medaugh and Johnson (1940) used a 1 in. diameter orifice and found that the discharge coefficient approached 0.595 at high heads. The small deviation from Judd and King's data was explained to be due to minor differences in the orifice geometry.

Tuve and Sprenkle (1933) studied the flow of viscous fluid through orifices. They correlated the orifice coefficient with the Reynolds number ($=dV\rho/\mu$) for $100 < Re < 40{,}000$. Such data are also given in Crane's Handbook for Flow of Fluids (1985) and are given here in Figure 3. More importantly they discussed the advantages and disadvantages of using the Reynolds number as the independent variable. They experimentally proved that the same coefficients were obtained for the same value of Reynolds number though the parameters contributing to the Reynolds number were changed. This finding is very helpful since we can use any data obtained with different conditions and use it for an

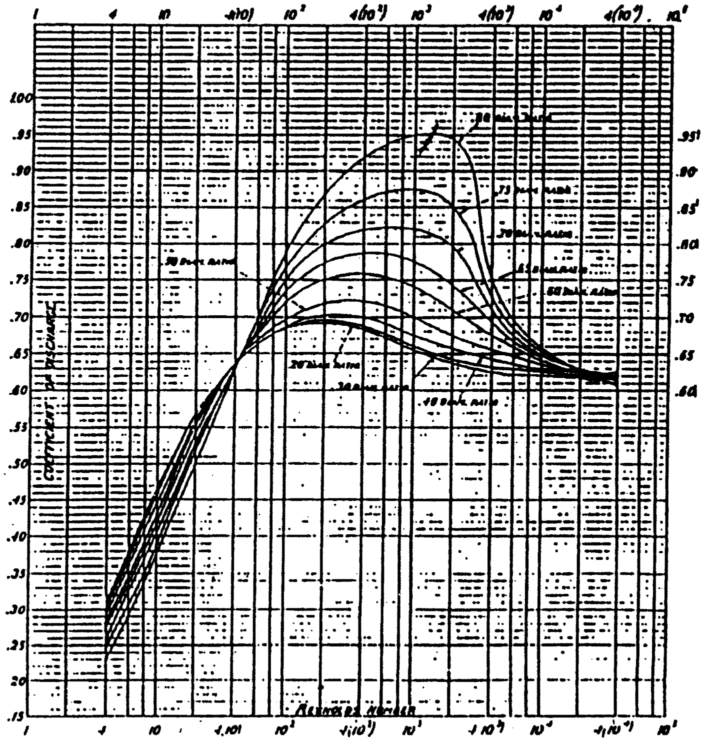

Figure 3. Orifice Coefficient Data Obtained by Tuve and Sprenkle. *(Tuve, G. L. and Sprenkle, R. E., "Orifice discharge coefficients for viscous liquids",* *<u>Instruments</u>, 6, 201-6 (November, 1933).*

entirely different set of conditions using the Reynolds number as the independent variable. Tuve and Sprenkle also discussed that the Reynolds number generalization involves a small error due to the effects of relative roughness, relative orifice edge finish, orifice plate thickness finish and the orifice thickness to the diameter ratio, which are not entirely reproducible. In other words, though we can adjust the gross physical conditions to obtain the same Reynolds number, it is not feasible to perfectly duplicate the geometrical conditions of a different orifice. They have quantified that the error involved due to the geometrical uncertainty is only 1.5%. Hence, if that error is permissible, the Reynolds number approach is very useful.

Lienhard and Lienhard (1984) tried to explain the data obtained by Judd and King by predicting the value of the coefficient of velocity in terms of dimensionless quantities. They based their prediction on conservation of mechanical energy. By including the input, output and dissipated energy terms , they were successful in evaluating the effect of viscosity and surface tension on the liquid jet. They concluded that surface tension cannot prevent the flow of the jet for values of $We > 8\sqrt{C_c}$ but can choke off any circular liquid jet flow for $We \leq \sqrt{C_c}$. They also derived a model for the prediction of the discharge coefficient for a sharp-edged circular orifice. For Re > 10,000 the coefficient of velocity approaches unity with a variation of 0.1%. They also predicted the coefficients for Borda mouthpieces but could not validate them due to the absence of available data.

Linden and Othmer (1949) studied the flow for low values of orifice Reynolds number (Re < 3000). Though their application was entirely different, the results obtained were applicable to all flow conditions involving such low Reynolds number. They analyzed the flow behavior for $d/D < 0.2$ which is typical of our application. Because of the relatively large diameter of the channel compared to the orifice diameter, they were able to eliminate the velocity of approach from their derivation. They used thicker plates than the earlier investigators and predicted the effect of plate thickness and the hole diameter by the ratio r, or the l/d ratio. They did not determine the effect of the plate thickness, but pointed out the possible effects. They gave a nomograph for the determination of gas flow through a square-edged orifice. Perry (1949) investigated the flow rates for compressible flow through square-edged orifices in which the pressure drops below the critical pressure, which is the minimum pressure obtained at the smallest cross section of the liquid path at a given upstream pressure. Perry also studied the relationship between pressure, temperature and orifice area. He also compared the performance of a nozzle with respect to an orifice and derived equations for orifice flow for both the critical and subcritical regions.

Flow Through an Orifice From a Transverse Stream

Several investigators have studied the discharge coefficient for flow out of an orifice which has a stream passing over it transverse to the orifice axis. This condition is central to our application since the distributor is composed of channels in which holes are drilled in the bottom or on the sides. Hence the liquid coming out from one orifice is only a fraction of the total liquid passing over it. Andrews and Sabersky (1990) have studied these flow patterns on an exploratory basis. They have concluded that the orifice coefficients, or the discharge coefficients C_d, differ significantly from the coefficients obtained by the symmetrical flow present in a reservoir. They have measured an increase in flow rate of 30% at high channel Reynolds number ($Re_s = \frac{wu_s}{\nu} > 1200$, where w = width of channel, u_s= velocity in channel and ν = kinematic viscosity) and a decrease of 10% for $Re_s < 200$. They have attributed these changes to the velocity of the main stream. The dynamic pressure associated with the main fluid stream is found responsible for the increase in the discharge coefficients. Their results are reproduced in Figure 4.

In a series of articles published by Ramamurthy et al., the authors analyzed the flow of fluid from an orifice in a channel. Ramamurthy and Carballada (1977) modeled the flow through a rectangular orifice on the side of a channel. They found an empirical correlation for the discharge coefficient. In another paper (1979), the authors solved the problem of inviscid flow past a lateral outlet in a conduit using the Schwarz-Christoffel transformation and streamline theory. The angle between the outlet axis and the orifice plane has been considered as a parameter and the problem was solved using numerical techniques. They have also found the variation in the contraction coefficient to be from nearly 0 to 0.61 for the angle of inclination of the outlet between 0 and $\pi/2$. Later, Ramamurthy, Tim and

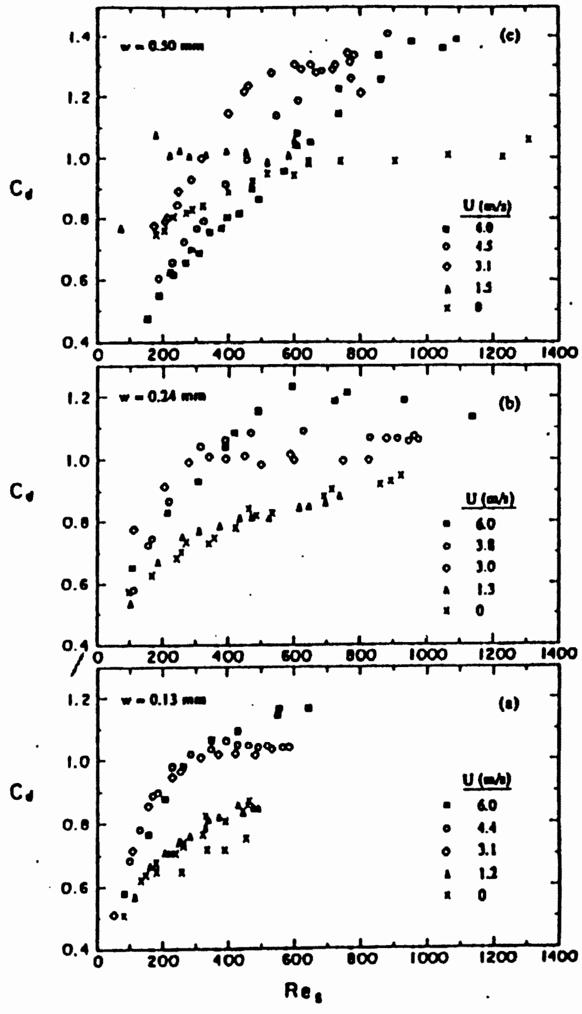

Figure 4. Discharge Coefficients for Various Horizontal Velocities.(*Andrews, K. A. and Sabersky, R. H., "Flow through an orifice from a transverse stream.", Transactions of the ASME, 112, 524-6 (December 1949).*

Saraaf (1986) experimentally analyzed these flow conditions and concluded that the coefficient is a function of the ratio l/w (where l is the length of the orifice and w is the width of the channel) and the velocity ratio between the channel and the jet. Hager (1986) also studied open channel flow with spatially decreasing discharge. He considered the frictional slope, the head loss due to the lateral flow and the lateral flow rate relation. He has also found out that the discharge coefficient for lateral flow depends on the shape of the lateral orifice and not on the dynamic effects. For thin plate orifices, he has found the coefficient to be 0.61 and for laterals with small tubes attached to them (Borda mouthpiece configuration), he has found the coefficient to be 0.815.

Contraction coefficient

Because of the reduction in the cross sectional area at the orifice, the fluid streamlines converge and reduce the jet diameter. Hence, the inertial forces dominate the viscous forces. This results in vena contracta formation a few pipe diameters downstream of the orifice as shown in Figure 5. The contraction coefficient, as defined earlier, is the ratio of the area of the jet at the minimum cross-section to the orifice cross-sectional area. Much work has been done to predict the contraction coefficient for flow through an orifice

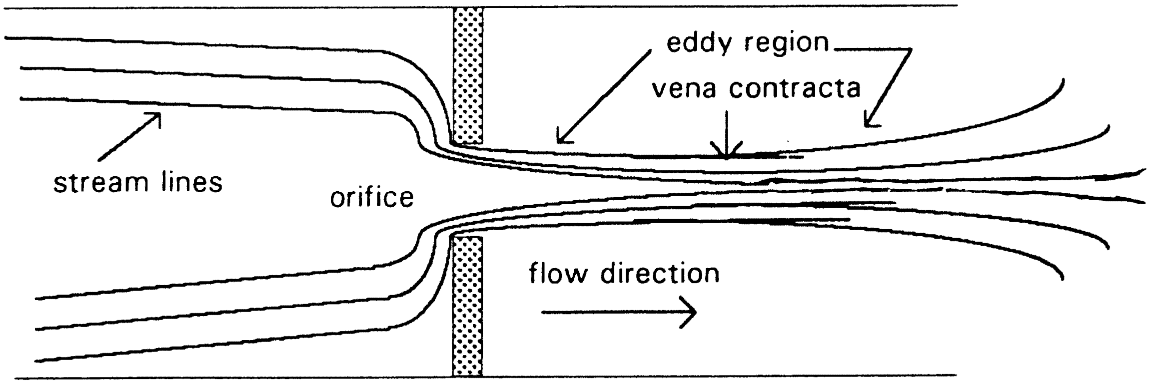

Figure 5. Vena Contracta Formation.

In general, the results agree well but some difference exists among the published results. In inviscid orifice flow, the discharge coefficient and the contraction coefficient are almost identical. Milne-Thompson (1957) used potential flow theory successfully to predict the contraction coefficient for two dimensional flow through an orifice using the conformal transformation technique. He determined the coefficient to be

$$C_C = \frac{\pi}{\pi + 2} = 0.611 \qquad (2\text{-}1)$$

which is in good agreement with some of the experimental results. Streeter (1962) found that when a Borda mouthpiece is fitted to an orifice, the discharge coefficient is 0.5. He attributed this result to the contraction effects. In contrast, extensive data collected by American Society of Mechanical Engineers (1971) shows that the discharge coefficient has a lower value than 0.611 at high Reynolds number. Flugge (1960) confirmed by complex numerical analyses that the value of the contraction coefficient is less than predicted by potential flow theory.

Grose (1985) used the global control volume momentum balance to predict the orifice contraction effect. He predicted the orifice contraction coefficient as a function of the upstream area ratio for an incompressible and inviscid flow. The value of 0.5858 obtained for zero diameter ratio on theoretical grounds agrees well with experimental data. He also proved that at diameter ratios near 0 (<0.2) and near 1 (>0.99), the same contraction coefficient is obtained for circular and non-circular orifices. But at other values of the diameter ratio, the contraction coefficients differ.

Deshpande and Kar (1979) studied the flow of fluid through an orifice as a spread of a confined jet. They modeled the reattachment point of the confined jet and they modeled the contraction coefficient as a function of β and l/d ratio. Their correlation is given as

$$C_C = 0.225\left(\frac{l}{d}\right)\beta + \left[\frac{0.0965 + \beta}{0.2020 + \beta}\right]^2 \qquad (2\text{-}2)$$

where l is the plate thickness; d is the hole diameter and β is the diameter ratio. They have found the deviation between the model and the experiments to be less than 5%.

Jet Structure

The jet discussed here is a free falling jet issuing from an orifice under the influence of gravity. The jet is surrounded by the atmosphere, which in distributors is the vapor of the distillation column. It has been observed that the jet is affected by the disturbances in the flow upstream of the orifice. The structure of the jet is influenced by entrance effects and the orifice geometry as well as the Reynolds number. The jet tends to be turbulent and breaks down into liquid droplets downstream of the orifice.

Many studies have been performed on jet hydrodynamics. McCarthy and Molloy (1974) have given a thorough analysis of the literature on this topic. They concluded that many problems associated with jet hydrodynamics are unsolved. Ohnesorge (1936) distinguished three types of jet breakup. (i) Axisymmetrical disturbance ; (ii) Asymmetrical disturbance ; (iii) Aerodynamic loading. He has modeled the breakup on the basis of the Laplace ($= \frac{\mu}{\sqrt{\sigma \rho d}}$) and Reynolds numbers. Fenn and Middleman (1969) introduced a different criterion, the ambient Weber number We_a , for the disintegration and atomization state. According to them, jet breakup is observed at $We_a < 5.3$ due to axisymmetrical disturbances such as vortices and geometrical deformations.

The jet character, laminar or turbulent, is also an important criterion for studying the effect of jet hydrodynamics. When drag is significant, the disturbances grow along the jet length resulting in sinuous breakup and atomization. Despite vast literature, the reason for turbulence generation and development in the initial part of the jet remains unknown. Accuracy of machining of the orifice and method of liquid supply are also critical with regard to jet behavior. Grant and Middleman (1966) have cited many widely differing papers in which the jet structure is characterized by Reynolds number. They have concluded that the Reynolds number alone is not sufficient for describing the jet behavior. They have experimentally found that the transition from a laminar to a turbulent jet is dependent on the Ohnesorge number, which is given by $Z = \upsilon/\sqrt{\rho d \delta}$, where υ is the dynamic viscosity, ρ is the density and σ is the surface tension. They obtained a relationship of the critical Reynolds number when the transition from laminar to turbulent flow takes place:

$$\mathrm{Re}_C = 325 Z^{-0.28} \tag{2-3}$$

Similar results with different coefficients were obtained by Fenn and Middleman (1969) and Phinney (1975). Van de Sande (1974) and Van de Sande & Smith (1976) investigated the effect of the two dimensional orifice on the jet and concluded that, though the outlet shape is not of major significance, the leading edge has an effect on jet structure.

The breakup length has also been analyzed. Savart (1833), Rayleigh (1878 and Weber (1931) were among the first to study this phenomenon. The breakup length is dependent on many parameters such as inlet velocity, orifice geometry, jet structure, physical properties of the liquid and the surrounding conditions. Orzechowski (1976) analyzed the effect of jet diameter on the breakup length. He concluded that, as the jet diameter increases, the breakup length also increases. Weber (1931) proposed a relation for the breakup length

$$\frac{L}{d} = \ln\frac{d}{2\delta}\sqrt{We_j}\,(1+3Z) \tag{2-4}$$

where δ is the initial disturbance level and $We = \rho v^2 d/\sigma$. The value of (ln d/2δ) is to be found experimentally. Weber found it to be 12 but Grant and Middleman (1966), Fenn and Middleman (1969) and Phinney (1972) found different values. Grant and Middleman (1966) found that the value of (ln d/2δ) is dependent on the Ohnesorge number; the relation is:

$$\ln d/2\delta = -2.66 \ln Z + 7.68 \tag{2-5}$$

McCarthy and Molloy (1974) and Phinney (1972) claim that the breakup length is independent of nozzle geometry.

Iciek (1982 a, b) experimentally studied the effect of the individual parameters on the jet hydrodynamics. He concluded that laminar jets are very unstable and can be reproduced only if all the disturbance-causing sources (such as orifice geometry, inlet turbulence, etc.) are eliminated. The effect of orifice geometry for laminar jets is negligible; for the case when inertial forces dominate the viscous forces, the geometry plays an important role. Iciek showed that the Grant and Middleman correlation is valid for predicting the jet breakup length. For turbulent jets he concluded that the effect of plate thickness is insignificant, and he proposed a correlation for predicting the breakup length. In the second paper, he concluded that, for sharp edged orifices, the outflow can occupy the full orifice cross-section for turbulent flow with or without wetting the orifice wall. Due to air entrapment, the transition from full cross-sectional flow to non-wetting flow can take place. In this case, air occupies the area between the jet and the wall. He proposed a model for the conditions when the transition from full cross-sectional flow to non-wetting flow takes place. This transition is believed to be responsible for hysteresis effects at low heads and low Reynolds number. This effect is discussed in the next section.

Hysteresis Effect

It has been observed by some investigators that at low heads the flow pattern undergoes hysteresis, i.e., the flow behavior changes for increasing as compared to decreasing head. This effect can be attributed to the wetting characteristic of the liquid on the wall of the orifice. When the flow has an established flow pattern, which is the case in decreasing head tests, the fluid has more chance of wetting the inner wall. Iciek (1982) concluded that the change of flow pattern can produce the hysteresis effect. It is more evident at low values of l/d (l/d <2) and low inlet velocities. He has attributed this effect to the 'dead zone' that is formed due to entrapment of air at the inner wall of the orifice at low velocities. But with decreasing head, the dead zone is more stable and prevents the liquid from wetting the walls as in the increasing head case. This results in delayed wetting of the walls.

Deckker (1966) also found similar results and reasons for the hysteresis effect which he observed with square-edged circular orifices with different diameters but the same l/d ratio. McVeigh (1966) contradicted Deckker's statement that the hysteresis effect is a new phenomenon; He gave references to workers who observed the hysteresis effect for different systems with different l/d ratios. McVeigh concluded that this effect is unstable, which is contradicted by Deckker who stated that it is reproducible at low heads. Grace and Lapple (1951) also observed this effect and have discussed secondary factors such as minor pressure fluctuations, surface roughness of the orifice throat and orifice approach conditions.

Existing Correlations

Existing correlations were studied as starting points for future model development. There are several empirical correlation available for predicting the discharge coefficients for a flat plate orifice. Miller (1979) has evaluated the merits of the two most widely used equations with available data. He concluded that the ISO-Stolz equation is significantly better than the ASME-AGA equation for a beta ratio of less than 0.75. The Stolz equation (1975, 1977) is given as

$$C = 0.5959 + 0.0312\beta^{2.1} - 0.184\beta^{8} + 0.0029\beta^{2.5}\left[\frac{10^{6}}{R_D}\right]^{0.75} \qquad (2\text{-}6)$$

This equation was developed for upstream and downstream tap locations whereas in our application the pressure difference is equal to the hydrostatic head at the orifice entrance. Because of the uncomplicated formulation and overall accuracy, this equation is preferred.

The uncertainty in the orifice coefficient is ±1%. On the other hand the ASME-AGA equation was empirically correlated by Buckingham working with the data produced at Ohio State University Tests, documented by Beitler (1935). Until recently, it was the most widely accepted equation for orifice flow data. Bean (1971) has reported the procedures and the detailed development of the ASME-AGA equation.

Miller and Kinsle (1974) also developed an empirical equation. The advantage of their equation is that the regression coefficient can be adjusted to produce 'zero' systematic error, but it is not dimensionless. It also is applicable for pipe sizes 4 in. and larger. Eubank, Hall and Holste (1984,1986) developed an equation for the mass flow rate based on the thermodynamic conditions of the flow. In this equation all the frictional effects are associated with the pressure drop and the temperature change. It is more applicable to compressible flow problems.

Other approaches are also available in literature to obtain numerical solutions of the Navier-Stokes equations. These formulations are grouped by Reed and Oberkampf (1979)into four categories.

1. Primitive variable: Harlow and Welch (1965), Vladimirova et al. (1966), Hirt and Harlow (1967).
2. Vorticity-stream function: Fromm (1963), Fromm and Harlow (1963), Fromm (1964).
3. Vector potential: Aziz and Hellums (1967), Hirasaki and Hellums (1968)
4. Vorticity-velocity: Fasel (1974), Wu (1975).

All of the above employ various stream functions which can be applied with various finite element and finite difference techniques to different boundary conditions.

Reed and Oberkampf (1979) proposed using angular vorticity to reduce the computational complexity involved with the boundary condition for through-flow type problems. This and all other references may be helpful for developing a new theoretical model.

CHAPTER III

EXPERIMENTAL APPARATUS

The two main purposes of this work were: 1) to construct and test a pilot plant scale experimental facility for the analysis of the liquid distributors and 2) measure and analyze the discharge coefficients from different single hole plates available from various commercial manufacturers. The data obtained from the single hole plates will later be applied to the analysis of commercial scale distributors. Hence, in addition to the pilot plant scale experimental facility, we designed and constructed an ideal single orifice test facility. The single orifice test facility is discussed first and then the pilot plant scale recirculating loop test facility will be described.

Single Orifice Test Facility

Almost all of the testing discussed in this study was done on the single orifice test facility. The apparatus is simple and easy to operate. The main components of the apparatus are:

1) Cylindrical tank

2) Plates, each with a single orifice

Cylindrical Tank

A cylinder made of Plexiglas with an inside diameter of 11.5 in. and height of 3 ft.

was supported on an adjustable frame. A schematic diagram of the apparatus is shown in Figure 6. Circular plates of 14.5 in. diameter were attached to the base of the cylinder. The plates were tightly sealed between the cylinder and the supporting metal flange by o-rings and eight peripheral bolts. A scale (in centimeters) was attached on the outer surface of the cylinder to measure the liquid level.

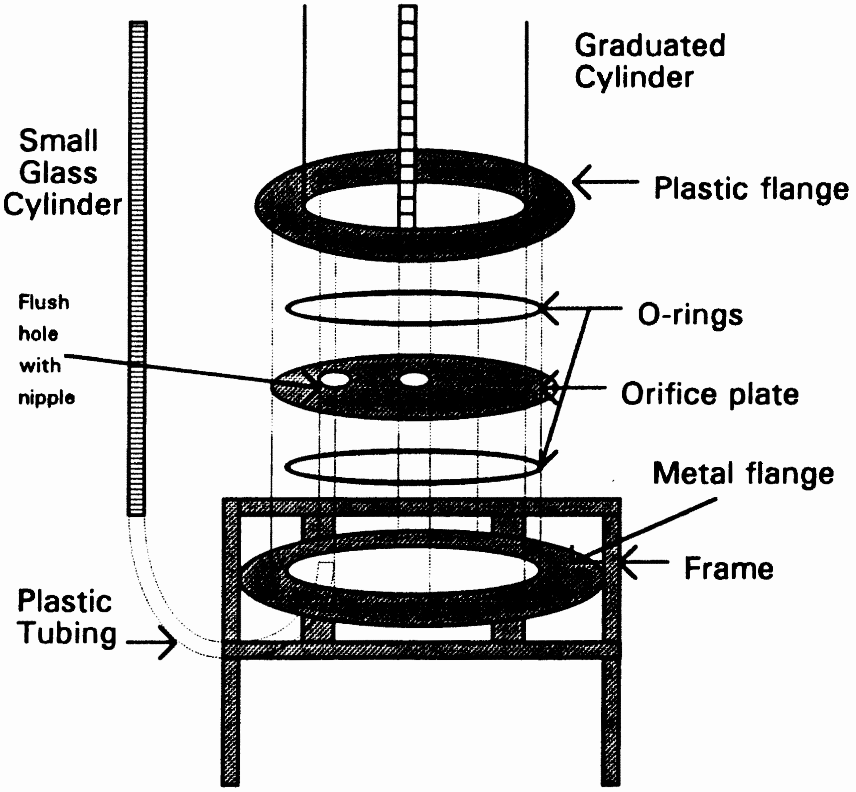

Figure 6. A Schematic Diagram of the Single Orifice Test Facility.

A liquid level indicator was constructed which gave accurate readings of the liquid level. A flush hole with a nipple screwed on the underside of the plates was connected by a small plastic tubing to a small diameter glass cylinder which also had a centimeter scale marked on it. Because of this arrangement, small fluctuations in the liquid level in the cylinder did not affect the level in the small cylinder. Hence, the readings were stable and the precision was higher.

Plastic tubing of 0.75 in. inside diameter was used as the liquid inlet to the cylinder. A control valve was used to vary the flow into the cylinder and thereby vary the liquid level. The liquid jet coming out of the orifice in the plates was collected over a measured period of time before sending it to drain. Since the jet sometimes was found to be turbulent and broken with splashing, a large diameter funnel was used to collect the outcoming liquid.

Plates

Eighteen orifice plates, supplied by two commercial manufacturers, each with a single circular orifice punched or drilled in the center were tested. The purpose was to test the effect of the various parameters involved such as plate thickness, hole diameter, punch direction relative to the flow direction, deburring, etc., and to find out if there were considerable differences in the plates manufactured by different commercial manufacturers for the same geometrical configuration. Each manufacturer provided us with a set of nine plates of three plate thicknesses, viz. 0.25 in., 12 gage and 14 gage and three hole diameters, viz. 0.25 in., 0.5 in. and 0.75 in. All of these plates had punched holes. The magnified view of the cross-section of the plate near the orifice is shown in Figure 7. The rounding effect shown in the figure is our estimation of the surface near the orifice due to the punching effect. Some plates provided by one manufacturer had a deburred surface on the opposite side of the plate.

An attempt was made to compare the punched holes with 'standardized' drilled holes. Plates with the same geometrical configuration as the punched plates, but with drilled and reamed holes were obtained. These were referred to as the 'standard plates'. These plates

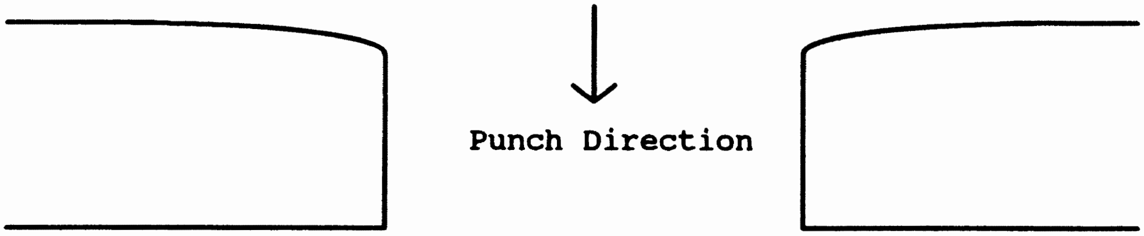

Figure 7. Cross-Sectional View of the Plates Near the Orifice.

were prepared in the Physics Department machine shop at Oklahoma State University. Since the holes in these plates were drilled, we assume that there was little or no rounding of the edge of the hole. The presumed cross-sectional view of these plates is shown in Figure 8.

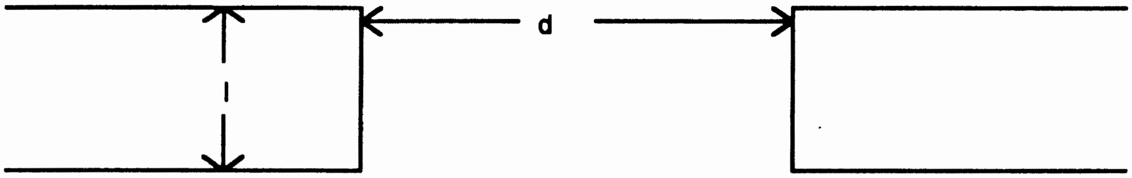

Figure 8. Cross-Sectional View of the Plate with the Drilled Holes.

The nomenclature adopted for identifying the plates is given in Appendix A. We also measured the hole diameters. Each hole diameter was measured by two persons with five measurements for each hole diameter by each person. A set of measurements with their average values is shown in Appendix B.

Recirculating Flow Test Loop

Objective

A substantial part of this work was devoted to the design, construction and running of a pilot plant scale experimental facility for testing liquid distributors. The aim was to construct a recirculating loop for flow rates from less than 1 to 50 gpm. In addition to the large flow rates, the liquid was to be supplied at a constant head to the control valves in the lines to the distributors. Since we were trying to simulate an industrial scale distributor, it was essential to supply the liquid at a constant flow rate. Emphasis was also on the precise measurement of the flow rates and liquid level. A pumping system was designed and constructed as shown in Figure 9. To accommodate the range of flow rates and to reduce throttling of the pumps, we constructed a smaller diameter line for the 1-10 gpm range and a bigger line for 10-50 gpm range.

Description of the Pumping System and its Components

The pumping system is shown in Figure 9. Water was used for the present studies. Water is first collected in the feed tank. From the feed tank, the water is pumped by two centrifugal pumps to a constant head tank at a height of 10 ft. To keep the velocity in the pipes less than 10 ft/sec, the pipe with a maximum flow capacity of 10 gpm is built of 1/2 in. schedule 40 PVC pipe. The other line with 50 gpm capacity is built of 2 in. schedule 40 PVC pipe. A rotameter was used in each line for measuring the flow rates involved.

A constant head tank was installed at a height of 10 ft. above the floor level to provide liquid at a constant head to the control valves in the lines leading to the distributor.

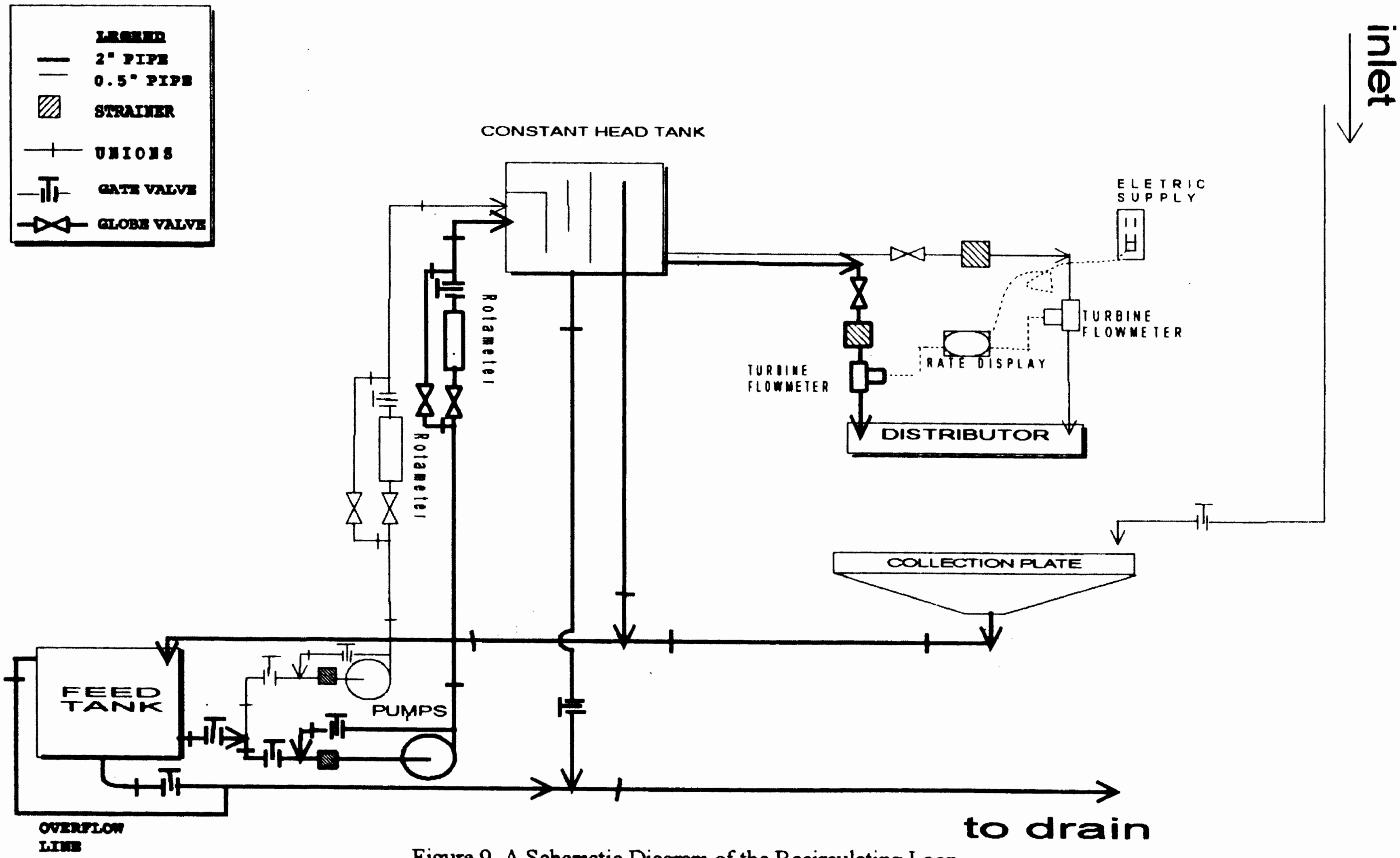

Figure 9. A Schematic Diagram of the Recirculating Loop

Control valves are used to vary the flow rate in each line. The flow rate is measured by turbine flow meters which give digital readouts of the flow rates with an accuracy of ±0.5 % of reading. A collection trough is installed below the distributor to collect the water and recirculate it back to the feed tank.

The main components of this system are --

-- Feed tank

-- Strainers

-- Pumps

-- Rotameters

-- Constant head tank

-- Collection trough

-- Turbine flowmeters

-- Connections, support system and control panel

Each component is discussed in detail below.

Feed Tank: The feed tank is an off-the-shelf plastic tank with a cover and a capacity of 60 gallons. A schematic diagram of the tank is shown in Figure 10. The main purpose of this tank is to store the water in the system. Two 2.375 in. holes were drilled in the tank for the drain and for the feed line to the pumps. Since the tank is of plastic, the tank and the pipes were connected with necessary precautions. A gate valve is provided on the feed line to close the system while not in operation. Another gate valve is provided on the drain line.

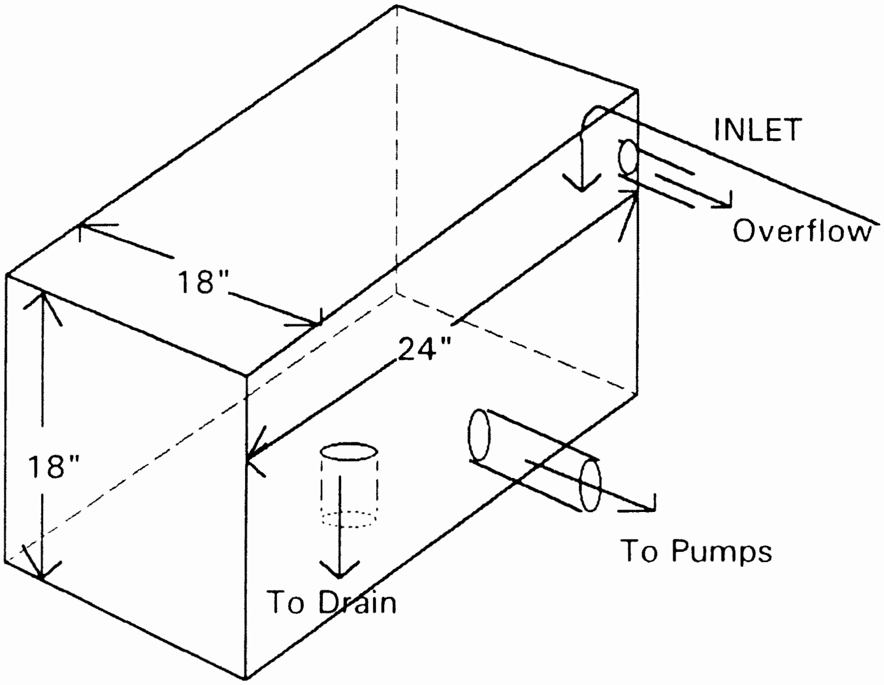

Figure 10. A Schematic Diagram of the Feed Tank.

Since the drainage line is from the bottom of the tank, the tank is raised from the floor about 8 in. In addition to the inlet, outlet and drain, an overflow line is also provided. The tank is properly supported.

Pumps: The input flow rate to the distributors is to be varied from less than 1 gpm to 50 gpm. The smaller line (1/2 in.) is designed to be used for the 1-10 gpm range and the bigger line (2 in.) is designed for the 10-50 gpm range. This helps avoid throttling the pumps to very low flow rates.

Besides the flow rates, the other consideration was head loss. In addition to the static head of 10 ft., the head loss due to the rotameter and four valves was considered. The heads required for delivering the maximum flow rates for each pipe were estimated to be less than 35 ft. of water for the 1/2 in. line and 22 ft. of water for the 2 in. line. The pumping arrangement is shown in Figure 11. A gate valve is provided upstream of each

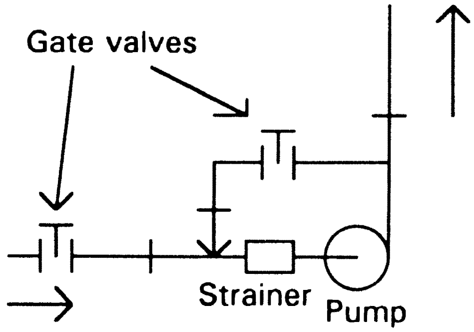

Figure 11. Connections and accessories around the pump.

pump. The bypass line is used when less than maximum flow is desired. This improves the stability and constancy of the flow rate delivered to the constant head tank. A gate valve in the bypass line controlled the flow in the bypass.

Strainers: Strainers were provided on each line upstream of the pumps to remove any entrained particles and protect the pumps. The strainers have a mesh screen with 3/64 in. perforations. The screen can be cleaned by opening a blowoff valve installed at a blowoff connection or by simply removing a plug in the blowoff flange. The strainers are made of cast bronze. Another set of strainers is installed in front of the turbine flowmeters since the turbines can also be damaged by the solid particles.

Rotameters: Rotameters were installed in each of the two lines between the pump and the constant head tank. The main purpose of the rotameters was to indicate the flow in each line. The higher side of the flow rate is of minor significance because any extra water is circulated back to the feed tank.

The rotameters are glass tube variable-area flow meters providing a visual indication of the flow rate on a linear scale. In addition to the ease of observation on the linear scale (in gpm), the glass meter tube and the float can be easily removed for change of range or for repair without disturbing the piping. The rotameter body is constructed of stainless steel. A polycarbonate shield protects against injuries in the event of glass breakage. The accuracy of the meter is ±2% of maximum flow. Since the rotameters are heavy, they are supported on the frame structure built for the constant head tank.

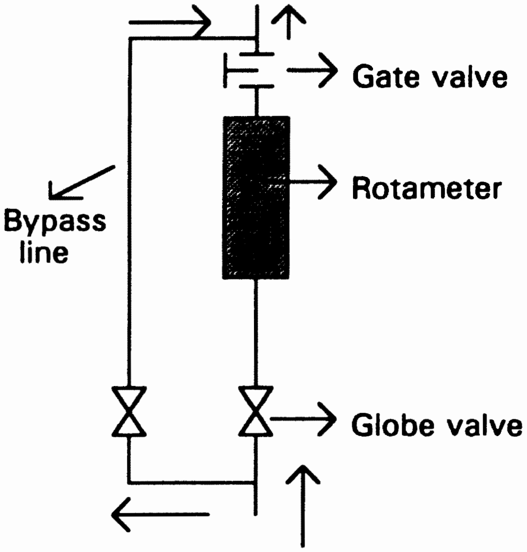

Figure 12. Piping Arrangement for the Rotameter.

As shown in Figure 12, bypass lines are provided around the rotameters to protect them from sudden shocks at startup. A globe valve is placed in each of the lines before the rotameter to control the flow rate in the system. Another globe valve is placed in the bypass line. A gate valve is provided downstream of the rotameter to shut off the rotameter while operating with the bypass line. At startup, the flow is diverted through the bypass line. Then, the globe valve and the gate valve above the rotameter are opened and the globe valve in the bypass line is closed. This startup procedure reduces the thrust on the tube and the float.

Constant Head Tank: This tank supplies liquid to the distributor piping and metering system at a constant head. The tank is designed to hold 25-30 gallons of water, with dimensions of 18 in. x 15 in. x 18 in. The tank is built of plexiglass. The schematic diagram of the tank and the baffles are shown in Figure 13(a), (b), (c) and (d). All the baffle plates with dimensions are also shown separately.

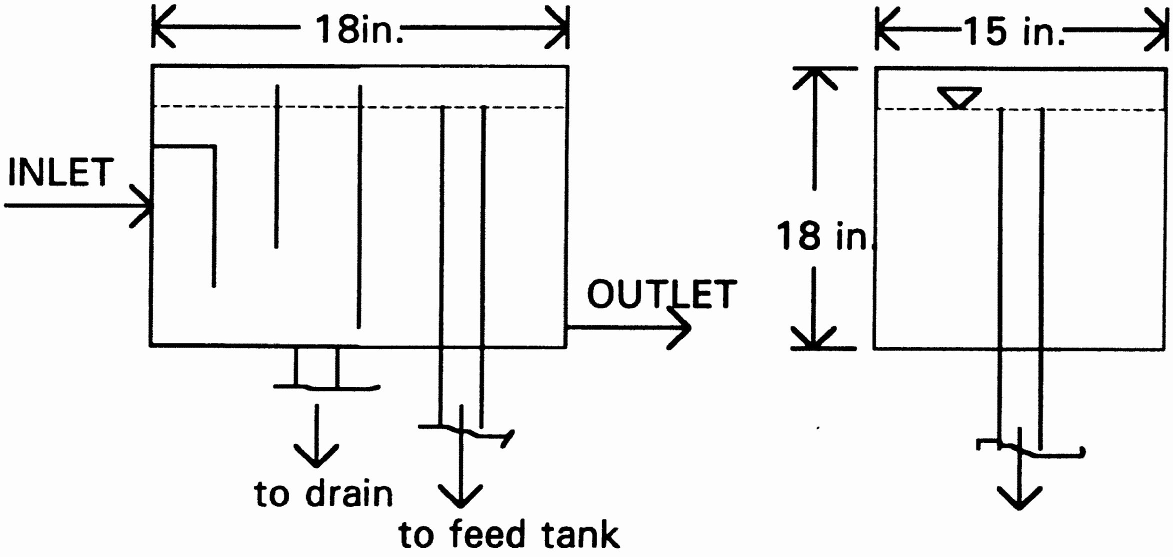

Figure 13(a). A Schematic Diagram of the Constant Head Tank.

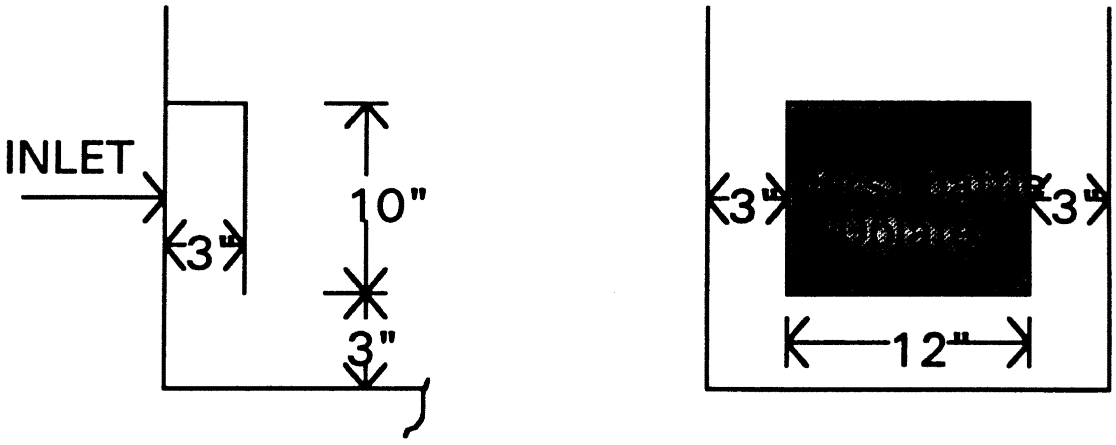

Figure 13(b). The First Baffle Plate.

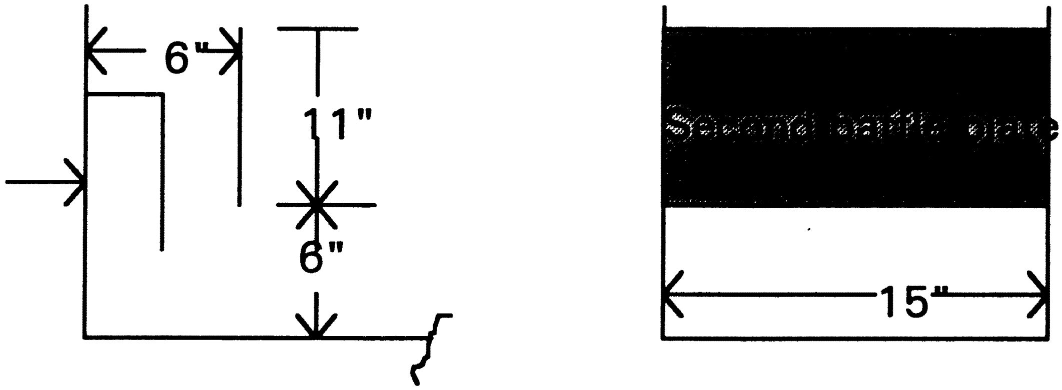

Figure 13(c). The Second Baffle Plate

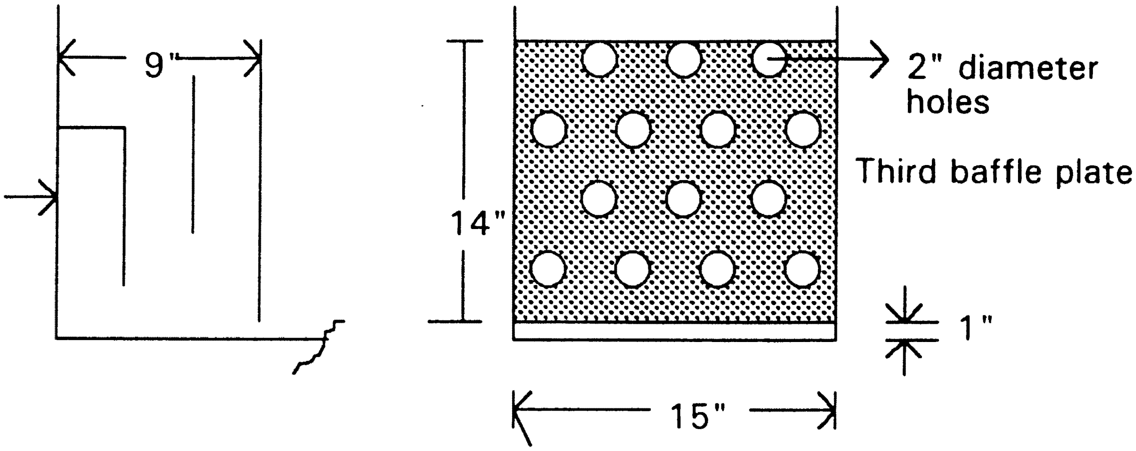

Figure 13(d). The Third Baffle Plate.

To obtain a constant head outlet we need to do two things.

1) Reduce the velocity of the incoming water substantially.

2) Provide a constant head outlet.

The first goal is met by three baffles. Each baffle plate has a different geometry but is used to break up the jet of incoming water. The maximum velocity of the water in the 1/2 in. pipe line is 10 ft/sec. This is reduced to 0.1 ft/sec in the tank.

The constant head section provides the arrangement for supplying constant head outlet. This section contains a 2 in. pipe projecting upwards from the base of the tank. The desired height of liquid in the tank is about 15 in. The pipe is 14.5 in. high from the base. The water in excess of the desired flow rates is recirculated back to the feed tank. Hence, at all times, the outlet from the constant tank has a head of 15 in. A drainage line is also connected to the base of the tank.

Two outlets are provided on the bottom of the tank, one each for the 1/2 in. and 2 in. pipe line. These pipes feed water to the distributor. All pipes are connected to this tank by rubber hose connectors which are flexible enough to absorb any vibration associated with the pipes and thereby avoid stresses in the tank.

Turbine Flow Meters: The flow rates into the distributor are measured by turbine flow meters (OMEGA Engineering, FTB-100 series) which have an accuracy of 0.5% of the reading.

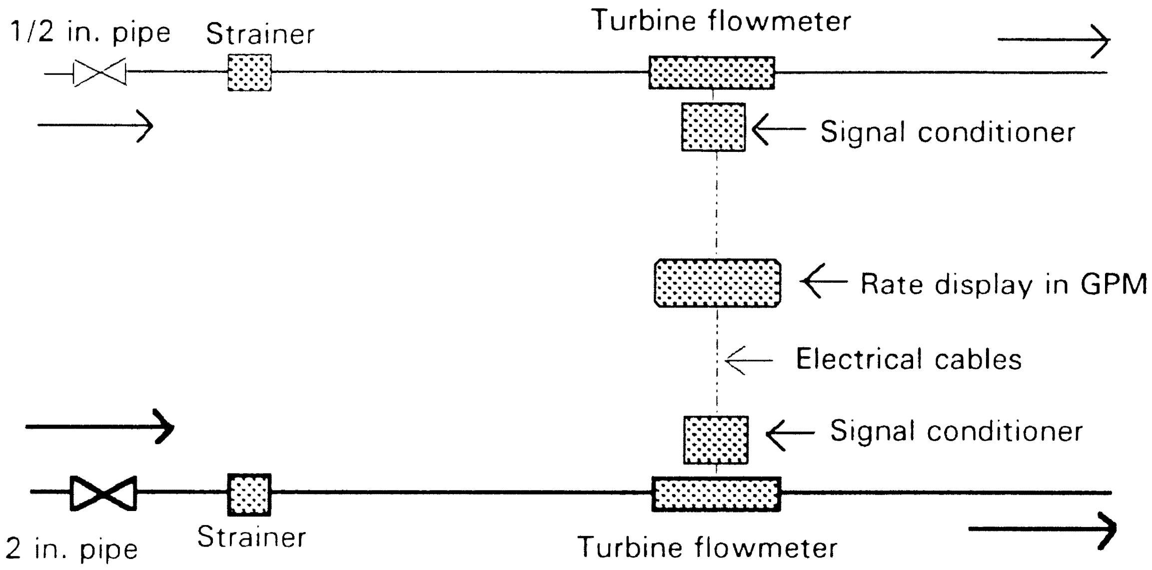

Figure 14. A Schematic Diagram of the Turbine Flowmeter Connections.

The turbine flow meter has a vaned rotor which rotates at an angular velocity proportional to the velocity of the water. Due to the rotation of the turbine, a pulsed AC output is produced. This output is proportional to the velocity and thereby the flow rate of the water. This signal goes to the signal conditioner which accepts the low-level sensor output and conditions and amplifies it to a high-level signal, which is not affected by ambient noisy conditions. The signal conditioner is mounted on the turbine flow meter itself so that the possibility of signal interference and distortion is greatly reduced. The output from the signal conditioner goes to the display unit. The display unit senses the signal from the conditioner and converts it into a display in gpm. The display unit is programmed to accept the pulsed output from the conditioner and convert it to gpm units using the K-factor of the flow meter. Presently, we are using only one display unit for both flow meters so we need to feed in the value of the corresponding K-factor for each flow meter.

The turbine flow meter is made of 304 stainless steel to minimize corrosion. The turbine flow meter requires at least 10 pipe diameters of straight pipe upstream of the meter and at least 5 pipe diameters downstream of the meter for proper installation and performance of the meter. The flow rates we are using need a $1\frac{1}{4}$ in. flow meter for the larger pipe and 3/4 in. flow meter for the smaller pipe. To account for the change in diameters, reducers and enlargers have been provided. The reducers and enlargers are kept sufficiently far from the meter to meet the uniform diameter requirements.

Strainers are mounted upstream of the meters to remove any undesirable solid material. The strainers have a screen with 3/64 in. perforations which are capable of removing any destructive particle flowing in the system. Globe valves are also provided upstream of the meter to vary the flow into the distributor.

Collection Trough: The water coming out of the distributor is collected and recycled back to the feed tank. A collection trough has been designed and constructed. A schematic diagram of this device is shown in Figure 15.

The collection trough has a slanted bottom so that the water collected is circulated back to the feed tank. The distributor is estimated to be 4 ft long and 6 in. wide. Also, the water jet issuing from the orifices may become turbulent and have a larger spread. Hence, to avoid spillage, the collecting device has been made larger. The dimensions of the collection plate are 5 ft x 2 ft x 1 ft. A screen is placed on top of the plate so that the splashes are greatly reduced. The collecting device is made of galvanized steel.

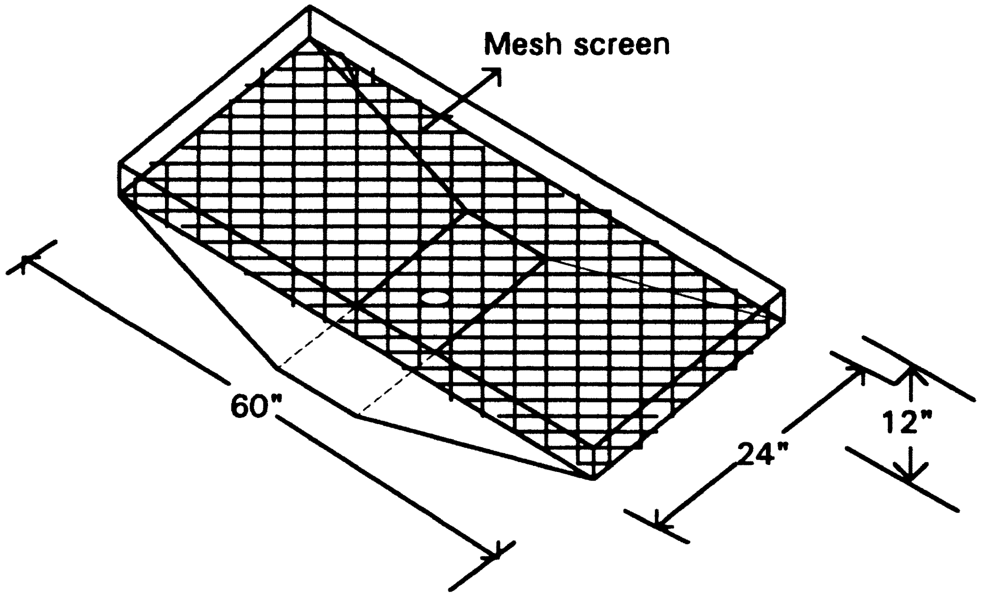

Figure 15. A Schematic Diagram of the Collecting Trough.

Connections, Support System and Control Panel: PVC piping was selected because of its low weight and protection against corrosion. All the piping used was schedule 40. Sufficient compression couplings were used so that the removal of any component for repair or replacement from the system may be done easily.

All of the major units in the system are properly supported. Since the constant head tank carries a substantial weight of water at a height of 10 ft., it was necessary to build a firm support structure. A 3 ft x 2.75 ft x 10 ft frame structure of angle iron is built and attached to the wall. All the pipes connected to the constant head tank are supported on this frame. Since the valves and other components are heavy, all fittings are secured to the wall or to the frame.

The pumps are mounted on the floor. The feed tank is firmly secured on a small table-like stand. The collecting trough is also mounted on a firm stand. The height of the stand was selected so that the water from the collecting trough flows by gravity to the feed tank. Since the overflow from the overhead tank is also connected to this line, the height of the collecting trough was selected so that the flow of water does not back up in the collecting trough.

The turbine meters and the signal conditioners are also properly secured to a support fastened to the wall. All electric connections are insulated and grounded. The pumps are also connected and grounded properly. The control switches for the pumps, the turbine meters and the display unit are placed on a control panel fixed on the frame.

CHAPTER IV

EXPERIMENTAL PROCEDURES

In chapter III, the apparatus used for the test of single orifice plates and the recirculating flow loop are discussed. In this chapter a brief overview is given regarding the operation, problems and troubleshooting of these apparatuses. The majority of the present runs were taken on the single orifice facility. Some runs were also taken on the recirculating flow loop.

Single Orifice Test Apparatus

This apparatus provided data on the flow of fluid through a single orifice punched or drilled in a plate. As described earlier, plates obtained from two commercial distributor manufacturers and the 'standard plates' were tested and evaluated. Some runs were repeated to check the reproducibility of the data. Necessary precautions were taken to reduce the experimental error.

Procedure

[1] The apparatus was leveled.

[2] The plate to be tested was fixed to the cylindrical reservoir by the peripheral bolts.

[3] The point corresponding to zero liquid level in the cylinder was accurately measured in the level indicator (zero point).

[4] The inlet tubing to the cylinder was straightened and centered to reduce vortex formation.

[5] Water feed input was slowly started by opening the gate valve on the input piping.

[6] The liquid head was accurately measured on the level indicator when it achieved steady state.

[7] At steady state, the flow rate out of the orifice was measured by collecting approximately 400-1000 ml of water over a measured time interval.

[8] The head was slowly increased to a new steady state and the next reading was taken.

[9] This process was continued until a high head (around 2 ft.) was reached (distributors are normally operated at a liquid head between 2 in. and 8 in.) or until the flow rate through the orifice was too high to be easily and accurately measured.

[10] The same process was repeated while decreasing the input flow rate.

[11] Readings for the decreasing head were taken until the head was very low, i.e., less than 5 mm.

[12] A new plate was installed and the procedure repeated.

Precautions

A] The plate should be examined for any bend on the surface.

B] The apparatus should be perfectly leveled. The liquid level measurement is affected if the leveling of the apparatus is not perfect. Especially at low heads, different fluid motion might be experienced due to a small inclination.

C] The zero point should be accurately measured. The level indicator is to be repositioned each time the plates are changed; this changes the zero point. Since the actual liquid head is obtained by subtracting the reading in the indicator by the zero point, the error in the zero point is translated to all the readings. Especially, at low heads i.e. less than 1 in., the error can be significant.

D] At low heads (less than 6 in.), the head should be increased slowly . Normally, distributors are designed for a liquid level not more than 8-10 in. Experience shows that the majority of uncertainty involved is for the low to very low heads (less than 1 in.). Various phenomena such as hysteresis, vortex formation, etc., are important in this range. This justifies the approach of taking more readings in this range to check the reproducibility of the data.

E] The inlet tubing should be adjusted so that vortex formation is avoided. If the incoming liquid is introduced at an angle, a stable vortex is caused. (We were cautioned by one of the commercial manufacturers regarding the formation of vortices.) If a vortex forms, at a given flow rate, the liquid head may increase by a factor of 2 or 3. This decreases the orifice coefficient since the coefficient is inversely proportional to the square root of the head.

Recirculating Flow Test Procedures

This apparatus was constructed to measure the flow characteristics of multiple orifices in a common distributor. A few runs were made on this facility for testing purposes and for validating the data obtained by the single orifice tests.

Startup

1] The maximum flow rate for the run is estimated. On that basis, the pumping system (2 in. or 1/2 in.) is selected.

Flow rate < 10 gpm → 1/2 in.

Flow rate > 10 gpm → 2 in.

2] The feed tank drainage valve is closed.

3] The inlet valve is opened and the feed tank is filled.

4] After the tank is full, the outlet to the required pump is opened

5] The valves in the bypass lines of the pump and the rotameter are opened. The bypass around the pumps helps in reducing the stress on the pumps if throttled heavily. The bypass around the rotameter helps in reducing the sudden thrust on the tube and the float of the rotameter. The upstream valve at the rotameter is closed.

6] The drain valve in the constant head tank and the outlet valve to the distributor are closed.

7] The pump is started and the constant head tank is filled.

8] The bypass to the rotameter is slowly closed and the rotameter is brought on-line

10] The outlet from the constant head tank to the distributor is slowly opened so that the turbine meter is not subjected to sudden surge.

11] The electrical connection to the signal conditioner and the meter is turned on and the rate indicator is programmed for the K-factor according to the pipe line used.

TABLE 2

K-FACTORS FOR THE FLOW METERS

Line size	K-factor
1/2 in.	5093.95 pulses/gallon
2 in.	418.79 pulses/gallon

12] The readings are taken as in the single orifice tests.

Shutdown

1] The valves around the rotameter are closed. The valve in the bypass line around the rotameter is opened.
2] The pump, the turbine flow meter and the rate meter are switched off.
3] The outlet from the feed tank to the pumps is closed.
4] The drain valve from the feed tank is opened.
5] After the feed tank is drained off, the drain valve from the overhead tank is opened and the drain valve from the feed tank is closed to prevent any back flow into the feed tank.

Maintenance Procedures

Some steps need to be taken for the maintenance of the system.

1] The turbine flow meters should be recalibrated every 3 months.
2] The rotameters should be recalibrated regularly.
3] The strainers are to be regularly checked to remove any particulate material.
4] The pumps also need to be lubricated and serviced at least once a year to prevent damage.

CHAPTER V

DATA INTERPRETATION

The data obtained is in terms of volume of liquid collected in measured time interval at a measured head. This data needs to be converted to Reynolds number and the corresponding orifice coefficient. The same data is also plotted as liquid head vs. volumetric flow rate. The later plot is very useful for design purposes since the designer needs the head along with the hole diameter and the plate thickness to achieve a required flow rate from the orifice. On the other hand, the Reynolds number vs. orifice coefficient relation is more general and can be used to generate head vs. volume curves for any liquid of known density and viscosity. The advantage of converting the data to dimensionless quantities is the generality obtained in interpreting the data.

Head vs. Flow Rate Relationship

This relationship is easily obtained since the data is in terms of the head vs. volume of liquid collected in a specific time. The volume is divided by the time to give the flow rate. Such data is available in Appendix C.

Reynolds Number vs. Orifice Coefficient

The Reynolds number is defined as

$$\mathrm{Re} = \frac{dV\rho}{\mu} \tag{5-1}$$

where, d = hole diameter, m or ft

V = velocity calculated assuming that uniform flow occurs through the entire cross sectional area of the orifice, m/s or ft/sec

ρ = density of the liquid, kg/m^3 or lb/ft^3

μ = viscosity of the liquid, kg/m·s or lb/ft·sec

The orifice coefficient is obtained by considering Bernoulli's equation applied to the two stations as shown in Figure 16.

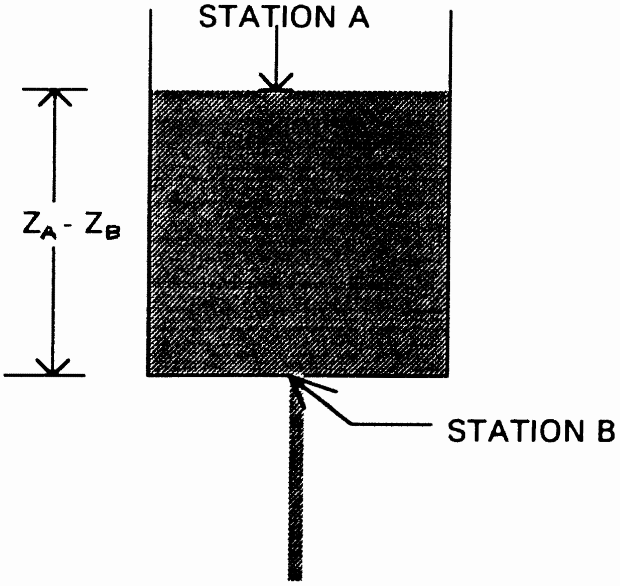

Figure 16. Flow System with Reference Points For Bernoulli's Equation.

Assumptions:

1. Incompressible fluid
2. Frictionless flow (frictional effects will be considered later)
3. Velocity at A is uniform across the surface.
4. Velocity at B is uniform across the area of the orifice.
5. Steady state
6. Pressure at A and B is atmospheric and constant.

Applying Bernoulli's equation for the station A and B,

$$\frac{P_A}{\rho}+\frac{gZ_A}{g_C}+\frac{\alpha_A V_A^2}{2g_C}=\frac{P_B}{\rho}+\frac{gZ_B}{g_C}+\frac{\alpha_B V_B^2}{2g_C} \tag{5-2}$$

Now, collecting the velocity terms, we get

$$\frac{\alpha_A V_A^2-\alpha_B V_B^2}{2g_C}=\frac{P_B-P_A}{\rho}+\frac{g}{g_C}(Z_B-Z_A) \tag{5-3}$$

From the continuity equation, taking density as constant,

$$V_A=\left(\frac{D_B}{D_A}\right)^2 V_B \tag{5-4}$$

Considering the diameter ratio as β,

$$V_A=\beta^2 V_B \tag{5-5}$$

From equation (5-3) and (5-5), we get

$$\frac{\alpha_A\beta^4 V_B^2-\alpha_B V_B^2}{2g_C}=\frac{P_B-P_A}{\rho}+\frac{g}{g_C}(Z_B-Z_A) \tag{5-6}$$

which leads us to the equation for V_B as

$$V_B^2 = \frac{1}{\left(\alpha_A \beta^4 - \alpha_B\right)}\left[2g_C\left(\frac{P_B - P_A}{\rho}\right) + 2g\left(Z_B - Z_A\right)\right] \tag{5-7}$$

Now, since the stations are subjected to the same atmospheric pressure, $P_A = P_B$ and $(Z_B - Z_A) = -h$, where h is the head of liquid above the orifice. Substituting in equation (5-7),

$$V_B^2 = \frac{1}{\left(\alpha_A \beta^4 - \alpha_B\right)}\left[2g(-h)\right] \tag{5-8}$$

The effect of any difference in orifice area and jet area, kinetic energy correction factors and friction are lumped into a coefficient term which is the orifice coefficient, C_o, given by:

$$V_B = \frac{C_O}{\sqrt{1-\beta^4}}\sqrt{2gh} \tag{5-9}$$

This is the equation for the orifice coefficient. The Reynolds number is obtained by equation (5-1). In both equations, (5-1) and (5-9), the velocity term is substituted by:

$$V_O = \frac{\text{Volumetric flow rate}}{\text{orifice cross-sectional area}} \text{ ft/sec} \tag{5-10}$$

The same solution is obtained by considering two stations just above and below the orifice. Hence, we can prove that we can use this equation for further analysis.

The effect of jet contraction:

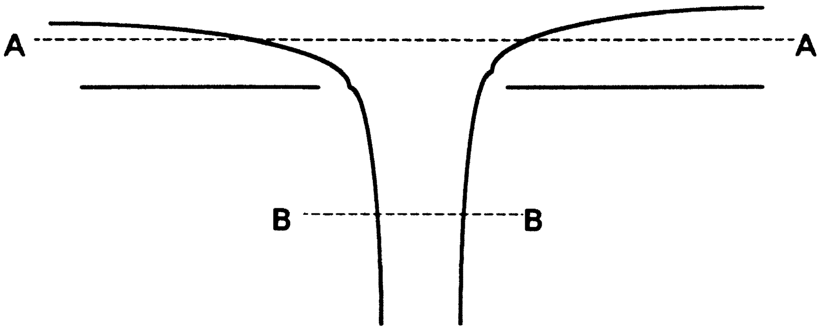

Figure 17. The Formation of Vena Contracta.

As the liquid flows into the orifice, a vena contracta is formed which reduces the cross-sectional area of the jet than the hole diameter. To account for this effect, we modify the equation as follows.

Considering the section at B-B, the coefficient is approximately 1.00 if the orifice area is replaced by the jet area in (5.10).

$$V_B = \frac{1}{\sqrt{1-\beta^4}}\sqrt{2gh} \tag{5-11}$$

Now considering the section at A-A

$$V_H = \frac{C_O}{\sqrt{1-\beta^4}}\sqrt{2gh} \tag{5-12}$$

where, The subscript 'H' denotes the location is at the 'hole'.

Comparing Equations (5-12) and (5-11),

$$V_H \cong C_O V_B \tag{5-13}$$

Also by the continuity equation, we can prove that

$$\frac{V_B}{V_H} = \frac{A_H}{A_B} \tag{5-14}$$

Combining equations (5-13) and (5-14), we finally get the effect of contraction in terms of the orifice coefficient

$$C_O = \frac{V_H}{V_B} = \frac{A_B}{A_H} \tag{5-15}$$

where, A_B is the area of the jet

A_H is the hole (orifice) area.

Here, the ratio of the area is the effect of contraction.

Concluding, we can say that equation (5-9) was used to find out the relation for interpreting the data in terms of the Reynolds number and the orifice coefficient and equation (5-15) shows the effect of contraction.

CHAPTER VI

RESULTS AND DISCUSSION

Our objective in this study was to create a database for the effect of the various parameters involved in the flow of fluid through square-edged orifices. To analyze all the parameters involved, we had obtained a set of plates each from three commercial manufacturers namely Koch, Nutter and Norton; Plates from other manufacturers may also be tested. Each set contained nine different plates of three different thicknesses [0.25 in., 12 gage (0.109 in.) & 14 gage (0.083 in.)] and 3 different hole diameters (0.25 in., 0.5 in., 0.75 in.). Most of the present work was done on 20 of the 27 plates obtained. Some of the plates were also deburred on one of the surfaces. To analyze the effect of commercial punching compared to machine drilling, we also obtained a set of plates with the same dimensions but which had drilled and reamed holes. To analyze the effect of hysteresis, two sets of runs were taken on each plate, one with increasing head and the other with decreasing head. All of the results were analyzed in terms of flow rate vs. head and Reynolds number vs. orifice coefficient relationships obtained by Eq.(5-1) and (5-9). All of the results are attached in Appendix C.

Though the hole diameter and plate thickness are precisely measured (Appendix B), parameters such as hole edge shape, deburring, roughness of the orifice edge, etc., cannot be easily quantified; they are characteristic of each orifice. Tuve and Sprenkle (1933) stated that the error introduced due to this does not exceed 1.5% of the evaluated value of the orifice coefficient.

The Effect of Hole Diameter

Hole diameter has been found to be the single most important parameter affecting the magnitude of the orifice coefficient apart from Reynolds number (or, liquid head). Values of orifice coefficient and Reynolds number are found from Eqs.(5-1) and (5-9) respectively. All other parameters considered had less effect on the orifice coefficient than the hole diameter. The effect of hole diameter is depicted in Figure 18, Figure 19, and Figure 20 keeping all other parameters such as plate thickness, flow direction, etc., constant.

The following points can be concluded from these figures.

- Since distributors usually operate at liquid levels between 2 in. and 10 in., our main attempt is to carefully study the orifice coefficients for this range.
- At low Reynolds number (less than 4500), an increase in hole diameter (decrease in l/d) decreases the orifice coefficient by around 30-35%. As is seen in Table 3 , for a Reynolds number of 3000, the orifice coefficients are found to vary substantially.

TABLE 3

THE EFFECT OF HOLE DIAMETER AT REYNOLDS NUMBER = 3000.

Plate Thickness	0.25 in.			12 Gage (0.109 in.)			14 Gage (0.083 in.)		
Hole Diameter, in.	0.25	0.5	0.75	0.25	0.5	0.75	0.25	0.5	0.75
l/d	1	0.5	0.33	0.436	0.218	0.145	0.332	0.166	0.111
Orifice Coefficient	0.94	0.74	0.46	0.84	0.66	0.48	0.84	0.62	0.45

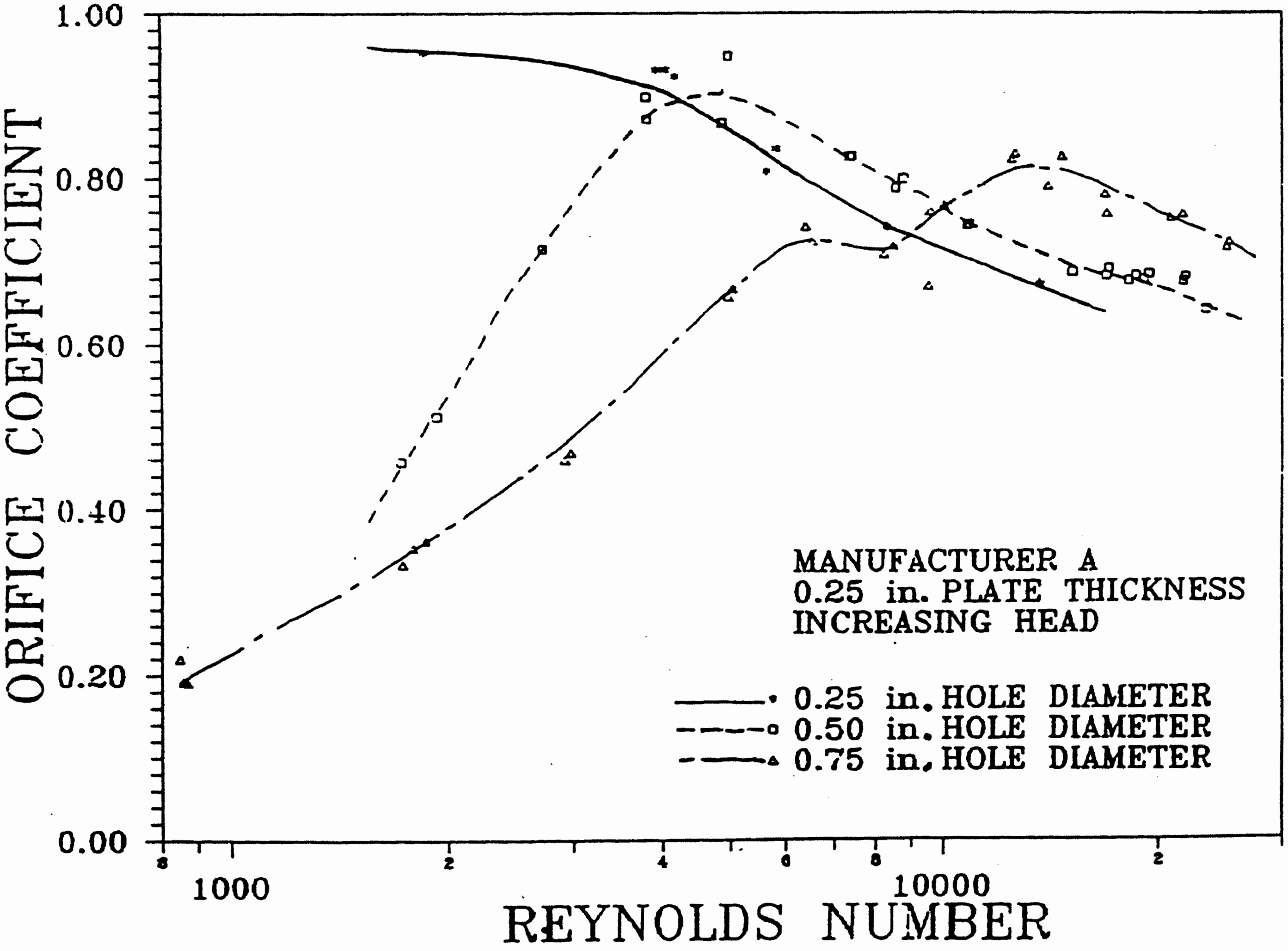

Figure 18. The Effect of Hole Diameter for 0.25 in. Plate Thickness

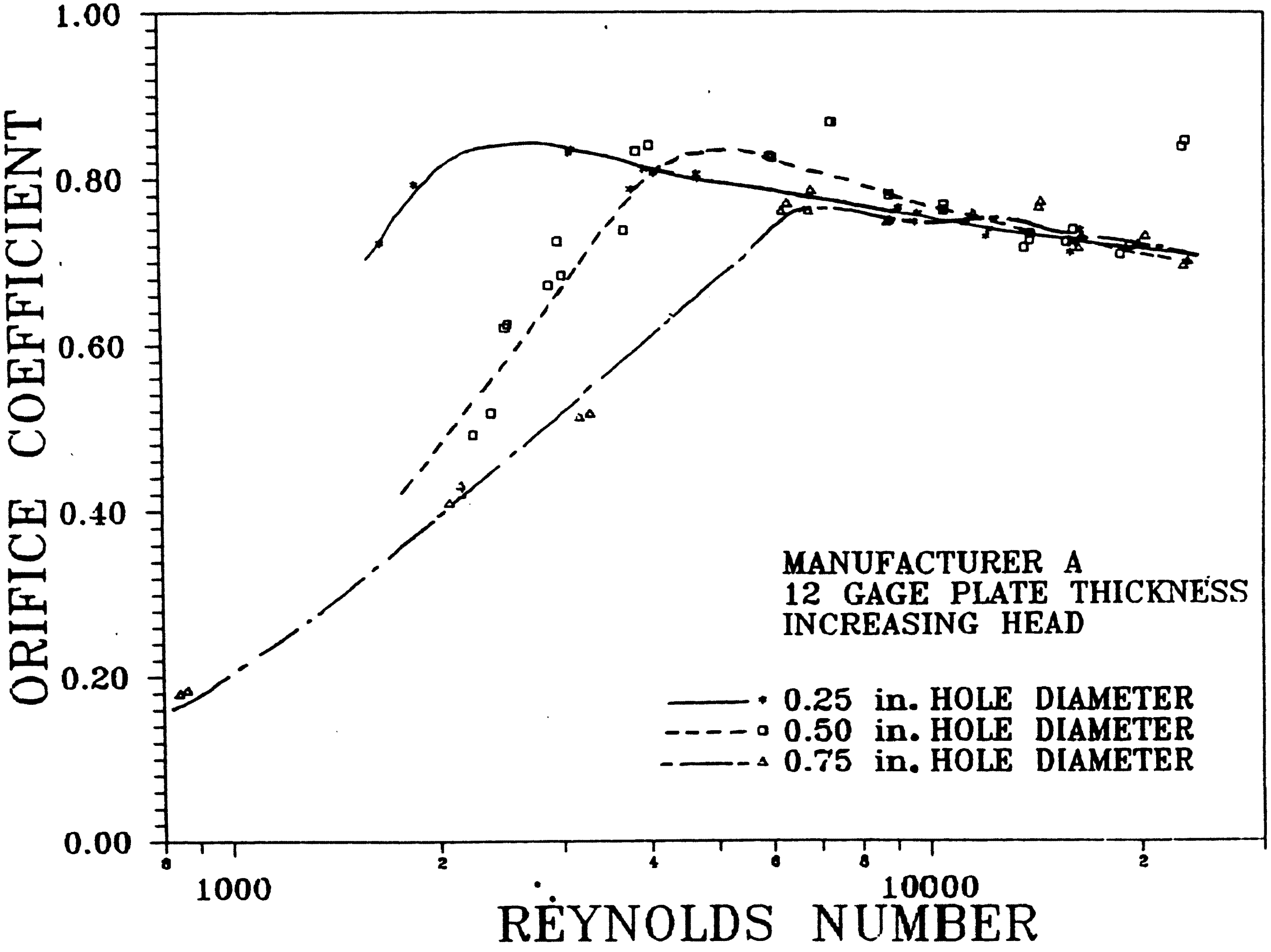

Figure 19. The Effect of Hole Diameter for 12 Gage Plate Thickness

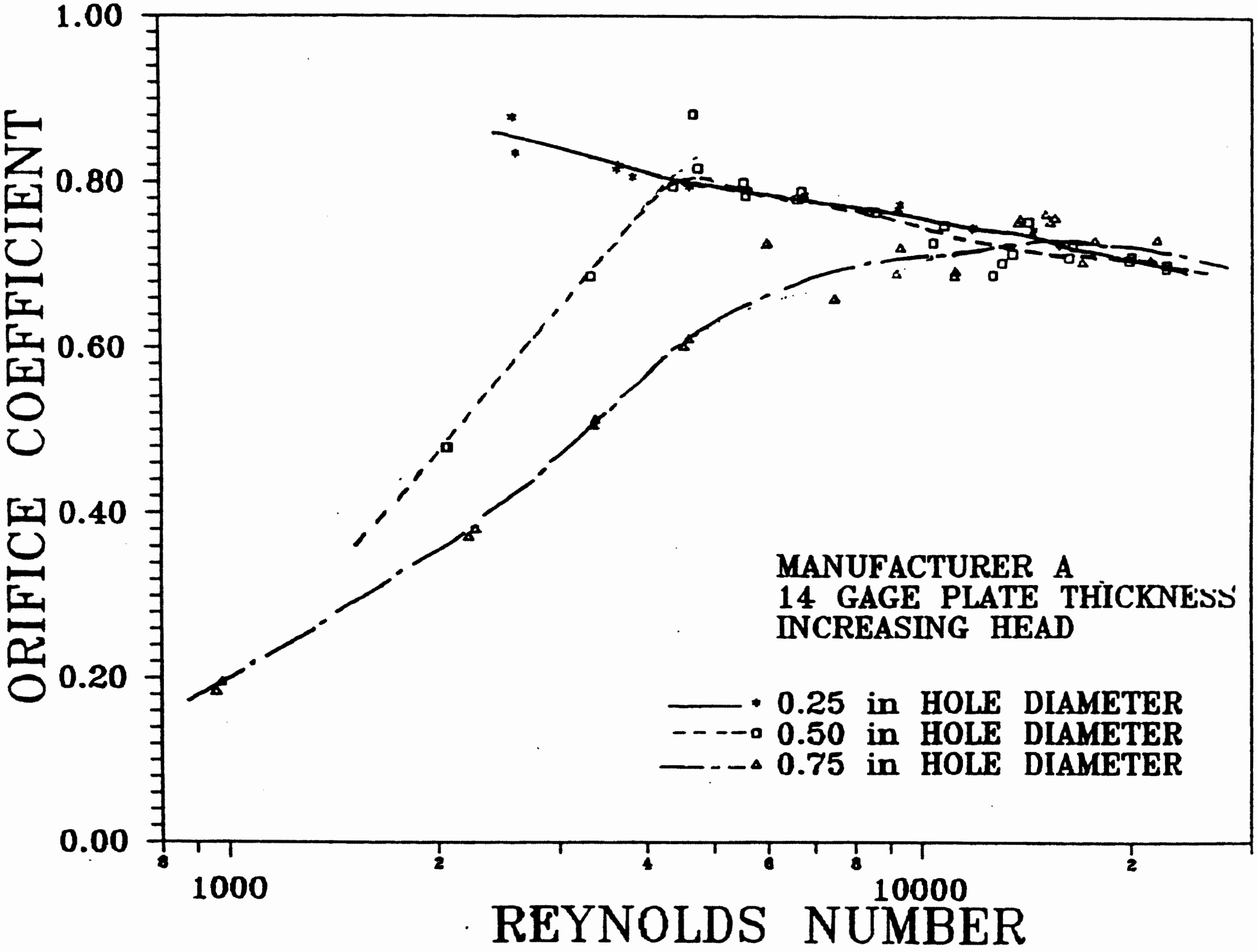

Figure 20. The Effect of Hole Diameter for 14 Gage Plate Thickness

At this Reynolds number, the orifice coefficient decreases by about 40-50% for an increase of a factor of three in hole diameter or a factor of nine in terms of the orifice area.

- It is evident from the above table that the effect of plate thickness is comparatively less than the effect of hole diameter. In terms of l/d ratio, the same decrease in the orifice coefficient is obtained for larger difference in the l/d value (1 to 0.33) for higher plate thickness than for low plate thickness (0.332 to 0.111).
- In laminar flow, the orifice coefficient increases as Reynolds number increases and achieves a maximum value at a specific Reynolds number, Re_{max}. After reaching Re_{max}, an increase in Reynolds number results in a decrease in the orifice coefficient. It is clear from Table 4 that at higher Reynolds number the effect of hole diameter is negligible.

TABLE 4

THE EFFECT OF HOLE DIAMETER AT REYNOLDS NUMBER = 10,000.

Plate Thickness	0.25 in.			12 Gage			14 Gage		
Hole Diameter, in.	0.25	0.5	0.75	0.25	0.5	0.75	0.25	0.5	0.75
l/d	1	0.5	0.33	0.436	0.218	0.145	0.332	0.166	0.111
Orifice Coefficient	0.70	0.76	0.76	0.74	0.76	0.75	0.78	0.74	0.72

- The following values for Re_{max} and the corresponding orifice coefficient have been obtained from Figure 18, Figure 19 and Figure 20.

TABLE 5

THE EFFECT OF HOLE DIAMETER AT RE_{MAX}

Plate Thickness	0.25 in.			12 Gage			14 Gage		
Hole Diameter, in.	0.25	0.5	0.75	0.25	0.5	0.75	0.25	0.5	0.75
Re_{max}	2000	4300	11000	2500	4500	11000	2500	4500	11000
Orifice Coefficient	0.96	0.93	0.82	0.84	0.83	0.78	0.86	0.82	0.78
Liquid Head, in. (appr.)	0.26	0.55	0.8	0.26	0.6	0.8	0.26	0.55	0.85

- Another point worth mentioning is that in laminar flow, the orifice coefficient is proportional to the Reynolds number which in turn is proportional to the velocity of the liquid. The velocity of the liquid is directly proportional to the liquid head in laminar flow.

  $C_o \propto Re \propto V \propto h$

  But in the turbulent region, the orifice coefficient is not a direct function of the Reynolds number and the velocity is proportional to the square root of the liquid head.

  $C_o \neq f(Re), \quad V \propto h^{1/2}$

  Hence, there is a direct relation between the head and the orifice coefficient in the laminar flow but not so in the turbulent region.

The Effect of Plate Thickness

Plate thickness is an important parameter influencing the orifice coefficient. Though its effect is not as much as the effect of hole diameter, the variation in plate thickness can alter the coefficient by about 10-15%. Generally, in existing literature, both the parameters are grouped together in the form of 'l/d', the ratio of the thickness to the hole diameter. In Figure 21, Figure 22 and Figure 23, we have kept hole diameter constant and plotted the results for the three thicknesses.

From the figures, we can conclude the following points.

- For low Reynolds number ($Re < Re_{max}$), the orifice coefficient is found to decrease with a decrease in plate thickness. As shown in Table 6, for a Reynolds number of 3000, the variation is small compared to that due to the variation in hole diameter. The maximum decrease obtained is about 10-15% and the corresponding Re for the maximum decrease is close to Re_{max}.

TABLE 6

THE EFFECT OF PLATE THICKNESS AT REYNOLDS NUMBER = 3000.

Hole Diameter	0.25 in.			0.5 in.			0.75 in.		
Plate Thickness	0.25 in.	12 Gage	14 Gage	0.25 in.	12 Gage	14 Gage	0.25 in.	12 Gage	14 Gage
l/d	1	0.436	0.332	0.5	0.218	0.166	0.33	0.145	0.111
Orifice Coefficient	0.95	0.84	0.83	0.75	0.69	0.63	0.51	0.50	0.46

The maximum decrease is around 15% for a decrease of plate thickness from 0.25 in. to 14 gage and is similar for all hole diameters.

- At Re_{max}, the deviation reaches a maximum as shown in Table 7. The Re_{max} is almost the same for different plate thicknesses but the same hole diameter.

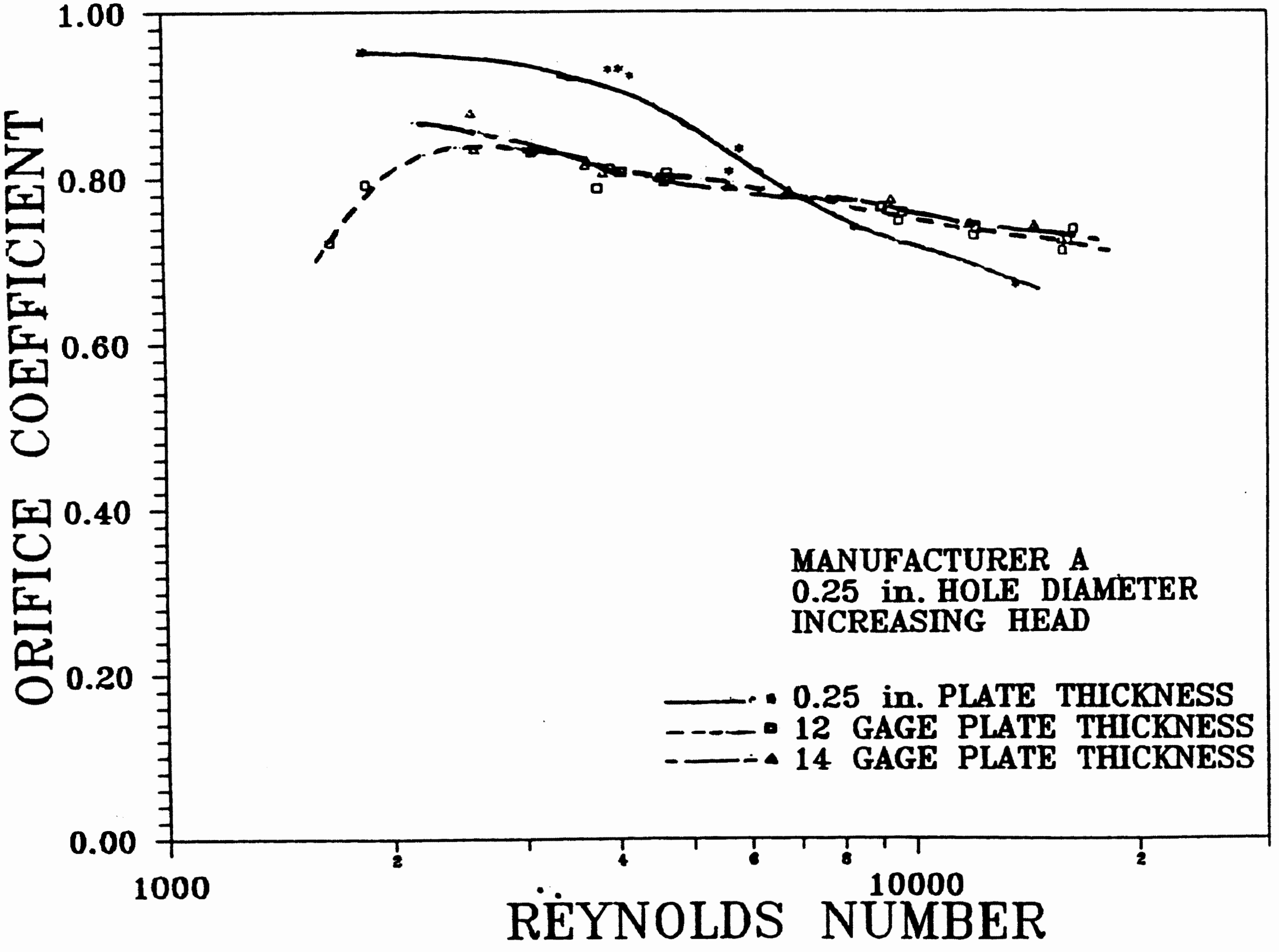

Figure 21. The Effect of Plate Thickness for 0.25 in. Hole Diameter

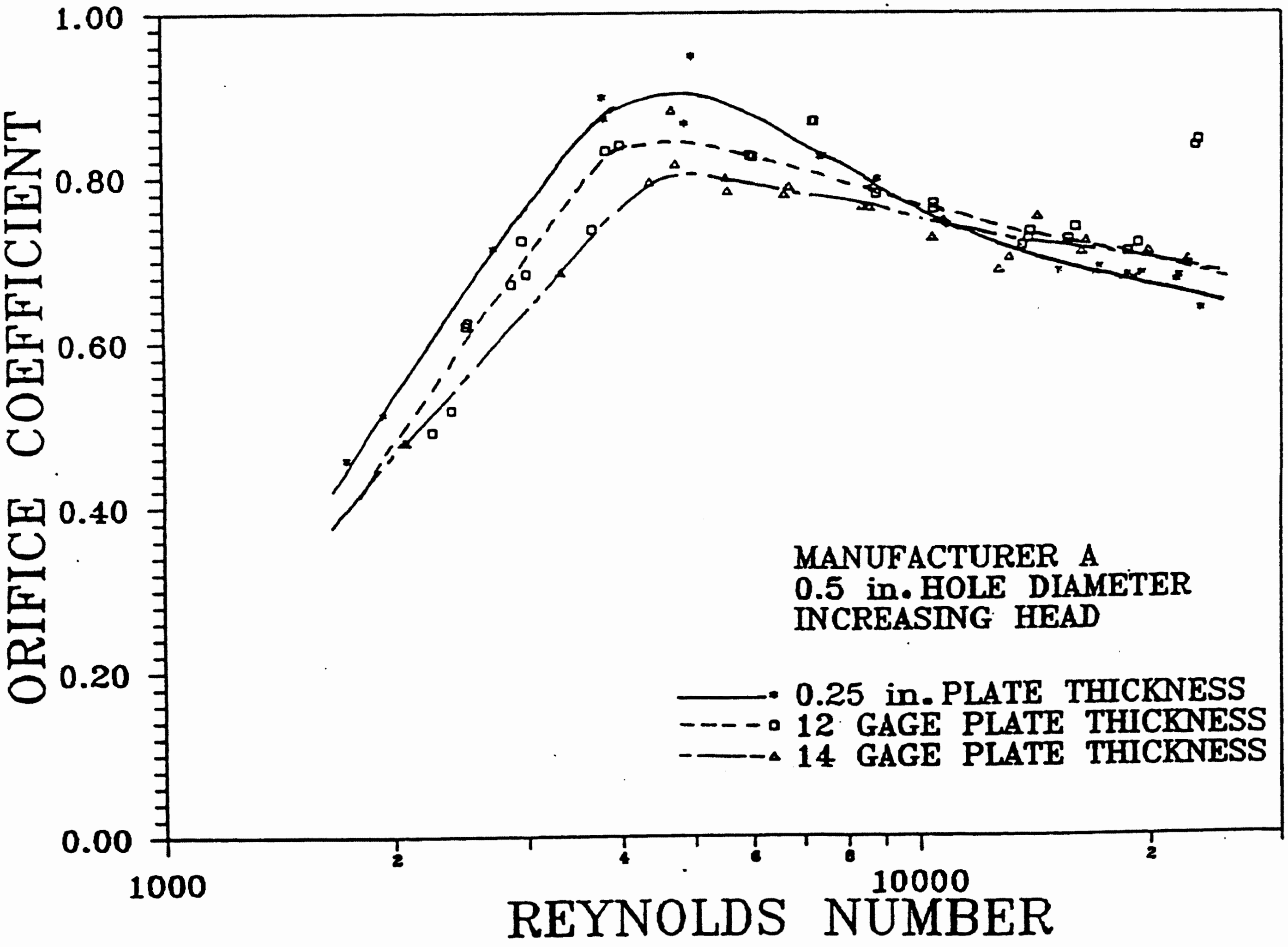

Figure 22. The Effect of Plate Thickness for 0.50 in. Hole Diameter

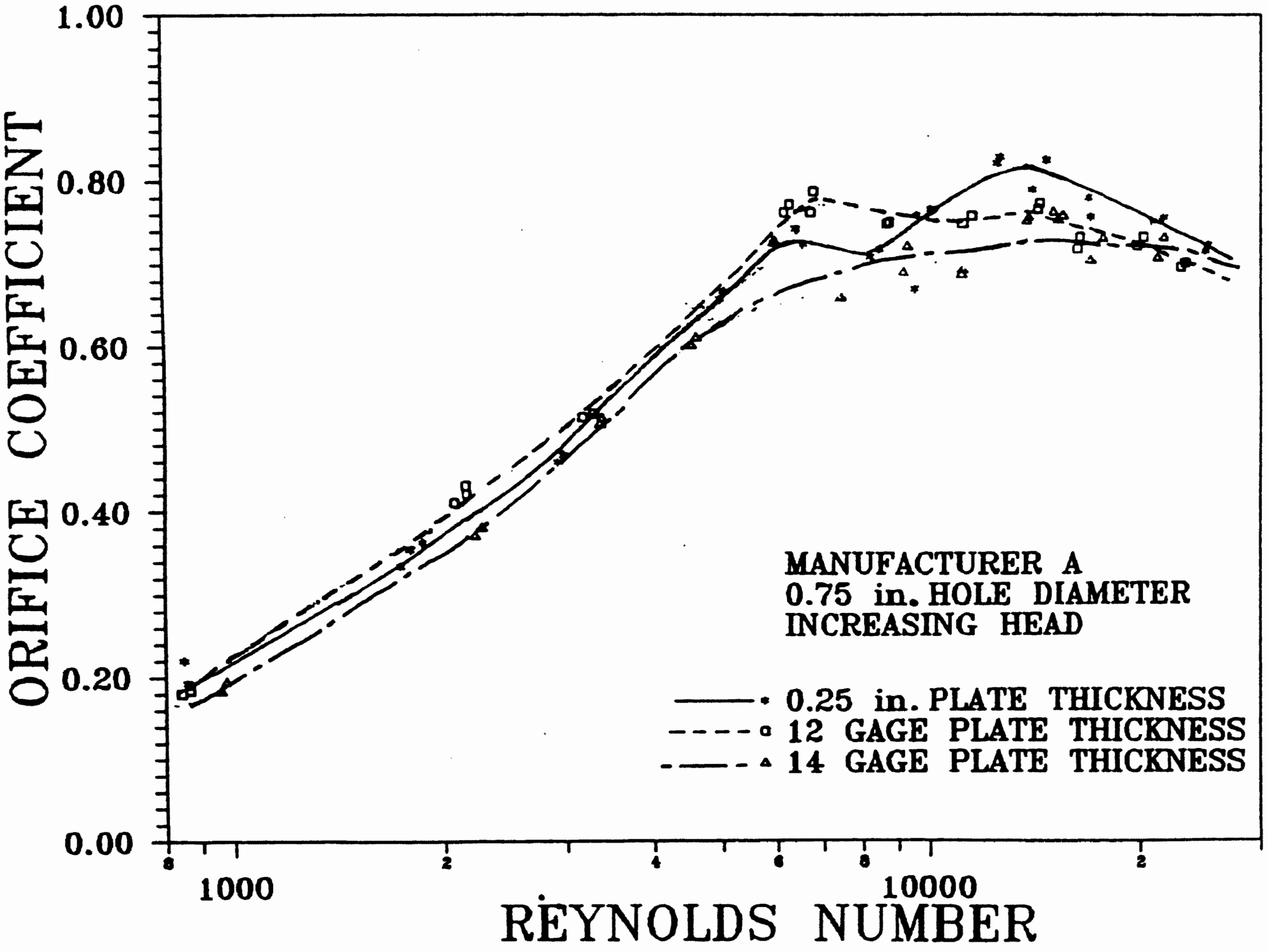

Figure 23. The Effect of Plate Thickness for 0.75 in. Hole Diameter

TABLE 7

THE EFFECT OF PLATE THICKNESS AT RE_{MAX}.

Hole Diameter	0.25 in.			0.5 in.			0.75 in.		
Re_{max} (app.)	2,500			4,500			11,000		
Plate Thickness	0.25 in.	12 Gage	14 Gage	0.25 in.	12 Gage	14 Gage	0.25 in.	12 Gage	14 Gage
l/d	1	0.436	0.332	0.5	0.218	0.166	0.33	0.145	0.111
Orifice Coefficient	0.96	0.87	0.84	0.95	0.86	0.82	0.85	0.78	0.76

- At Re > Re_{max}, the deviation again tends to decrease and the curves may even cross. For Re = 20,000, the orifice coefficients are listed in Table 8.

TABLE 8

THE EFFECT OF PLATE THICKNESS AT REYNOLDS NUMBER = 20,000.

Hole Diameter	0.25 in.			0.5 in.			0.75 in.		
Plate Thickness	0.25 in.	12 Gage	14 Gage	0.25 in.	12 Gage	14 Gage	0.25 in.	12 Gage	14 Gage
l/d	1	0.436	0.332	0.5	0.218	0.166	0.33	0.145	0.111
Orifice Coefficient[1]	0.66	0.71	0.72	0.68	0.70	0.71	0.76	0.74	0.74

---

[1] Since the orifice coefficient for 0.25 in. hole diameter is not available for Re = 20,000, the values at the maximum available Reynolds number (11,000) are used.

It is clear from the above table that at higher Reynolds number ($Re > Re_{max}$), the orifice coefficient increases with decrease in plate thickness but the effect is comparatively small.

Concluding, we can say that a change of plate thickness from 0.25 in. to 14 gage gives a maximum variation of 10-15% in the orifice coefficient. In terms of the l/d ratio, we can say that for l/d = 1, we get higher coefficients than for l/d less than 1 for low Reynolds number. The trend reverses for high Reynolds number (greater than 20,000). Data are not available for l/d > 1 (plate thickness is greater than the hole diameter).

Hysteresis in Measurements

Different value of orifice coefficient was obtained for the same Reynolds number when the head was either increased or decreased. This behavior is termed as 'Hysteresis'. It has been observed that for low Reynolds number the hysteresis effect becomes more prominent. As described by Iciek [29,30], the possible reason is the adherence (or non-adherence) of the liquid to the orifice wall. To analyze the hysteresis effect, each plate obtained was tested with increasing and decreasing head. These data were compared at the same Reynolds number. Figure 24 and Figure 25 show the hysteresis effect clearly. It seems plausible that while the head is increasing, the jet formed is under no influence of previous flow history. Hence it separates from the orifice edge and forms a vena contracta. As the head is increased the jet diameter becomes bigger due to the high flow rate and that results in the jet adhering to the orifice wall. While the head is decreased the jet diameter tends to decrease. But at low heads when the jet is still attached to the wall, the formation of the vena contracta is delayed which in turn gives different coefficients. This is not proved by us experimentally but this reasoning is obtained from the literature [29,30] and

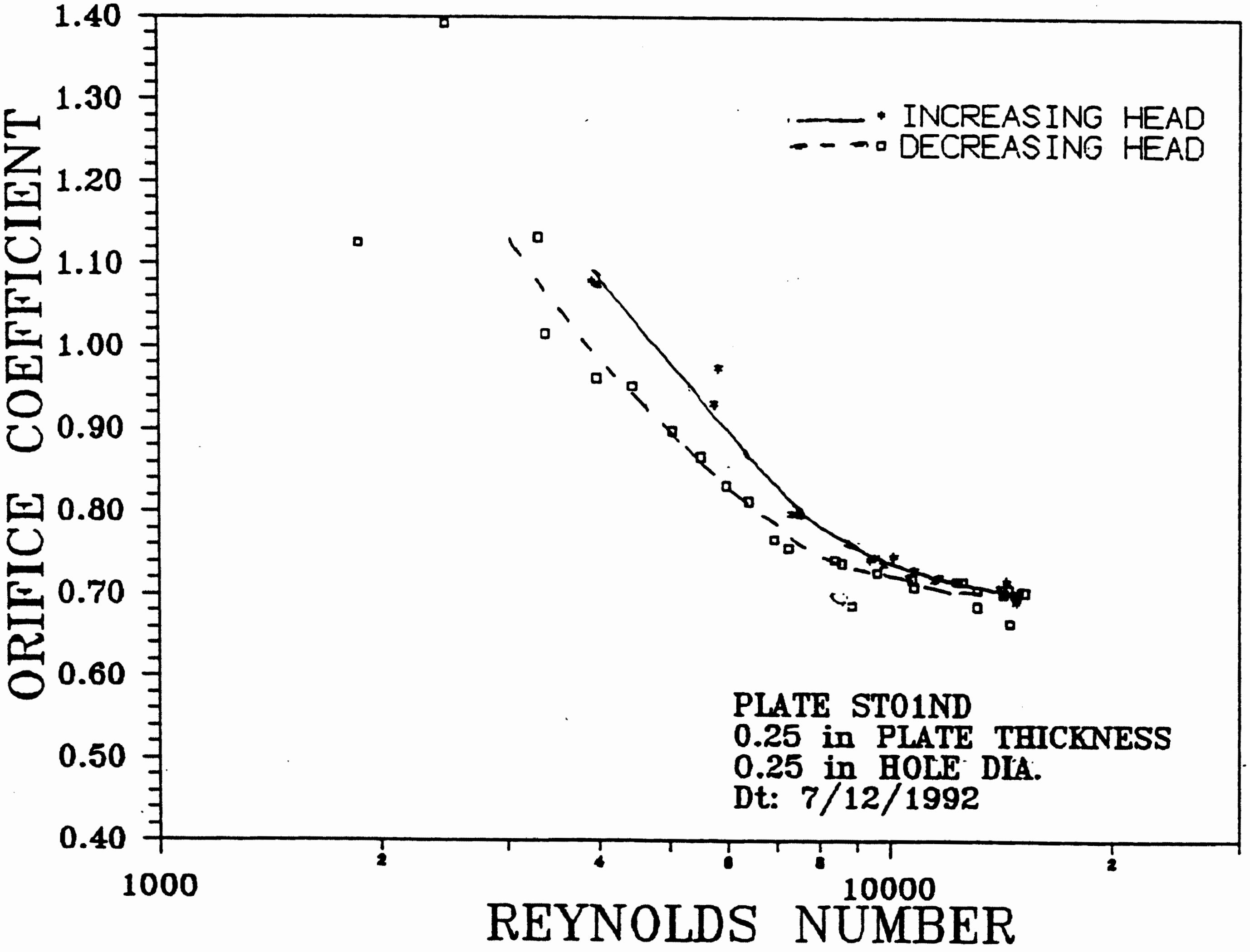

Figure 24. The Hysteresis Effect

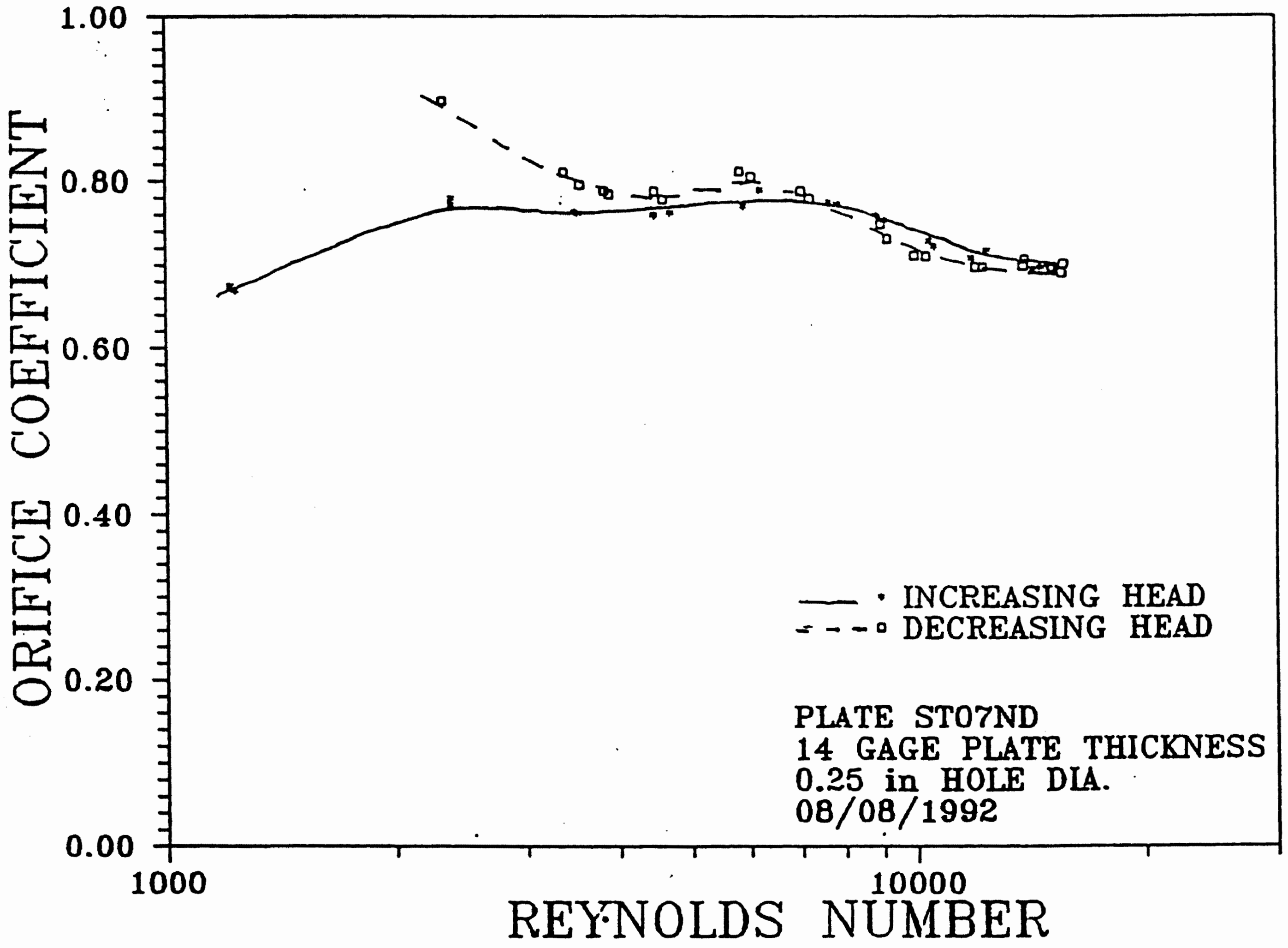

Figure 25. The Hysteresis Effect

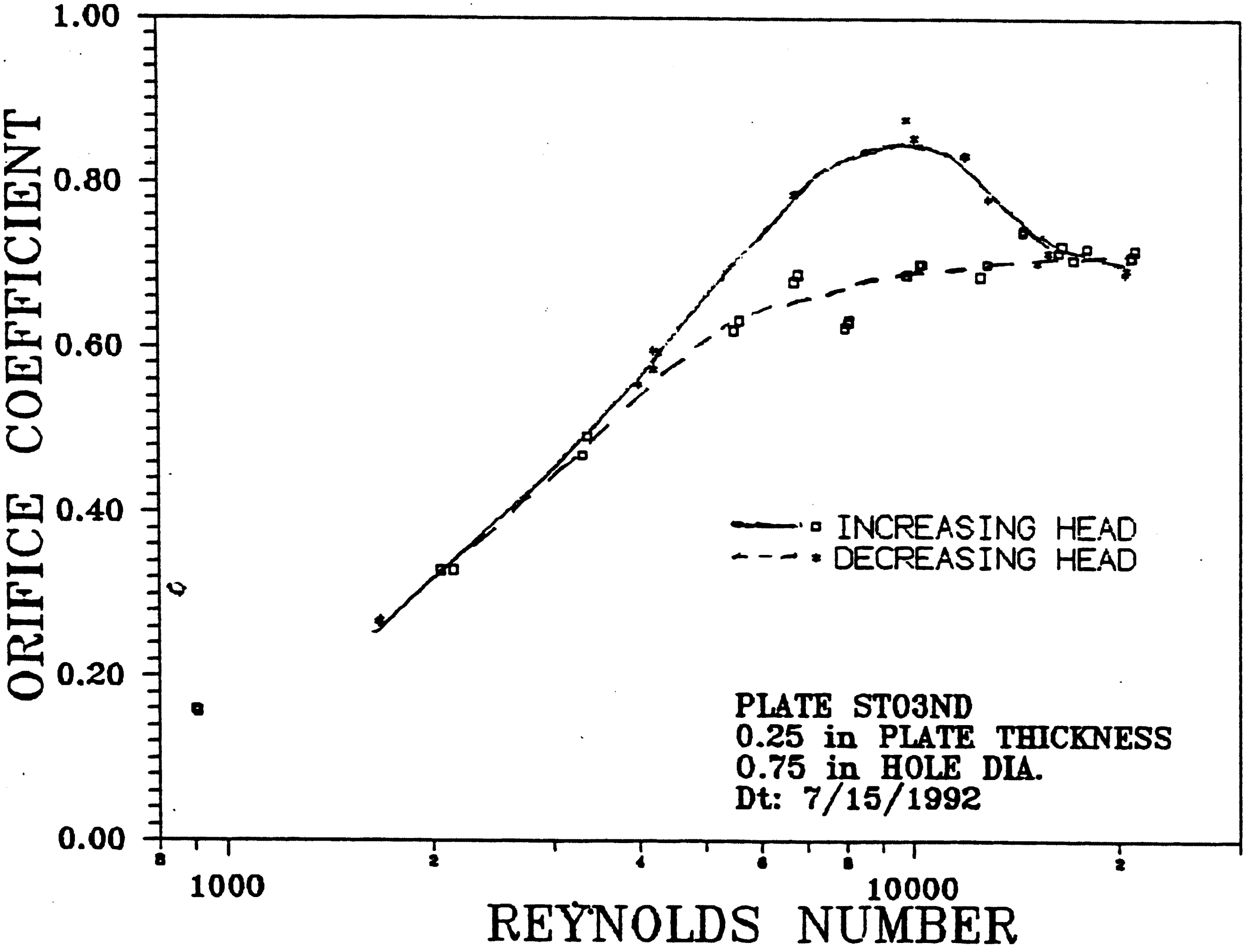

Figure 26. The Hysteresis Effect

offers one explanation to the observed phenomenon.

The following points should be remembered while considering the hysteresis effect.

- Understanding of the hysteresis phenomenon is based on empirical knowledge and not theoretical analysis.
- Hysteresis effects are not consistent. In some cases, the effect is very obvious and in some it is negligible.
- Even in the worst case, the relative difference between the coefficients is small (less than 5%). See Appendix C.
- The low Reynolds number region (less than 10,000) is more susceptible to hysteresis; since the outcome is uncertain, caution should be applied while designing for this region. For better estimation more data, preferably with viscous fluids which give higher head at lower Re, should be obtained.
- At higher Reynolds numbers, one data set shows a hysteresis effect (Figure 26). But it is not evident in any other data. This behavior might be due to other parameters such as angular motion of fluid which is responsible for vortex formation, etc.

Effect of Drilling vs. Commercial Punching

Distributors are generally made of channels with punched holes in the bottom and/or sides. Because of the punching an indentation is formed on the surface of the plate as shown in Figure 7. To analyze the effect due to punching compared to drilling on orifice, we tested a set of plates with the same dimensions as the commercial plates but with drilled holes. Figure 27, Figure 28 and Figure 29 show the effect of drilling compared to punching. Other data is found in Appendix C.

Based on the data collected, we can conclude:

- The orifice coefficients obtained from the punched holes are normally slightly higher (5-10%) than the drilled holes. This effect is explained due to rounding obtained on the orifice edges. Because of the small rounded edge, the jet diameter is increased. This results in an increased value of the contraction coefficient which in turn results in a higher orifice coefficient. In the case of drilled holes, we believe that the jet separates from the orifice wall almost instantaneously.
- The effect of punching is more evident at low heads. The overall effect on the coefficient is found to be less than 10%, as shown in Table 9, which is for a hole diameter of 0.5 in.

TABLE 9

THE EFFECT OF DRILLING VS. PUNCHING FOR 0.5 IN. HOLE DIAMETER

Plate thickness	0.25 in.			12 gage			14 gage		
Re	3000	10,000	20,000	3000	10,000	20,000	3000	10,000	20,000
C_o ,(drilled)	0.70	0.70	0.65	0.70	0.75	0.71	0.72	0.76	0.66
C_o ,(punched)	0.76	0.74	0.68	0.69	0.78	0.72	0.64	0.75	0.70

- It is clear from the above table that as the plate thickness decreases, the effect due to punching decreases. Also, as the Reynolds number increases the effect decreases; i.e., the effect is more significant for thicker plates and lower Reynolds number.

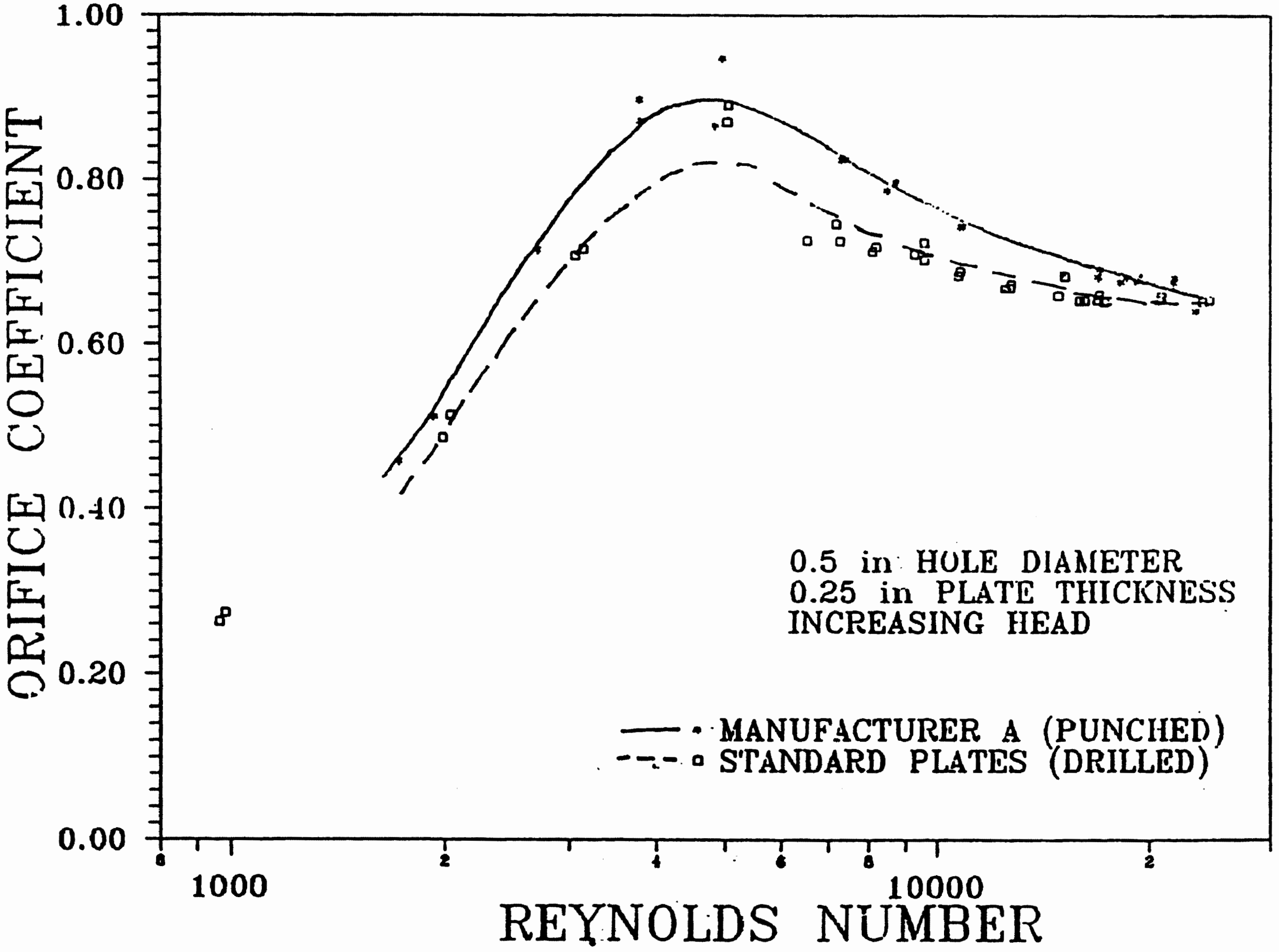

Figure 27. The Effect of Drilling Compared to Punching

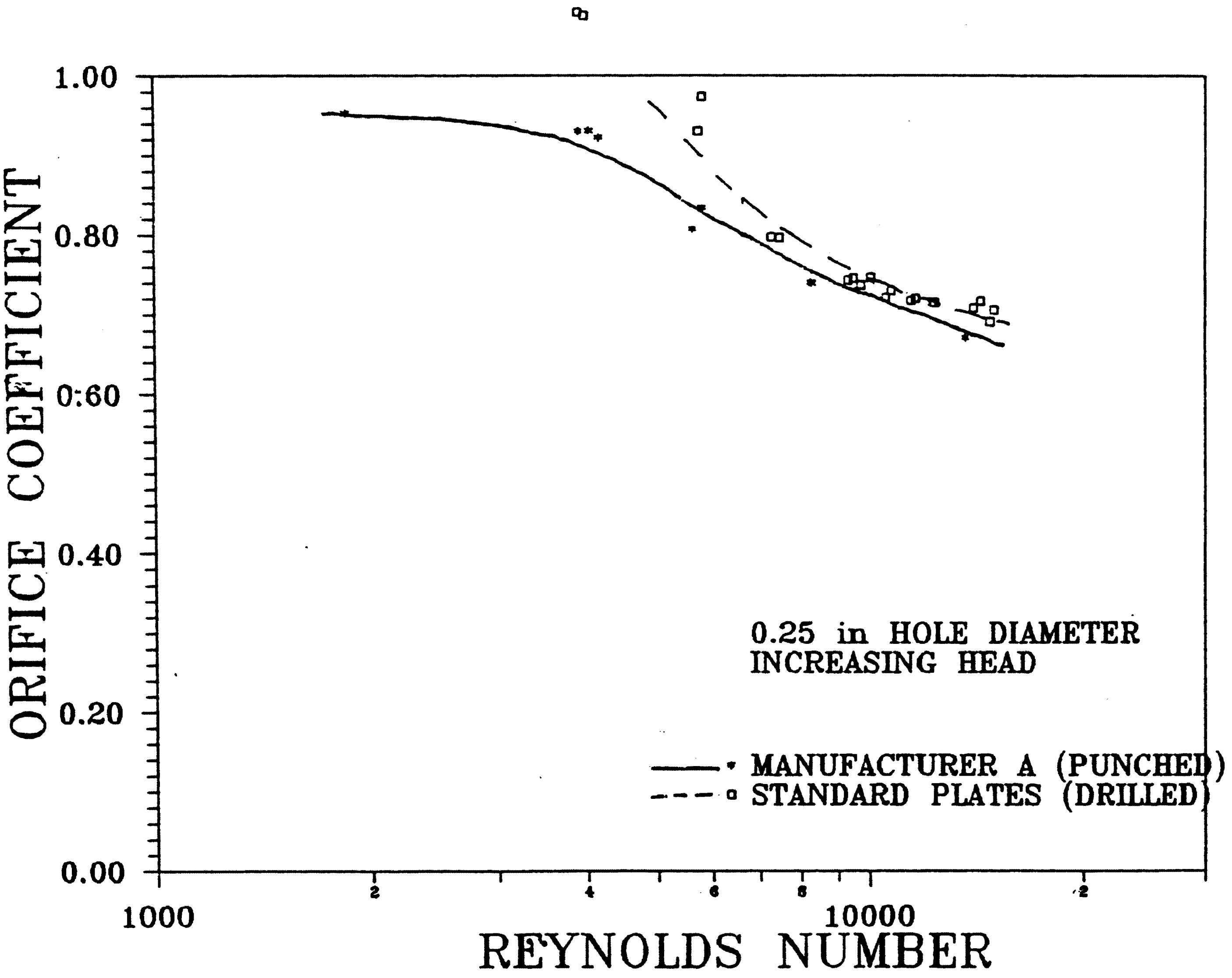

Figure 28. The Effect of Drilling Compared to Punching.

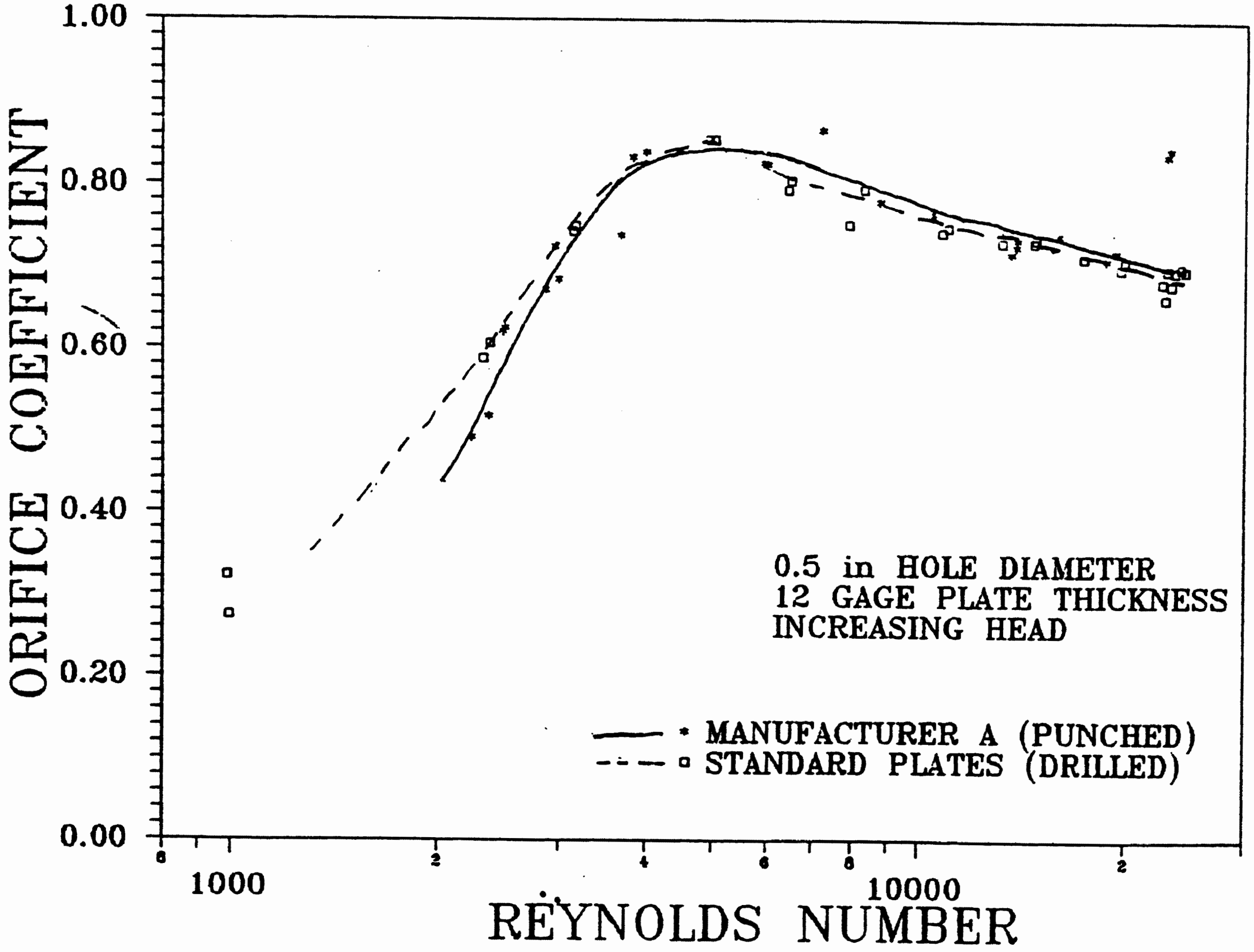

Figure 29. The Effect of Drilling Compared to Punching

- For designing purposes, if thick plates are to be selected because of higher orifice coefficients at low Reynolds number, the effect of rounding of edges (due to punching) should be considered. In other cases they offer a slight advantage at moderate Reynolds number (5,000 - 10,000). At higher Reynolds number, the trend is slightly reversed.

Effect of Deburring

As seen in the previous section, the edge on the upstream side of the orifice significantly influences the magnitude of the orifice coefficient. Many investigators ([3], [5]) have found that the sharpness of the orifice edge and the smoothness of the orifice wall can introduce substantial variation in the coefficients. To measure the effect of deburring on the coefficient, some plates were deburred on one of the surfaces. This provided the opportunity of observing the jet configuration while measuring the flow. Figure 30 and Figure 31 are examples of the deburring effect.

We can conclude:

- The orifice coefficient apparently increases significantly at low heads due to deburring. However, because of the difficulty of accurately measuring low heads, the data are questionable. The effect is shown in Table 10.

TABLE 10

THE EFFECT OF DEBURRING FOR HOLE DIAMETER = 0.25 IN. AND PLATE THICKNESS = 12 GAGE.

Flow direction	Increasing Head			Decreasing head		
Reynolds Number	2000	8,000	11,000	2000	8,000	11,000
C_O, Non-Deburred	0.80	0.76	0.71	0.82	0.75	0.69
C_O, Deburred	0.96	0.70	0.66	0.95	0.70	0.66

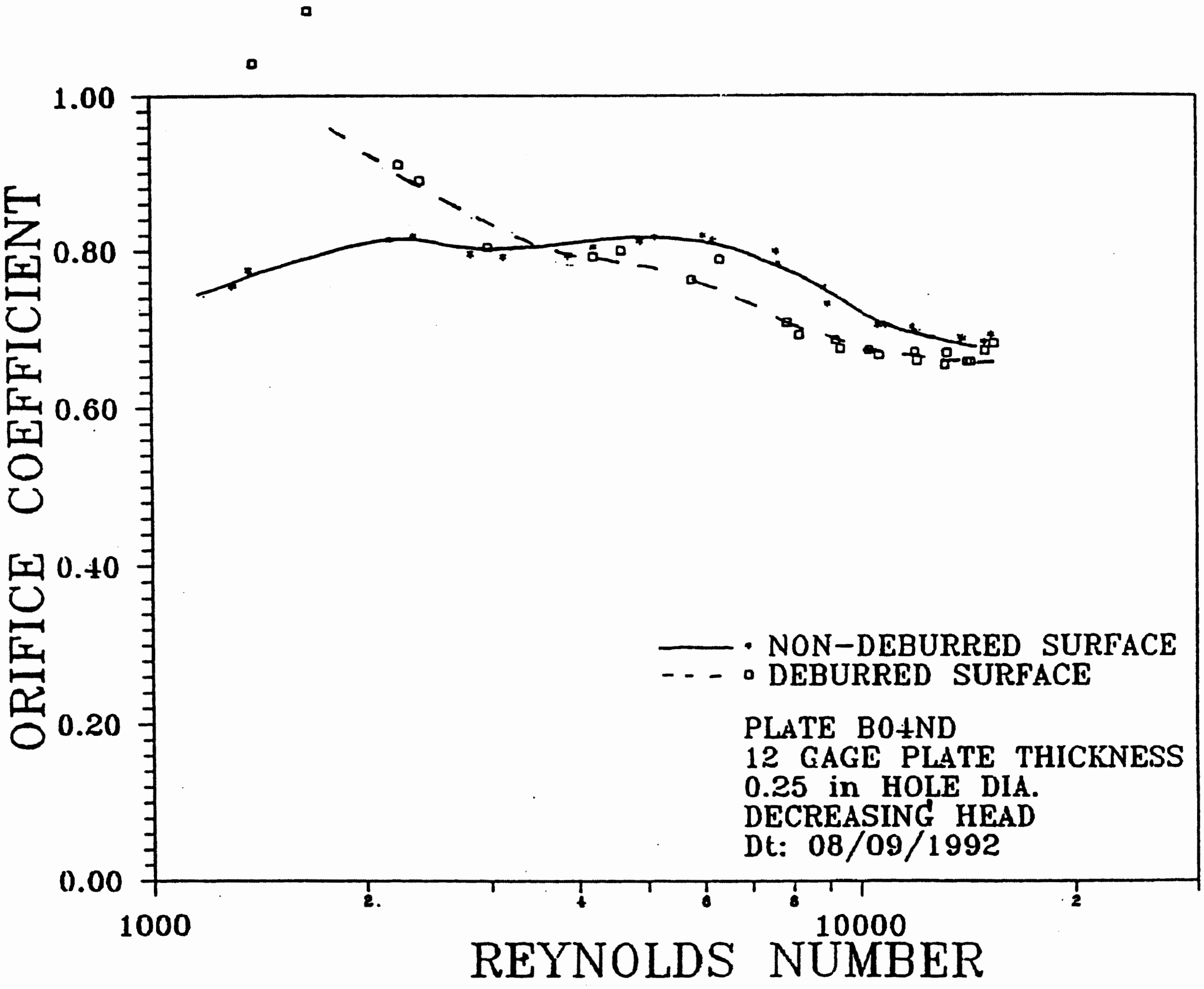

Figure 30. The Effect of Deburring.

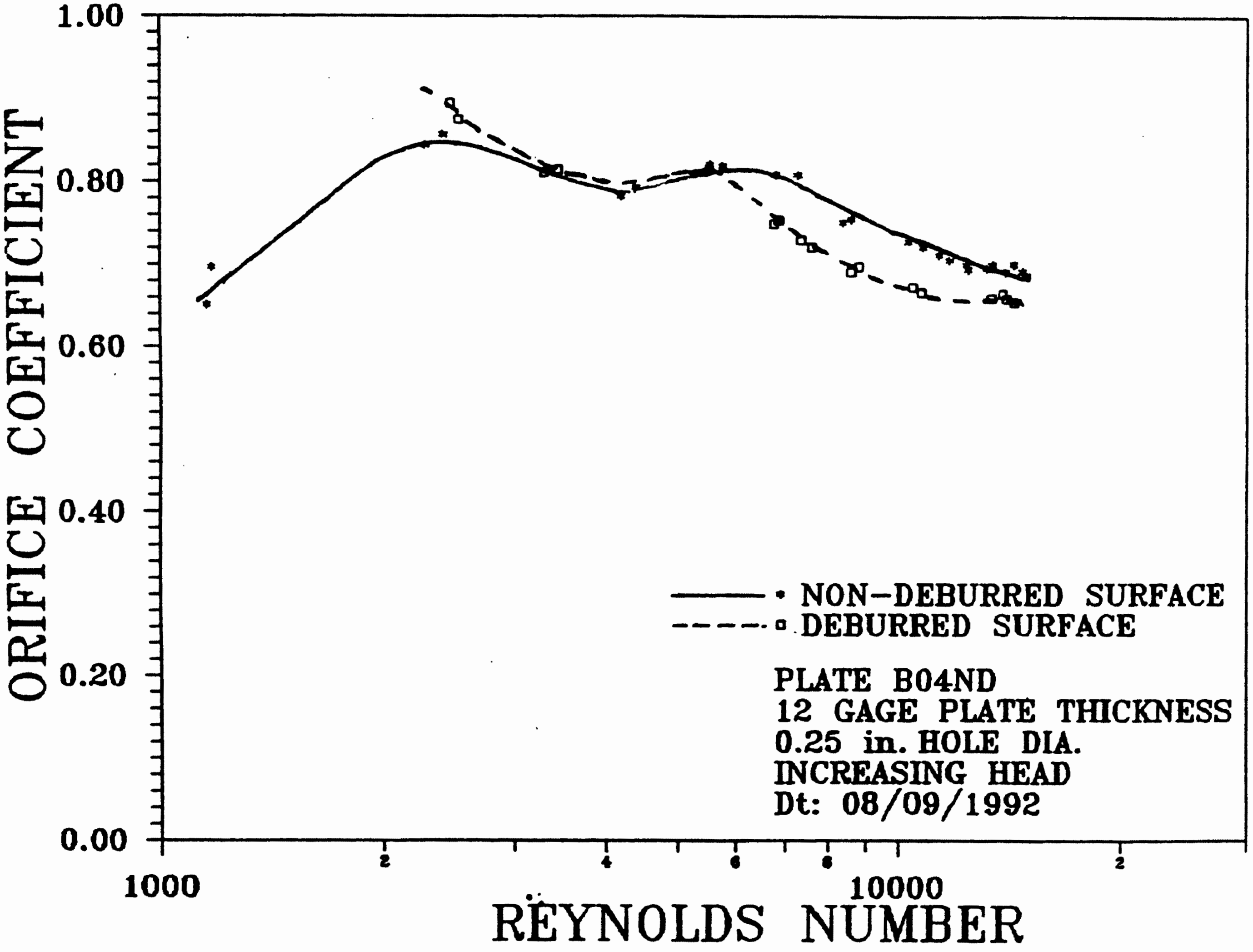

Figure 31. The Effect of Deburring.

- As is seen from the above table, the orifice coefficient apparently increases by about 20% due to the deburring at low to very low Reynolds number. But the difference reduces quickly and the effect is minimized or reversed at moderate to large (Re>8,000) Reynolds number. This data was collected for 0.25 in. hole diameter for which Reynolds number of 8,000 results from a head of 3 in.-4 in..
- More data need to be taken to validate the above result for larger diameters and different plate thicknesses. Also, visual examination of the edge is needed.
- Based on present data, we can conclude that for low to very low Reynolds number, the effect of deburring may be very significant.

The Effect of Vortex Formation

Vortices have been found to form almost automatically at low heads. Vortex formation is less frequently observed at high heads. A vortex is formed when the angular motion of the bulk fluid becomes significant compared to the horizontal or vertical motion of the liquid. The possible cause of vortex formation in our experiments is the angle of introduction of the fluid in the channel. If the inlet is introduced at an angle, the angular momentum of the inlet is translated to the angular motion of the bulk liquid due to the conservation of angular momentum. Hence the bulk liquid starts to rotate which culminates in a vortex. The effect of vortex is substantial at low heads. In one run, the liquid head rose from 1 in. to 3.5 in. due to the vortex formation at the same inlet flow rate. In other words, vortex is capable of increasing the liquid level by 2-3 times at the same inlet flow rate. One possible reason is that only a fraction of the orifice is occupied by fluid. This in turn results in the increase in head and a substantial decrease in the orifice coefficient. Various reasons such as viscous dissipation, coring of the jet by air, etc., can be attributed to vortex formation.

It has been found experimentally that at low heads, it is hard to get rid of a stable vortex. At higher heads, the linear velocity of the liquid retards build-up of angular momentum. Because of the results discussed above, there is incentive to study the formation and inhibition of vortexes in such flow conditions.

Other Effects

Some other effects such as the difference in the punches of different commercial manufacturers were also analyzed. Relatively small deviations were found from different punches.

The effect of flow direction relative to the direction of punch was also studied. Because of the dent caused by the punch on the surface, a slightly different coefficient is obtained (Appendix C). This effect is the same as described for drilled vs. punched holes.

Summary and Recommendations

The flow behavior of non-viscous fluid through square-edged orifices was measured experimentally. An experimental setup capable of simulating industrial conditions was designed, constructed and tested for this analysis. Another setup was also designed and built for the measurement of orifice coefficients in a single orifice plate. Plates punched with a single orifice were obtained from different commercial distributor manufacturers. These plates were tested to determine the effects of hole diameter, plate thickness, deburring, punch direction (relative to flow direction), hysteresis, effect of drilling vs. punching, etc. Based on the experience that we have obtained in this work, we can recommend the following points for further research.

- These data should be used for measuring the orifice coefficient for multiple orifices in series. As described earlier, the orifice coefficient for a single orifice might differ in the presence of another orifice in the vicinity. Also important is the effect of the horizontal velocity component which is due to the liquid passing over the orifice.

- A substantial degree of uncertainty is involved at low heads (< 2"). This region should be preferably avoided for commercial practice.
- Liquids with different viscosity should be tested to analyze the generality of the Reynolds number. We have observed certain interesting behavior such as hysteresis and vortex formation at low heads which incidentally is in the laminar region for our fluid (water). Liquids with higher viscosity which can give higher heads at lower Reynolds number should be tested. This will help in attributing the uncertainty to the low liquid heads.
- Extreme precautions should be taken while collecting data. As described earlier, vortex forming processes can increase the liquid head substantially at the same input flow rates. This changes the orifice coefficient substantially.
- The orifice coefficient being sensitive to the shape of the orifice edge, due precautions should be taken for the removal of any surface active agent or rust formation near the edge.

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APPENDIXES

APPENDIX A

NOMENCLATURE OF PLATES

The different plates that were obtained were each given an identification. The identity of the manufacturers is not disclosed due to commercial reasons. The 'STANDARD' plates are the plates with drilled holes prepared at the Physics Department workshop at Oklahoma State University. Manufacturer 'B' provided some plates with deburred surface near the orifice; the plates with such deburring are marked as 'DB'. All other plates were non-deburred. The following is a table showing the plates with the hole diameter and the plate thickness dimensions and the adopted nomenclature.

TABLE 11

NOMENCLATURE OF PLATES

Manufacturer	Hole Diameter,in.	Plate Thickness	Deburred surface	Non-deburred surface	Nomenclature
A	0.25	0.25 in.		X	A01ND
A	0.5	0.25 in.		X	A02ND
A	0.75	0.25 in.		X	A03ND
A	0.25	12 gage		X	A04ND
A	0.5	12 gage		X	A05ND
A	0.75	12 gage		X	A06ND
A	0.25	14 gage		X	A07ND

TABLE 11 (Continued)

Manufacturer	Hole Diameter,in.	Plate Thickness	Deburred surface	Non-deburred surface	Nomenclature
A	0.5	14 gage		X	A08ND
A	0.75	14 gage		X	A09ND
B	0.25	0.25 in.		X	B01ND
B	0.5	0.25 in.		X	B02ND
B	0.75	0.25 in.		X	B03ND
B	0.25	12 gage		X	B04ND
B	0.25	12 gage	X		B04DB
B	0.5	12 gage		X	B05ND
B	0.5	12 gage	X		B05DB
B	0.75	12 gage		X	B06ND
B	0.75	12 gage	X		B06DB
B	0.25	14 gage		X	B07ND
B	0.25	14 gage	X		B07DB
B	0.5	14 gage		X	B08ND
B	0.5	14 gage	X		B08DB
B	0.75	14 gage		X	B09ND
B	0.75	14 gage	X		B09DB
STANDARD	0.25	0.25 in.		X	ST01ND
STANDARD	0.5	0.25 in.		X	ST02ND
STANDARD	0.75	0.25 in.		X	ST03ND
STANDARD	0.25	12 gage		X	ST04ND
STANDARD	0.5	12 gage		X	ST05ND

TABLE 11 (Continued)

Manufacturer	Hole Diameter,in.	Plate Thickness	Deburred surface	Non-deburred surface	Nomenclature
STANDARD	0.75	12 gage		X	ST06ND
STANDARD	0.25	14 gage		X	ST07ND
STANDARD	0.5	14 gage		X	ST08ND
STANDARD	0.75	14 gage		X	ST09ND

APPENDIX B

MEASUREMENTS OF HOLE DIAMETER

Most of the plates had punched holes. Because of the possible deviation in the hole diameter due to punch wear, etc., all the orifices were measured by vernier calipers. Two sets of five readings each were taken which are presented below. The average value is also shown.

TABLE 12

MEASUREMENTS OF HOLE DIAMETER

Plate	Punch Diameter (in.)	Measured Hole Diameter, in.					Average Hole Diameter in.
		1	2	3	4	5	
A01ND	0.25	0.251	0.251	0.249	0.251	0.248	0.2499
		0.249	0.250	0.252	0.250	0.248	
A02ND	0.5	0.498	0.499	0.499	0.500	0.499	0.4995
		0.499	0.498	0.501	0.500	0.502	
A03ND	0.75	0.747	0.748	0.749	0.750	0.749	0.7497
		0.752	0.752	0.751	0.750	0.749	

TABLE 12 (Continued)

Plate	Punch Diameter (in.)	Measured Hole Diameter, in.					Average Hole Diameter in.
		1	2	3	4	5	
A04ND	0.25	0.250	0.250	0.251	0.252	0.251	0.2504
		0.249	0.251	0.249	0.250	0.251	
A05ND	0.5	0.500	0.502	0.502	0.501	0.502	0.5006
		0.500	0.500	0.499	0.499	0.501	
A06ND	0.75	0.751	0.752	0.751	0.752	0.751	0.7505
		0.748	0.750	0.749	0.750	0.751	
A07ND	0.25	0.248	0.249	0.250	0.250	0.249	0.2500
		0.251	0.251	0.251	0.251	0.250	
A08ND	0.5	0.502	0.502	0.501	0.502	0.501	0.5008
		0.500	0.499	0.501	0.500	0.500	
A09ND	0.75	0.751	0.751	0.750	0.751	0.751	0.7502
		0.749	0.750	0.750	0.750	0.749	
ST01ND	0.25	0.250	0.252	0.250	0.251	0.251	0.2508
		0.250	0.251	0.249	0.253	0.251	
ST02ND	0.5	0.500	0.500	0.500	0.500	0.498	0.4996
		0.500	0.500	0.499	0.498	0.501	
ST03ND	0.75	0.750	0.750	0.749	0.751	0.750	0.7500
		0.750	0.750	0.750	0.750	0.750	

TABLE 12 (Continued)

Plate	Punch Diameter (in.)	Measured Hole Diameter, in.					Average Hole Diameter in.
		1	2	3	4	5	
ST04ND	0.25	0.251	0.250	0.250	0.250	0.251	0.2504
		0.251	0.250	0.251	0.250	0.250	
ST05ND	0.5	0.500	0.498	0.499	0.501	0.501	0.4998
		0.500	0.500	0.500	0.498	0.501	
ST06ND	0.75	0.751	0.750	0.749	0.748	0.750	0.7496
		0.751	0.749	0.749	0.749	0.750	
ST07ND	0.25	0.251	0.252	0.252	0.253	0.251	0.2518
		0.252	0.251	0.252	0.252	0.252	
ST08ND	0.5	0.501	0.502	0.500	0.500	0.501	0.5008
		0.500	0.501	0.501	0.501	0.501	
ST09ND	0.75	0.751	0.750	0.750	0.751	0.751	0.7506
		0.751	0.751	0.749	0.751	0.751	
B04DS	0.25	0.248	0.250	0.250	0.249	0.249	0.2496
		0.251	0.251	0.251	0.249	0.248	

APPENDIX C

EXPERIMENTAL DATA

All experimental data is documented here. The measured data is in terms of head, volume of liquid collected, the time of collection and the liquid temperature. This data is used in the evaluation of Reynolds number and orifice coefficient. Each plate has two sets of data; one for the increasing head and the other for the decreasing head. First the plates from manufacturer 'A' are documented. It is followed by the 'standard' plates. Lastly, the runs on plates from manufacturer 'B' are documented. A short description of the plates is also attached.

TABLE 13

SINGLE ORIFICE PLATE DATA

PLATE: A01ND
HOLE DIAMETER: 0.2499 IN.
PLATE THICKNESS: 0.25 IN.
LIQUID: WATER

DATE:06/27/92
LIQUID TEMPERATURE: 70 F
LIQUID DENSITY: 998.0 KG/CU.M
LIQUID VISCOSITY: 0.988 cp

INCREASING HEAD

ZERO POINT = 12.24 CM

MEASURED QUANTITIES				DERIVED QUANTITIES		
LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
12.72	0.48	315.0	34.01	0.1468	1831	0.9536
14.49	2.25	459.0	23.44	0.3104	3872	0.9312
14.64	2.40	463.0	22.88	0.3208	4001	0.9318
14.84	2.60	389.0	18.64	0.3308	4126	0.9232
18.44	6.20	450.0	15.44	0.4620	5763	0.8349
18.44	6.20	374.0	13.26	0.4471	5577	0.8080
28.20	15.96	459.0	11.06	0.6579	8206	0.7410
28.34	16.10	407.0	9.78	0.6597	8229	0.7398
64.89	52.65	765.0	11.20	1.0827	13506	0.6715
64.54	52.30	875.0	12.84	1.0803	13475	0.6722

TABLE 14

SINGLE ORIFICE PLATE DATA

PLATE: A01ND	DATE:06/27/92
HOLE DIAMETER: 0.2499 IN.	LIQUID TEMPERATURE: 70 F
PLATE THICKNESS: 0.25 IN.	LIQUID DENSITY: 998.0 KG/CU.M
LIQUID: WATER	LIQUID VISCOSITY: 0.988 cp

DECREASING HEAD

ZERO POINT: 12.24 CM

MEASURED QUANTITIES

DERIVED QUANTITIES

LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
57.57	45.334	867.0	13.63	1.0083	12578	0.6686
57.32	45.079	891.0	13.95	1.0125	12630	0.6733
32.33	20.089	448.0	10.06	0.7059	8806	0.7033
32.01	19.774	452.0	10.22	0.7011	8745	0.7040
38.82	26.584	759.0	14.99	0.8026	10012	0.6951
39.09	26.851	895.0	17.69	0.8020	10004	0.6911
15.30	3.061	308.0	14.03	0.3480	4340	0.8894
14.92	2.677	441.5	21.12	0.3314	4133	0.9058
14.07	1.831	425.0	24.34	0.2768	3452	0.9157
14.17	1.930	498.0	28.18	0.2801	3494	0.9027
12.67	0.433	418.0	33.16	0.1998	2492	1.3712
13.28	1.042	462.0	30.50	0.2401	2995	1.0545

TABLE 15

SINGLE ORIFICE PLATE DATA

PLATE: A02ND
HOLE DIAMETER: 0.4995IN.
PLATE THICKNESS: 0.25 IN.
LIQUID: WATER

DATE:06/26/92
LIQUID TEMPERATURE: 71 F
LIQUID DENSITY: 997.8 KG/CU.M
LIQUID VISCOSITY: 0.975cp

INCREASING HEAD

ZERO POINT = 12.24 CM

MEASURED QUANTITIES				DERIVED QUANTITIES		
LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
12.69	0.45	442.0	22.92	0.3057	1920	0.5133
12.69	0.45	458.0	26.59	0.2730	1715	0.4584
12.70	0.46	448.0	16.47	0.4312	2708	0.7161
12.81	0.57	455.0	11.97	0.6026	3786	0.8989
12.85	0.61	360.0	9.43	0.6052	3801	0.8727
13.12	0.88	460.0	9.22	0.7909	4968	0.9496
13.25	1.01	434.0	8.89	0.7739	4862	0.8673
14.82	2.58	473.0	6.36	1.1789	7407	0.8267
14.78	2.54	452.0	6.13	1.1689	7343	0.8260
16.00	3.76	788.0	9.21	1.3563	8520	0.7878
16.10	3.86	855.0	9.72	1.3944	8760	0.7994
19.08	6.84	882.0	8.09	1.7282	10857	0.7443
18.98	6.74	872.0	8.06	1.7150	10775	0.7440
31.75	19.51	835.0	4.88	2.7124	17041	0.6916
31.95	19.71	895.0	5.27	2.6921	16913	0.6830
27.75	15.51	975.0	6.43	2.4037	15101	0.6874
35.39	23.15	879.0	4.82	2.8909	18162	0.6767
36.02	23.78	940.0	5.04	2.9565	18574	0.6829
37.79	25.55	901.0	4.70	3.0389	19092	0.6771
38.05	25.81	892.0	4.58	3.0873	19397	0.6845
44.89	32.65	907.0	4.16	3.4562	21714	0.6813
45.00	32.76	860.0	3.97	3.4339	21574	0.6757
54.45	42.21	845.0	3.62	3.7003	23247	0.6415

TABLE 16

SINGLE ORIFICE PLATE DATA

PLATE: A02ND	DATE:06/26/92
HOLE DIAMETER: 0.4995 IN.	LIQUID TEMPERATURE: 71 F
PLATE THICKNESS: 0.25 IN.	LIQUID DENSITY: 997.8 KG/CU.M
LIQUID: WATER	LIQUID VISCOSITY: 0.975cp

DECREASING HEAD

ZERO POINT = 12.24 CM

MEASURED QUANTITIES

DERIVED QUANTITIES

LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
52.30	40.06	886.0	3.73	3.7654	23656	0.6701
52.29	40.05	913.0	3.85	3.7592	23617	0.6690
52.45	40.21	846.0	3.63	3.6944	23211	0.6562
54.09	41.85	900.0	3.74	3.8147	23966	0.6642
54.45	42.21	805.0	3.35	3.8092	23932	0.6604
39.74	27.50	883.0	4.39	3.1885	20032	0.6848
39.77	27.53	950.0	4.80	3.1374	19711	0.6735
30.73	18.49	873.0	5.24	2.6410	16592	0.6918
30.77	18.53	800.0	4.86	2.6094	16394	0.6827
23.11	10.87	950.0	7.32	2.0573	12925	0.7028
23.29	11.05	882.0	6.13	2.2808	14329	0.7728
18.35	6.11	928.5	8.81	1.6707	10496	0.7613
18.35	6.11	890.0	8.38	1.6836	10577	0.7671
15.29	3.05	910.0	11.04	1.3066	8208	0.8427
15.32	3.08	859.0	10.55	1.2907	8109	0.8283
14.00	1.76	831.0	13.15	1.0017	6293	0.8505
13.98	1.74	792.0	12.78	0.9824	6172	0.8388
13.11	0.87	477.0	9.88	0.7653	4808	0.9242
13.15	0.91	468.0	9.81	0.7562	4751	0.8929
12.90	0.66	464.0	12.00	0.6129	3851	0.8498
12.90	0.66	463.0	12.42	0.5909	3713	0.8193
12.64	0.40	407.0	20.73	0.3112	1955	0.5543
12.62	0.38	463.0	24.46	0.3001	1885	0.5482

TABLE 17

SINGLE ORIFICE PLATE DATA

PLATE: A03ND
HOLE DIAMETER: 0.7497 IN.
PLATE THICKNESS: 0.25 IN.
LIQUID: WATER

DATE:07/09/92
LIQUID TEMPERATURE: 70 F
LIQUID DENSITY: 998.0 KG/CU.M
LIQUID VISCOSITY: 0.988 cp

INCREASING HEAD

ZERO POINT = 12.34 CM

MEASURED QUANTITIES				DERIVED QUANTITIES		
LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
12.63	0.29	464.5	35.66	0.2065	859	0.1917
12.55	0.21	424.0	33.31	0.2018	839	0.2202
12.62	0.28	445.0	34.55	0.2042	849	0.1929
12.70	0.36	458.0	17.07	0.4253	1769	0.3544
12.71	0.37	468.0	16.79	0.4419	1837	0.3632
12.72	0.38	473.0	18.21	0.4118	1711	0.3340
12.91	0.57	464.0	10.59	0.6946	2888	0.4600
12.91	0.57	492.0	11.02	0.7077	2942	0.4687
13.15	0.81	437.0	5.85	1.1842	4923	0.6578
13.15	0.81	450.0	5.94	1.2009	4993	0.6672
13.51	1.17	468.0	4.74	1.5651	6508	0.7235
13.40	1.06	456.0	4.73	1.5282	6354	0.7422
14.32	1.98	492.0	3.86	2.0205	8401	0.7179
14.25	1.91	909.0	7.36	1.9578	8140	0.7083
15.21	2.87	868.0	6.06	2.2706	9440	0.6701
14.61	2.27	958.0	6.64	2.2871	9510	0.7590
14.78	2.44	936.0	6.20	2.3931	9950	0.7660
15.62	3.28	869.0	4.63	2.9752	12371	0.8214
15.63	3.29	918.0	4.84	3.0066	12501	0.8288
16.80	4.46	970.0	4.61	3.3355	13869	0.7897
16.82	4.48	1000.0	4.54	3.4916	14518	0.8248
19.48	7.14	949.0	3.72	4.0440	16815	0.7567
18.98	6.64	933.0	3.68	4.0190	16711	0.7798
23.98	11.64	979.0	3.01	5.1559	21439	0.7556
23.21	10.87	1000.0	3.20	4.9538	20598	0.7512
29.40	17.06	938.0	2.49	5.9716	24830	0.7229
29.49	17.15	935.0	2.50	5.9286	24652	0.7158

TABLE 18

SINGLE ORIFICE PLATE DATA

PLATE: A03ND
HOLE DIAMETER: 0.7497 IN.
PLATE THICKNESS: 0.25 IN.
LIQUID: WATER

DATE:07/09/92
LIQUID TEMPERATURE: 70 F
LIQUID DENSITY: 998.0 KG/CU.M
LIQUID VISCOSITY: 0.988 cp

DECREASING HEAD

ZERO POINT = 12.34 CM

MEASURED QUANTITIES				DERIVED QUANTITIES		
LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
29.40	17.06	918	2.45	5.9396	24697	0.7190
28.45	16.11	890	2.41	5.8541	24341	0.7292
29.35	17.01	901	2.45	5.8297	24240	0.7067
18.48	6.14	924	3.76	3.8955	16197	0.7860
18.46	6.12	932	4.06	3.6389	15130	0.7355
16.72	4.38	968	4.58	3.3504	13931	0.8004
16.75	4.41	880	4.06	3.4359	14286	0.8180
16.81	4.47	964	4.60	3.3220	13813	0.7856
16.72	4.38	975	4.34	3.5612	14807	0.8508
15.10	2.76	980	6.14	2.5301	10520	0.7615
15.10	2.76	910	5.61	2.5714	10691	0.7739
14.51	2.17	911	6.20	2.3292	9684	0.7906
14.61	2.27	959	6.41	2.3716	9861	0.7870
13.58	1.24	933	7.74	1.9108	7945	0.8580
13.55	1.21	992	8.48	1.8544	7710	0.8429
13.29	0.95	940	10.87	1.3708	5700	0.7032
13.29	0.95	930	10.59	1.3921	5788	0.7141
13.10	0.76	940	14.06	1.0598	4406	0.6078
13.10	0.76	945	14.09	1.0632	4420	0.6098
12.91	0.57	483	10.44	0.7334	3049	0.4857
12.99	0.65	468	10.56	0.7025	2921	0.4357
12.71	0.37	467	18.03	0.4106	1707	0.3375
12.71	0.37	545	21.91	0.3943	1639	0.3241
12.64	0.30	455	33.29	0.2167	900	0.1978
12.63	0.29	459	34.93	0.2083	865	0.1934

TABLE 19

SINGLE ORIFICE PLATE DATA

PLATE: A04ND
HOLE DIAMETER: 0.2504 IN.
PLATE THICKNESS: 12GAGE
LIQUID: WATER

DATE:06/25/92
LIQUID TEMPERATURE: 71F
LIQUID DENSITY: 997.8 KG/CU.M
LIQUID VISCOSITY: 0.975cp

INCREASING HEAD

ZERO POINT = 11.88 CM

MEASURED QUANTITIES				DERIVED QUANTITIES		
LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
12.58	0.70	365.0	39.24	0.1475	1847	0.7899
12.55	0.67	268.0	32.27	0.1316	1650	0.7209
13.63	1.75	446.0	28.94	0.2443	3062	0.8277
13.65	1.77	397.0	25.50	0.2468	3092	0.8314
14.86	2.98	410.0	20.89	0.3111	3899	0.8078
14.80	2.92	390.0	20.67	0.2991	3748	0.7845
15.08	3.20	425.0	20.99	0.3210	4022	0.8042
15.10	3.22	426.0	20.96	0.3222	4038	0.8047
16.15	4.27	409.0	17.52	0.3701	4637	0.8026
16.25	4.37	435.0	18.56	0.3715	4656	0.7966
29.63	17.75	435.0	9.64	0.7153	8965	0.7610
29.70	17.82	395.0	8.72	0.7181	8999	0.7624
32.40	20.52	421.0	8.74	0.7636	9569	0.7555
32.50	20.62	459.0	9.64	0.7548	9459	0.7450
46.10	34.22	470.0	7.76	0.9601	12032	0.7356
46.30	34.42	450.0	7.49	0.9524	11936	0.7276
74.35	62.47	467.0	5.71	1.2965	16248	0.7352
74.40	62.52	462.0	5.85	1.2519	15690	0.7096
74.50	62.62	479.0	5.96	1.2740	15967	0.7216

TABLE 20

SINGLE ORIFICE PLATE DATA

PLATE: A04ND
HOLE DIAMETER: 0.2504 IN.
PLATE THICKNESS: 12 GAGE
LIQUID: WATER

DATE:06/25/92
LIQUID TEMPERATURE: 71 F
LIQUID DENSITY: 997.8 KG/CU.M
LIQUID VISCOSITY:0.975 cp

DECREASING HEAD

ZERO POINT = 11.88 CM

MEASURED QUANTITIES				DERIVED QUANTITIES		
LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
79.02	67.14	450.0	5.48	1.3017	16313	0.7120
79.20	67.32	435.0	5.35	1.2889	16153	0.7041
46.59	34.71	459.0	7.69	0.9462	11858	0.7198
46.28	34.40	435.0	7.30	0.9446	11838	0.7218
30.35	18.47	417.0	9.40	0.7032	8813	0.7334
29.96	18.08	467.0	10.44	0.7091	8887	0.7474
28.45	16.57	465.0	10.91	0.6756	8467	0.7439
28.55	16.67	434.0	10.22	0.6732	8436	0.7390
23.40	11.52	455.0	12.27	0.5878	7366	0.7762
23.58	11.70	452.0	12.06	0.5941	7445	0.7785
18.73	6.85	435.0	14.90	0.4628	5799	0.7925
18.75	6.87	407.0	14.00	0.4608	5775	0.7880
16.72	4.84	435.0	17.59	0.3920	4912	0.7986
16.80	4.92	441.0	18.16	0.3850	4825	0.7778
15.60	3.72	444.0	20.34	0.3460	4336	0.8041
15.50	3.62	407.5	21.63	0.2986	3742	0.7035
13.60	1.72	425.0	27.63	0.2438	3056	0.8333
13.54	1.66	420.0	28.05	0.2374	2974	0.8257
13.15	1.27	384.0	34.91	0.1744	2185	0.6935
13.12	1.24	420.0	35.11	0.1896	2376	0.7632
12.49	0.61	395.0	47.44	0.1320	1653	0.7574
12.48	0.60	238.0	31.73	0.1189	1490	0.6880

TABLE 21

SINGLE ORIFICE PLATE DATA

PLATE: A05ND
HOLE DIAMETER: 0.5006IN.
PLATE THICKNESS: 12 GAGE
LIQUID: WATER

DATE:06/16/92
LIQUID TEMPERATURE: 68 F
LIQUID DENSITY: 998.2 KG/CU.M
LIQUID VISCOSITY: 1.026 cp

INCREASING HEAD

ZERO POINT = 14.01 CM

MEASURED QUANTITIES				DERIVED QUANTITIES		
LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
14.32	0.31	330.0	51.60	0.1014	618	0.2042
14.41	0.40	388.0	34.52	0.1782	1086	0.3159
14.40	0.39	389.0	35.70	0.1727	1053	0.3102
14.68	0.67	411.0	17.31	0.3764	2294	0.5156
14.67	0.66	352.0	15.73	0.3547	2163	0.4896
14.52	0.51	394.0	15.74	0.3968	2419	0.6231
14.52	0.51	435.0	17.49	0.3943	2404	0.6191
14.54	0.53	436.0	14.74	0.4689	2858	0.7222
14.59	0.58	427.0	14.89	0.4546	2771	0.6694
14.62	0.61	445.0	14.85	0.4750	2896	0.6820
14.73	0.72	443.0	11.09	0.6332	3860	0.8368
14.80	0.79	446.5	12.14	0.5830	3554	0.7356
14.83	0.82	425.0	11.10	0.6069	3700	0.7516
15.65	1.64	438.0	7.38	0.9408	5736	0.8238
15.69	1.68	425.0	7.09	0.9502	5793	0.8221
16.21	2.20	437.0	6.06	1.1431	6969	0.8642
16.23	2.22	444.0	6.13	1.1482	7000	0.8641
18.03	4.02	464.0	5.29	1.3904	8477	0.7776
18.01	4.00	438.0	5.01	1.3859	8449	0.7770
19.89	5.88	463.5	4.44	1.6548	10089	0.7653
19.98	5.97	457.0	4.38	1.6540	10084	0.7591
25.60	11.59	479.0	3.46	2.1945	13380	0.7229
25.44	11.43	424.0	3.12	2.1542	13134	0.7145
25.43	11.42	460.0	3.31	2.2030	13430	0.7310
28.79	14.78	462.0	2.90	2.5254	15397	0.7366
28.78	14.77	482.0	3.09	2.4727	15075	0.7215
36.38	22.37	891.0	4.77	2.9610	18052	0.7020
36.82	22.81	850.0	4.41	3.0554	18628	0.7174
47.82	33.81	866.0	3.78	3.6317	22141	0.7004
47.88	33.87	884.0	3.82	3.6684	22365	0.7068

TABLE 22

SINGLE ORIFICE PLATE DATA

PLATE: A05ND
HOLE DIAMETER: 0.5006IN.
PLATE THICKNESS: 12 GAGE
LIQUID: WATER

DATE:06/16/92
LIQUID TEMPERATURE: 68 F
LIQUID DENSITY: 998.2KG/CU.M
LIQUID VISCOSITY: 1.026 cp

DECREASING HEAD

ZERO POINT = 13.08 CM

MEASURED QUANTITIES

DERIVED QUANTITIES

LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
72.45	59.37	868.0	2.94	4.6801	28533	0.6853
72.52	59.44	796.0	2.68	4.7083	28706	0.6890
72.28	59.20	844.0	2.84	4.7109	28722	0.6908
72.52	59.44	855.0	2.90	4.6736	28493	0.6839
59.55	46.47	850.0	3.28	4.1080	25045	0.6811
58.23	45.15	835.0	3.23	4.0980	24984	0.6894
57.46	44.38	896.0	3.49	4.0697	24812	0.6907
57.03	43.95	838.0	3.32	4.0012	24394	0.6824
56.84	43.76	854.0	3.34	4.0532	24711	0.6928
56.53	43.45	862.0	3.46	3.9493	24078	0.6775
40.32	27.24	859.0	4.31	3.1594	19262	0.6880
40.19	27.11	824.0	4.13	3.1627	19283	0.6904
40.33	27.25	870.0	4.38	3.1487	19197	0.6855
30.33	17.25	941.0	5.84	2.5542	15572	0.7045
30.27	17.19	904.0	5.56	2.5774	15713	0.7122
30.90	17.82	871.0	5.42	2.5474	15531	0.6908
30.54	17.46	920.0	5.65	2.5812	15736	0.7075
30.59	17.51	933.0	5.72	2.5856	15764	0.7076
23.22	10.14	909.0	7.28	1.9793	12067	0.7232
23.22	10.14	889.0	7.13	1.9765	12050	0.7221
19.47	6.39	856.0	8.84	1.5350	9358	0.7229
19.48	6.40	861.0	8.77	1.5563	9488	0.7323
19.34	6.26	927.0	9.53	1.5420	9400	0.7346
16.60	3.52	815.0	11.46	1.1273	6873	0.7555
16.56	3.48	857.0	12.09	1.1237	6850	0.7585
15.50	2.42	817.0	14.59	0.8877	5412	0.7634
15.49	2.41	430.0	7.63	0.8934	5447	0.7706
15.13	2.05	413.5	8.10	0.8092	4934	0.7869
15.10	2.02	427.0	8.14	0.8315	5069	0.8178
15.16	2.08	405.0	8.04	0.7985	4868	0.7678
14.79	1.71	427.0	10.32	0.6559	3998	0.7392
14.82	1.74	425.0	11.08	0.6080	3706	0.6751
14.42	1.34	425.0	24.92	0.2703	1648	0.3850
14.41	1.33	458.0	26.59	0.2730	1664	0.3920
14.41	1.33	423.5	25.06	0.2679	1633	0.3846
14.38	1.30	366.0	24.08	0.2409	1468	0.3548
14.38	1.30	388.0	25.76	0.2388	1455	0.3516

TABLE 23

SINGLE ORIFICE PLATE DATA

PLATE: A06ND	DATE: 07/07/92
HOLE DIAMETER: 0.7505	LIQUID TEMPERATURE: 69 F
PLATE THICKNESS: 12 GAGE	LIQUID DENSITY: 998.1 KG/CU.M
LIQUID: WATER	LIQUID VISCOSITY: 1.002 cp

INCREASING HEAD

ZERO POINT = 12.08 CM

MEASURED QUANTITIES				DERIVED QUANTITIES		
LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
12.39	0.31	427.5	33	0.2057	849	0.1843
12.39	0.31	430.0	34	0.2005	827	0.1797
12.43	0.35	457.0	14.2	0.5109	2109	0.4308
12.44	0.36	468.0	15.1	0.4926	2034	0.4096
12.45	0.37	451.0	14	0.5125	2116	0.4204
12.65	0.57	451.0	9.13	0.7831	3233	0.5175
12.62	0.54	473.0	9.92	0.7558	3121	0.5132
13.01	0.93	469.0	5.06	1.4693	6068	0.7601
13.02	0.94	482.0	5.11	1.4952	6175	0.7694
13.14	1.06	467.0	4.57	1.6199	6690	0.7850
13.19	1.11	473.0	4.67	1.6056	6630	0.7603
13.99	1.91	479.0	3.67	2.0690	8545	0.7469
14.01	1.93	479.0	3.64	2.0860	8615	0.7492
15.25	3.17	893.0	5.31	2.6659	11010	0.7470
15.35	3.27	832.0	4.81	2.7420	11324	0.7565
17.00	4.92	916.0	4.27	3.4006	14044	0.7649
16.98	4.90	961.0	4.45	3.4233	14138	0.7716
19.20	7.12	860.0	3.49	3.9062	16133	0.7304
19.35	7.27	890.0	3.64	3.8759	16008	0.7172
22.91	10.83	946.0	3.11	4.8219	19914	0.7310
22.75	10.67	910.0	3.06	4.7142	19470	0.7200
27.79	15.71	856.0	2.44	5.5612	22968	0.7000
27.55	15.47	919.0	2.66	5.4767	22619	0.6947

TABLE 24

SINGLE ORIFICE PLATE DATA

PLATE: A06ND
HOLE DIAMETER: 0.7505 IN.
PLATE THICKNESS: 12 GAGE
LIQUID: WATER

DATE: 07/07/92
LIQUID TEMPERATURE: 69 F
LIQUID DENSITY: 998.1 KG/CU.M
LIQUID VISCOSITY: 1.002 cp

DECREASING HEAD

ZERO POINT = 12.08 CM

MEASURED QUANTITIES

DERIVED QUANTITIES

LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
27.73	15.65	832.0	2.32	5.6849	23479	0.7113
28.06	15.98	932.0	2.61	5.6606	23378	0.7010
23.48	11.40	916.0	2.91	4.9898	20608	0.7316
22.78	10.70	930.0	3.09	4.7710	19704	0.7220
18.93	6.85	943.0	3.75	3.9862	16463	0.7539
19.24	7.16	869.0	3.49	3.9471	16301	0.7304
16.36	4.28	843.0	4.20	3.1817	13140	0.7611
16.43	4.35	942.0	4.62	3.2322	13349	0.7670
15.08	3.00	921.0	5.46	2.6739	11043	0.7639
15.10	3.02	942.0	5.58	2.6761	11052	0.7620
13.89	1.81	879.0	7.26	1.9193	7926	0.7059
13.89	1.81	968.0	7.72	1.9877	8209	0.7311
13.16	1.08	504.0	5.05	1.5821	6534	0.7526
13.18	1.10	469.0	4.51	1.6485	6808	0.7771
12.78	0.70	462.0	6.41	1.1425	4718	0.6765
12.77	0.69	497.0	6.60	1.1937	4930	0.7118
12.63	0.55	470.0	7.75	0.9613	3970	0.6409
12.61	0.53	478.0	7.96	0.9519	3931	0.6463
12.49	0.41	467.0	11.76	0.6295	2599	0.4846
12.49	0.41	475.0	12.10	0.6223	2570	0.4791
12.35	0.27	456.0	19.49	0.3709	1531	0.3561
12.32	0.24	470.0	20.89	0.3567	1472	0.3632
12.30	0.22	173.0	33.06	0.0830	342	0.0882
12.30	0.22	182.0	33.65	0.0857	353	0.0912

TABLE 25

SINGLE ORIFICE PLATE DATA

PLATE: A07ND
HOLE DIAMETER: 0.2500 IN.
PLATE THICKNESS: 14 GAGE
LIQUID: WATER

DATE: 05/16/92
LIQUID TEMPERATURE: 68F
LIQUID DENSITY: 998.2 KG/CU.M
LIQUID VISCOSITY: 1.026 cp

INCREASING HEAD

ZERO POINT = 13.72 CM

MEASURED QUANTITIES

DERIVED QUANTITIES

LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
14.95	1.23	452.0	34.82	0.2058	2512	0.8342
14.81	1.09	345.0	26.87	0.2035	2484	0.8765
16.60	2.88	437.0	22.82	0.3036	3705	0.8043
16.25	2.53	399.0	22.01	0.2874	3508	0.8123
16.25	2.53	454.0	24.87	0.2894	3532	0.8180
17.84	4.12	463.0	20.38	0.3601	4396	0.7977
18.02	4.30	373.0	16.17	0.3657	4464	0.7929
20.15	6.43	465.0	16.56	0.4451	5434	0.7893
20.15	6.43	394.0	14.06	0.4442	5423	0.7877
23.29	9.57	470.0	13.85	0.5379	6567	0.7819
23.21	9.49	263.0	7.83	0.5324	6500	0.7771
32.17	18.45	459.0	9.88	0.7364	8990	0.7709
32.18	18.46	469.0	10.16	0.7318	8933	0.7658
46.01	32.29	465.0	7.86	0.9378	11448	0.7420
46.00	32.28	401.0	6.76	0.9403	11479	0.7442
61.83	48.11	459.0	6.39	1.1387	13901	0.7381
61.85	48.13	474.0	6.57	1.1437	13961	0.7412
73.55	59.83	460.0	5.85	1.2465	15217	0.7246
73.56	59.84	474.0	6.04	1.2440	15187	0.7231

TABLE 26

SINGLE ORIFICE PLATE DATA

PLATE: A08ND
HOLE DIAMETER: 0.5008 IN.
PLATE THICKNESS: 14 GAGE
LIQUID: WATER

DATE:06/08/92
LIQUID TEMPERATURE: 72 F
LIQUID DENSITY: 997.7 KG/CU.M
LIQUID VISCOSITY: 0.962 cp

INCREASING HEAD

ZERO POINT = 13.80 CM

MEASURED QUANTITIES				DERIVED QUANTITIES		
LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
14.38	0.58	418.0	20.43	0.3243	2089	0.4772
14.39	0.59	426.0	20.63	0.3273	2107	0.4775
14.55	0.75	365.0	10.95	0.5284	3403	0.6837
14.88	1.08	380.0	8.06	0.7474	4813	0.8058
14.87	1.07	382.0	9.20	0.6582	4239	0.7130
15.32	1.52	395.0	7.15	0.8757	5639	0.7959
15.40	1.60	407.0	7.32	0.8814	5675	0.7807
16.10	2.30	457.0	6.81	1.0638	6850	0.7859
16.09	2.29	438.5	6.63	1.0484	6751	0.7763
17.61	3.81	447.0	5.34	1.3269	8544	0.7617
17.82	4.02	449.0	5.23	1.3609	8764	0.7605
20.30	6.50	443.0	4.26	1.6485	10615	0.7245
20.39	6.59	460.0	4.27	1.7077	10997	0.7454
25.17	11.37	458.0	3.39	2.1417	13792	0.7117
25.15	11.35	475.0	3.34	2.2544	14517	0.7498
24.78	10.98	460.0	3.52	2.0716	13339	0.7005
24.57	10.77	465.0	3.67	2.0085	12934	0.6858
30.29	16.49	484.0	2.94	2.6096	16805	0.7201
30.41	16.61	490.0	3.02	2.5720	16562	0.7071
38.73	24.93	435.0	2.20	3.1344	20184	0.7034
38.75	24.95	456.0	2.29	3.1566	20327	0.7081
46.25	32.45	860.0	3.84	3.5502	22862	0.6983
46.39	32.59	868.0	3.89	3.5372	22777	0.6942

TABLE 27

SINGLE ORIFICE PLATE DATA

PLATE: A08ND	DATE: 06/08/92
HOLE DIAMETER: 0.5008 IN.	LIQUID TEMPERATURE: 72 F
PLATE THICKNESS: 14 GAGE	LIQUID DENSITY: 997.7 KG/CU.M
LIQUID: WATER	LIQUID VISCOSITY: 0.962 cp
DECREASING HEAD	ZERO POINT = 13.80 CM
MEASURED QUANTITIES	DERIVED QUANTITIES

LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
39.89	26.09	861.0	4.31	3.1667	20392	0.6947
40.33	26.53	873.0	4.39	3.1523	20300	0.6858
30.10	16.30	857.0	5.36	2.5345	16321	0.7034
26.74	12.94	894.0	6.16	2.3006	14815	0.7166
26.78	12.98	881.0	6.23	2.2417	14435	0.6972
26.76	12.96	905.0	6.22	2.3064	14853	0.7179
20.82	7.02	935.0	8.66	1.7115	11021	0.7238
20.83	7.03	930.0	8.54	1.7263	11116	0.7295
17.44	3.64	440.0	5.44	1.2821	8256	0.7530
17.40	3.60	463.0	5.76	1.2742	8205	0.7525
15.67	1.87	425.0	7.14	0.9436	6076	0.7731
15.69	1.89	449.0	7.33	0.9710	6253	0.7914
15.34	1.54	385.0	11.68	0.5225	3365	0.4718
15.24	1.44	445.0	8.11	0.8698	5601	0.8122
15.26	1.46	394.0	7.27	0.8591	5532	0.7967
14.61	0.81	431.5	11.49	0.5953	3833	0.7411
14.59	0.79	425.0	11.72	0.5748	3701	0.7247
14.59	0.79	421.0	11.42	0.5844	3763	0.7367
14.57	0.77	416.0	12.16	0.5423	3492	0.6925
14.51	0.71	438.0	13.16	0.5276	3398	0.7016
14.45	0.65	437.5	13.95	0.4972	3201	0.6909
14.47	0.67	432.5	13.67	0.5015	3229	0.6865
14.42	0.62	400.0	14.84	0.4273	2751	0.6080
14.42	0.62	444.0	16.54	0.4255	2740	0.6055
14.38	0.58	420.0	19.25	0.3459	2226	0.5089
14.29	0.49	425.0	17.33	0.3888	2503	0.6223
14.30	0.50	441.5	18.12	0.3862	2487	0.6120
14.28	0.48	402.0	24.00	0.2655	1710	0.4294
14.15	0.35	272.5	50.29	0.0859	552	0.1627

TABLE 28

SINGLE ORIFICE PLATE DATA

PLATE: A09ND
HOLE DIAMETER: 0.7502
PLATE THICKNESS: 14 GAGE
LIQUID: WATER

DATE:07/06/92
LIQUID TEMPERATURE: 69 F
LIQUID DENSITY: 998.1 KG/CU.M
LIQUID VISCOSITY: 1.002 cp

INCREASING HEAD

ZERO POINT = 11.90 CM

MEASURED QUANTITIES				DERIVED QUANTITIES		
LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
12.28	0.38	446.0	31.06	0.2276	940	0.1844
12.25	0.35	490.0	33.53	0.2317	956	0.1955
12.40	0.50	476.0	14.31	0.5273	2179	0.3723
12.40	0.50	458.0	13.45	0.5398	2230	0.3812
12.52	0.62	460.0	9.13	0.7987	3300	0.5065
12.51	0.61	472.5	9.32	0.8037	3320	0.5138
12.70	0.80	437.0	6.32	1.0961	4528	0.6119
12.70	0.80	460.0	6.76	1.0787	4457	0.6022
12.85	0.95	460.0	5.13	1.4214	5872	0.7282
12.85	0.95	849.0	9.49	1.4182	5859	0.7265
13.70	1.80	903.0	8.08	1.7716	7320	0.6593
13.70	1.80	908.0	8.10	1.7770	7342	0.6613
14.40	2.50	945.0	6.85	2.1869	9035	0.6906
14.25	2.35	918.0	6.57	2.2149	9151	0.7214
15.56	3.66	948.0	5.65	2.6598	10989	0.6942
15.60	3.70	938.0	5.61	2.6505	10951	0.6880
16.63	4.73	957.0	4.63	3.2765	13537	0.7523
16.65	4.75	889.0	4.27	3.3003	13635	0.7561
17.40	5.50	958.0	4.24	3.5817	14798	0.7626
17.72	5.82	945.0	4.12	3.6360	15022	0.7525
17.81	5.91	822.0	3.53	3.6913	15252	0.7582
20.15	8.25	950.0	3.58	4.2065	17380	0.7313
20.12	8.22	960.0	3.76	4.0473	16722	0.7049
24.29	12.39	850.0	2.61	5.1625	21330	0.7323
24.65	12.75	913.0	2.86	5.0604	20909	0.7076

TABLE 29

SINGLE ORIFICE PLATE DATA

PLATE: A09ND
HOLE DIAMETER: 0.7502 IN.
PLATE THICKNESS: 14 GAGE
LIQUID: WATER

DATE: 07/06/92
LIQUID TEMPERATURE: 69 F
LIQUID DENSITY: 998.088 KG/CU.M
LIQUID VISCOSITY: 1.01 cp

DECREASING HEAD

ZERO POINT = 11.90 CM

MEASURED QUANTITIES				DERIVED QUANTITIES		
LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
24.75	12.85	894.0	2.82	5.0254	20764	0.7000
25.12	13.22	899.0	2.81	5.0715	20954	0.6965
20.19	8.29	883.0	3.20	4.3742	18072	0.7586
19.95	8.05	940.0	3.45	4.3191	17845	0.7601
17.99	6.09	899.0	3.89	3.6635	15136	0.7412
17.85	5.95	951.0	4.15	3.6326	15008	0.7436
16.19	4.29	910.0	4.64	3.1089	12845	0.7495
15.95	4.05	962.0	5.03	3.0317	12526	0.7522
14.92	3.02	970.0	5.88	2.615	10804	0.7514
14.95	3.05	943.0	5.67	2.6364	10892	0.7538
14.29	2.39	938.0	6.79	2.1899	9048	0.7073
14.26	2.36	971.0	7.13	2.1588	8919	0.7017
13.79	1.89	876.0	8.95	1.5515	6410	0.5635
13.25	1.35	945.0	8.72	1.7179	7097	0.7383
13.00	1.10	939.0	10.42	1.4285	5902	0.6801
13.00	1.10	960.0	10.47	1.4535	6005	0.6920
12.86	0.96	942.0	12.47	1.1975	4948	0.6103
12.85	0.95	898.0	11.84	1.2023	4967	0.6159
12.75	0.85	470.0	7.20	1.0348	4275	0.5604
12.77	0.87	482.0	6.99	1.0931	4516	0.5852
12.46	0.56	480.0	10.26	0.7416	3064	0.4948
12.45	0.55	490.0	10.32	0.7527	3109	0.5068
12.41	0.51	422.0	10.87	0.6154	2542	0.4303
12.42	0.52	457.0	11.96	0.6057	2502	0.4194
12.35	0.45	492.0	19.14	0.4075	1684	0.3033
12.37	0.47	445.0	17.61	0.4006	1655	0.2918
12.30	0.40	268.0	15.83	0.2684	1108	0.2119
12.30	0.40	345.0	20.85	0.2623	1083	0.2071
12.23	0.33	262.0	38.71	0.1073	442	0.0933
12.25	0.35	244.0	36.09	0.1072	442	0.0905

TABLE 30

SINGLE ORIFICE PLATE DATA

PLATE: A15ND	DATE:07/04/92
HOLE DIAMETER: 0.5006IN.	LIQUID TEMPERATURE: 71 F
PLATE THICKNESS: 12 GAGE	LIQUID DENSITY: 997.8 KG/CU.M
LIQUID: WATER	LIQUID VISCOSITY: 0.975 cp

INCREASING HEAD

ZERO POINT = 11.90 CM

MEASURED QUANTITIES				DERIVED QUANTITIES		
LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
12.30	0.40	438.0	25.77	0.2694	1689	0.4777
12.30	0.40	459.0	26.76	0.2719	1704	0.4821
12.40	0.50	462.0	16.81	0.4357	2731	0.6909
12.36	0.46	455.0	13.11	0.5502	3449	0.9096
12.38	0.48	497.5	14.21	0.5550	3478	0.8983
13.02	1.12	468.0	9.95	0.7456	4674	0.7900
12.98	1.08	475.0	10.36	0.7268	4556	0.7843
14.06	2.16	470.0	7.03	1.0598	6643	0.8086
14.05	2.15	483.0	7.38	1.0375	6504	0.7934
15.82	3.92	472.5	5.57	1.3447	8430	0.7616
15.81	3.91	498.0	5.80	1.3611	8532	0.7719
18.31	6.41	894.0	8.09	1.7518	10982	0.7759
18.35	6.45	958.0	8.90	1.7063	10696	0.7534
19.75	7.85	917.0	7.76	1.8732	11743	0.7497
19.86	7.96	971.0	8.27	1.8612	11667	0.7398
21.67	9.77	968.0	7.45	2.0597	12912	0.7389
21.86	9.96	909.0	6.99	2.0614	12923	0.7325
25.34	13.44	912.5	6.14	2.3559	14768	0.7206
25.15	13.25	981.0	6.54	2.3778	14906	0.7325
29.81	17.91	959.0	5.78	2.6301	16488	0.6969
30.02	18.12	940.0	5.56	2.6800	16801	0.7060
36.86	24.96	989.0	4.99	3.1418	19695	0.7052
37.45	25.55	855.0	4.38	3.0944	19398	0.6865
52.13	40.23	947.0	3.86	3.8891	24380	0.6876
52.82	40.92	855.0	3.46	3.9172	24556	0.6867

TABLE 31

SINGLE ORIFICE PLATE DATA

PLATE: A15ND
HOLE DIAMETER: 0.5006IN.
PLATE THICKNESS: 12 GAGE
LIQUID: WATER

DATE:07/04/92
LIQUID TEMPERATURE: 71 F
LIQUID DENSITY: 997.8 KG/CU.M
LIQUID VISCOSITY: 0.975 cp

DECREASING HEAD

ZERO POINT = 11.90 CM

MEASURED QUANTITIES				DERIVED QUANTITIES		
LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
52.92	41.02	930.0	3.73	3.9524	24777	0.6920
52.46	40.56	920.0	3.75	3.8890	24380	0.6848
43.05	31.15	892.0	4.06	3.4828	21833	0.6998
43.20	31.30	935.0	4.24	3.4957	21914	0.7007
30.55	18.65	913.0	5.60	2.5844	16201	0.6711
30.30	18.40	948.0	5.51	2.7273	17097	0.7130
27.66	15.76	979.0	6.12	2.5358	15897	0.7163
27.76	15.86	984.0	6.14	2.5405	15925	0.7153
18.85	6.95	996.0	8.83	1.7881	11209	0.7606
18.48	6.58	966.0	8.85	1.7303	10847	0.7564
17.30	5.40	878.0	8.84	1.5744	9870	0.7598
17.30	5.40	1010.0	10.07	1.5899	9966	0.7672
16.10	4.20	491.0	5.46	1.4255	8936	0.7800
16.12	4.22	468.0	4.99	1.4867	9319	0.8116
15.49	3.59	492.0	5.68	1.3731	8607	0.8127
15.42	3.52	487.0	5.78	1.3356	8373	0.7983
14.50	2.60	497.0	6.91	1.1402	7147	0.7929
14.38	2.48	435.0	6.21	1.1104	6961	0.7907
13.75	1.85	470.0	8.02	0.9290	5823	0.7659
13.63	1.73	463.0	7.99	0.9186	5758	0.7832
12.65	0.75	462.0	11.20	0.6539	4099	0.8467
12.70	0.80	465.0	11.18	0.6593	4133	0.8266
12.28	0.38	455.0	30.08	0.2398	1503	0.4362
12.28	0.38	471.0	31.41	0.2377	1490	0.4324

TABLE 32

SINGLE ORIFICE PLATE DATA

PLATE: A17ND	DATE:07/05/92
HOLE DIAMETER: 0.2500 IN.	LIQUID TEMPERATURE: 70 F
PLATE THICKNESS: 14 GAGE	LIQUID DENSITY: 998.0 KG/CU.M
LIQUID: WATER	LIQUID VISCOSITY: 0.988 cp

INCREASING HEAD

ZERO POINT = 11.88 CM

MEASURED QUANTITIES				DERIVED QUANTITIES		
LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
12.91	1.03	441.0	34.88	0.2004	2499	0.8879
12.91	1.03	444.5	34.84	0.2022	2521	0.8960
13.28	1.40	437.0	30.70	0.2256	2813	0.8575
13.40	1.52	438.0	30.16	0.2302	2870	0.8396
15.82	3.94	448.0	19.77	0.3592	4479	0.8137
16.25	4.37	442.0	18.34	0.3820	4763	0.8217
19.20	7.32	448.0	14.32	0.4959	6184	0.8242
19.51	7.63	477.5	14.96	0.5060	6308	0.8236
23.52	11.64	438.0	11.24	0.6177	7702	0.8141
23.92	12.04	461.0	12.21	0.5985	7462	0.7755
33.10	21.22	458.0	9.13	0.7952	9916	0.7762
34.50	22.62	446.0	8.67	0.8155	10168	0.7709
35.05	23.17	440.0	8.35	0.8353	10415	0.7803
49.69	37.81	468.0	7.40	1.0025	12500	0.7331
50.35	38.47	459.0	7.10	1.0248	12778	0.7429
67.10	55.22	882.0	11.79	1.1859	14786	0.7175
67.75	55.87	921.0	12.25	1.1918	14861	0.7169
70.34	58.46	925.0	12.09	1.2128	15122	0.7132

TABLE 33

SINGLE ORIFICE PLATE DATA

PLATE: A17ND
HOLE DIAMETER: 0.2500 IN.
PLATE THICKNESS: 14 GAGE
LIQUID: WATER

DATE:07/05/92
LIQUID TEMPERATURE: 70 F
LIQUID DENSITY: 998.0 KG/CU.M
LIQUID VISCOSITY: 0.988 cp

DECREASING HEAD

ZERO POINT = 11.88 CM

MEASURED QUANTITIES				DERIVED QUANTITIES		
LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
70.55	58.67	954.0	12.41	1.2186	15194	0.7153
71.23	59.35	930.0	12.02	1.2265	15293	0.7158
57.90	46.02	921.0	13.31	1.0969	13677	0.7270
45.01	33.13	927.0	15.45	0.9511	11859	0.7430
44.41	32.53	910.0	15.25	0.9459	11795	0.7457
38.35	26.47	494.0	8.88	0.8819	10995	0.7707
37.32	25.44	482.0	8.81	0.8673	10814	0.7731
34.61	22.73	475.0	9.31	0.8088	10085	0.7627
34.32	22.44	490.0	9.48	0.8194	10216	0.7777
32.29	20.41	465.0	9.55	0.7719	9624	0.7682
32.20	20.32	482.5	9.88	0.7741	9653	0.7722
25.51	13.63	453.0	11.18	0.6423	8009	0.7822
24.32	12.44	442.0	11.23	0.6239	7780	0.7954
23.66	11.78	482.0	12.41	0.6157	7677	0.8066
19.82	7.94	479.0	14.82	0.5124	6388	0.8175
19.35	7.47	476.0	15.17	0.4974	6202	0.8183
19.04	7.16	467.0	15.31	0.4835	6029	0.8125
16.35	4.47	455.0	18.89	0.3818	4760	0.8120
16.18	4.30	461.0	19.47	0.3753	4680	0.8138
14.65	2.77	455.0	23.98	0.3008	3750	0.8126
14.55	2.67	445.0	25.82	0.2732	3407	0.7518
12.53	0.65	437.0	40.05	0.1730	2156	0.9646
12.45	0.57	447.5	42.98	0.1650	2058	0.9829
12.10	0.22	155.0	35.28	0.0696	867	0.6676
12.10	0.22	160.0	37.13	0.0683	852	0.6548

TABLE 34

SINGLE ORIFICE PLATE DATA

PLATE: A18ND
HOLE DIAMETER: 0.5008 IN.
PLATE THICKNESS: 14 GAGE
LIQUID: WATER

DATE:07/12/92
LIQUID TEMPERATURE: 69 F
LIQUID DENSITY: 998.1 KG/CU.M
LIQUID VISCOSITY: 1.002 cp

INCREASING HEAD

ZERO POINT = 12.06 CM

MEASURED QUANTITIES				DERIVED QUANTITIES		
LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
12.36	0.30	445.0	36.59	0.1928	1193	0.3944
12.37	0.31	453.0	36.20	0.1984	1227	0.3992
12.49	0.43	455.0	19.56	0.3687	2282	0.6301
12.50	0.44	465.0	19.82	0.3719	2301	0.6282
12.78	0.72	465.0	12.45	0.5921	3664	0.7818
12.75	0.69	475.0	12.77	0.5896	3649	0.7954
13.25	1.19	455.0	8.76	0.8234	5095	0.8457
13.45	1.39	457.0	8.55	0.8473	5243	0.8052
13.61	1.55	465.0	8.48	0.8692	5379	0.7823
13.65	1.59	451.0	8.13	0.8794	5442	0.7814
14.91	2.85	470.0	6.41	1.1623	7193	0.7714
14.98	2.92	456.0	6.20	1.1659	7215	0.7645
17.12	5.06	460.0	4.80	1.5192	9401	0.7567
17.20	5.14	461.0	4.64	1.5750	9746	0.7784
20.75	8.69	930.0	7.82	1.8852	11666	0.7166
20.96	8.90	850.0	6.70	2.0111	12446	0.7553
29.17	17.11	915.0	5.42	2.6761	16561	0.7249
29.91	17.85	953.0	5.61	2.6929	16664	0.7142
39.30	27.24	864.0	4.16	3.2923	20375	0.7068
40.15	28.09	919.0	4.30	3.3879	20966	0.7162
45.25	33.19	906.0	4.01	3.5815	22165	0.6966
46.15	34.09	941.0	4.04	3.6923	22850	0.7086
53.32	41.26	920.0	3.70	3.9416	24393	0.6876
53.39	41.33	940.0	3.75	3.9736	24590	0.6926

TABLE 35

SINGLE ORIFICE PLATE DATA

PLATE: A18ND	**DATE:07/12/92**
HOLE DIAMETER: 0.5008 IN.	**LIQUID TEMPERATURE: 69 F**
PLATE THICKNESS: 14 GAGE	**LIQUID DENSITY: 998.1 KG/CU.M**
LIQUID: WATER	**LIQUID VISCOSITY: 1.002 cp**

DECREASING HEAD **ZERO POINT = 12.06 CM**

MEASURED QUANTITIES				DERIVED QUANTITIES		
LIQUID ELEVATION CM	**NET HEAD CM**	**VOLUME COLLECTED ML.**	**TIME SEC**	**FLOW RATE GPM**	**REYNOLDS NUMBER**	**ORIFICE COEFF.**
55.27	43.21	938.0	3.66	4.0626	25145	0.6925
56.10	44.04	959.0	3.72	4.0866	25293	0.6900
38.91	26.85	985.0	4.76	3.2803	20302	0.7093
37.79	25.73	900.0	4.46	3.1988	19798	0.7066
36.72	24.66	922.0	4.64	3.1499	19496	0.7107
36.36	24.30	920.0	4.64	3.1431	19453	0.7144
24.42	12.36	930.0	6.32	2.3327	14437	0.7434
23.85	11.79	972.0	6.84	2.2527	13942	0.7351
18.39	6.33	926.0	8.67	1.6931	10479	0.7540
18.48	6.42	961.0	8.95	1.7021	10534	0.7527
16.87	4.81	966.0	10.38	1.4752	9130	0.7537
16.71	4.65	946.0	10.47	1.4323	8864	0.7442
15.80	3.74	915.0	11.00	1.3186	8161	0.7640
15.81	3.75	955.0	11.40	1.3280	8219	0.7684
14.26	2.20	475.0	7.27	1.0357	6410	0.7824
14.10	2.04	484.0	7.57	1.0135	6273	0.7951
14.01	1.95	478.0	7.72	0.9815	6075	0.7876
14.00	1.94	465.0	8.00	0.9214	5703	0.7412
13.10	1.04	475.0	9.71	0.7755	4799	0.8520
12.99	0.93	463.0	10.25	0.7160	4432	0.8320
12.50	0.44	460.0	17.56	0.4153	2570	0.7014
12.51	0.45	475.0	18.13	0.4153	2571	0.6937
12.45	0.39	445.0	19.87	0.3550	2197	0.6370
12.44	0.38	458.0	20.37	0.3564	2205	0.6478
12.39	0.33	437.0	37.35	0.1855	1148	0.3618
12.39	0.33	455.0	39.10	0.1845	1141	0.3598

TABLE 36

SINGLE ORIFICE PLATE DATA

PLATE: ST01ND
HOLE DIAMETER: 0.2508 IN.
PLATE THICKNESS: 0.25 IN.
LIQUID: WATER

DATE:07/12/92
LIQUID TEMPERATURE: 71 F
LIQUID DENSITY: 997.8 KG/CU.M
LIQUID VISCOSITY: 0.975 cp

INCREASING HEAD

ZERO POINT = 12.45 CM

MEASURED QUANTITIES				DERIVED QUANTITIES		
LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
14.12	1.67	432.0	22.06	0.3104	3884	1.0732
14.20	1.75	474.0	23.74	0.3165	3960	1.0689
17.00	4.55	442.0	15.16	0.4622	5783	0.9680
17.31	4.86	452.0	15.70	0.4564	5710	0.9249
23.16	10.71	452.0	12.35	0.5802	7259	0.7920
23.82	11.37	463.0	12.30	0.5967	7466	0.7906
32.61	20.16	444.0	9.49	0.7417	9280	0.7380
33.20	20.75	455.0	9.55	0.7553	9450	0.7407
34.71	22.26	453.0	9.29	0.7730	9672	0.7319
35.60	23.15	475.0	9.43	0.7985	9991	0.7414
39.74	27.29	463.0	8.76	0.8378	10483	0.7165
40.00	27.55	500.0	9.30	0.8523	10663	0.7254
44.77	32.32	445.0	7.77	0.9079	11360	0.7135
45.46	33.01	470.0	8.09	0.9209	11523	0.7161
49.52	37.07	460.0	7.52	0.9697	12133	0.7115
50.26	37.81	475.0	7.70	0.9779	12235	0.7105
62.35	49.90	455.0	6.48	1.1131	13927	0.7040
63.52	51.07	470.0	6.54	1.1392	14254	0.7122
69.91	57.46	460.0	6.13	1.1895	14884	0.7011
70.95	58.50	492.0	6.64	1.1746	14697	0.6861

TABLE 37

SINGLE ORIFICE PLATE DATA

PLATE: ST01ND	DATE:07/12/92
HOLE DIAMETER: 0.2508 IN.	LIQUID TEMPERATURE: 71 F
PLATE THICKNESS: 0.25 IN.	LIQUID DENSITY: 997.8 KG/CU.M
LIQUID: WATER	LIQUID VISCOSITY: 0.975 cp

DECREASING HEAD

ZERO POINT = 12.45 CM

MEASURED QUANTITIES

DERIVED QUANTITIES

LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
72.09	59.64	463.5	6.09	1.2065	15096	0.6980
72.99	60.54	444.0	6.11	1.1519	14414	0.6614
69.92	57.47	465.0	6.27	1.1756	14710	0.6928
69.22	56.77	462.0	6.24	1.1737	14685	0.6959
65.69	53.24	444.0	6.13	1.1482	14366	0.7030
64.72	52.27	473.0	6.65	1.1275	14108	0.6967
58.93	46.48	451.5	6.89	1.0388	12997	0.6807
56.32	43.87	490.0	7.48	1.0384	12993	0.7004
51.29	38.84	459.0	7.33	0.9926	12420	0.7116
49.95	37.50	485.0	7.89	0.9744	12193	0.7109
41.60	29.15	485.0	9.02	0.8524	10664	0.7053
40.57	28.12	468.0	8.75	0.8479	10608	0.7143
34.57	22.12	458.0	9.56	0.7594	9502	0.7214
33.50	21.05	447.0	10.12	0.7002	8761	0.6818
29.52	17.07	461.0	10.78	0.6779	8482	0.7330
28.65	16.20	472.0	11.27	0.6639	8307	0.7369
24.12	11.67	473.0	13.05	0.5746	7189	0.7514
22.85	10.40	476.0	13.73	0.5496	6876	0.7613
20.35	7.90	448.0	13.99	0.5076	6351	0.8069
19.00	6.55	482.0	16.15	0.4731	5920	0.8259
17.59	5.14	465.0	16.87	0.4369	5467	0.8610
16.45	4.00	483.0	19.17	0.3994	4997	0.8922
15.22	2.77	445.0	20.02	0.3524	4409	0.9458
14.62	2.17	479.0	24.11	0.3149	3940	0.9551
13.86	1.41	446.0	26.36	0.2682	3355	1.0091
13.54	1.09	467.0	28.17	0.2628	3288	1.1245
12.85	0.40	390.0	31.58	0.1958	2449	1.3829
12.80	0.35	344.0	36.81	0.1481	1853	1.1187
12.70	0.25	105.5	35.62	0.0470	587	0.4195

TABLE 38

SINGLE ORIFICE PLATE DATA

PLATE: ST02ND	DATE:07/14/92
HOLE DIAMETER: 0.4996 IN.	LIQUID TEMPERATURE: 72 F
PLATE THICKNESS: 0.25 IN.	LIQUID DENSITY: 997.7 KG/CU.M
LIQUID: WATER	LIQUID VISCOSITY: 0.962 cp

INCREASING HEAD

ZERO POINT = 12.37 CM

MEASURED QUANTITIES				DERIVED QUANTITIES		
LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
12.80	0.43	450.0	46.51	0.1534	990	0.2633
12.78	0.41	475.0	48.18	0.1563	1009	0.2748
12.87	0.50	490.0	24.04	0.3231	2086	0.5145
12.90	0.53	480.0	24.16	0.3149	2033	0.4871
12.97	0.60	445.0	14.47	0.4875	3147	0.7086
12.99	0.62	478.0	15.13	0.5008	3232	0.7161
13.45	1.08	463.0	9.13	0.8039	5189	0.8709
13.41	1.04	474.0	9.30	0.8079	5215	0.8920
14.98	2.61	476.0	7.24	1.0422	6727	0.7263
15.35	2.98	958.0	13.26	1.1453	7392	0.7469
15.61	3.24	953.0	13.02	1.1603	7489	0.7257
16.51	4.14	932.0	11.46	1.2892	8321	0.7133
16.55	4.18	946.0	11.49	1.3051	8424	0.7187
18.00	5.63	945.0	9.82	1.5255	9847	0.7238
17.85	5.48	935.0	10.04	1.4763	9529	0.7100
18.34	5.97	939.0	9.75	1.5267	9855	0.7035
20.22	7.85	939.0	8.74	1.7031	10993	0.6844
20.22	7.85	965.0	8.92	1.7149	11069	0.6891
23.55	11.18	990.0	7.90	1.9865	12823	0.6689
23.85	11.48	961.0	7.56	2.015	13007	0.6696
23.81	11.44	954.0	7.47	2.0245	13068	0.6739
28.65	16.28	940.0	6.30	2.3652	15267	0.6600
28.25	15.88	990.0	6.49	2.4181	15608	0.6832
31.50	19.13	1000.0	6.24	2.5404	16398	0.6539
32.10	19.73	989.0	6.08	2.5786	16645	0.6536
33.58	21.21	941.0	5.52	2.7023	17443	0.6606
33.73	21.36	919.0	5.42	2.6878	17350	0.6548
34.92	22.55	895.0	5.16	2.7495	17748	0.6519
35.12	22.75	900.0	5.15	2.7703	17882	0.6539
44.30	31.93	878.0	4.24	3.2826	21189	0.6540
44.29	31.92	898.0	4.31	3.3028	21320	0.6582
55.25	42.88	878.0	3.67	3.7924	24480	0.6520
56.84	44.47	867.0	3.55	3.8715	24991	0.6536

TABLE 39

SINGLE ORIFICE PLATE DATA

PLATE: ST02ND	DATE:07/14/92
HOLE DIAMETER: 0.4996IN.	LIQUID TEMPERATURE: 72 F
PLATE THICKNESS: 0.25 IN.	LIQUID DENSITY: 997.7 KG/CU.M
LIQUID: WATER	LIQUID VISCOSITY: 0.962 cp

DECREASING HEAD

ZERO POINT = 12.37 CM

MEASURED QUANTITIES				DERIVED QUANTITIES		
LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
58.30	45.93	882.0	3.58	3.9054	25210	0.6488
60.44	48.07	942.0	3.69	4.0468	26122	0.6571
61.41	49.04	930.0	3.63	4.0613	26216	0.6529
49.37	37.00	879.0	3.95	3.5276	22770	0.6529
48.53	36.16	930.0	4.24	3.4770	22444	0.6510
40.50	28.13	929.0	4.77	3.0873	19928	0.6554
40.00	27.63	909.0	4.78	3.0145	19459	0.6457
39.35	26.98	920.0	4.87	2.9946	19330	0.6491
29.15	16.78	940.0	6.40	2.3283	15029	0.6399
28.20	15.83	924.0	6.41	2.2851	14750	0.6466
27.63	15.26	956.0	6.59	2.2996	14844	0.6628
27.10	14.73	948.0	6.63	2.2666	14631	0.6649
26.60	14.23	939.0	6.78	2.1954	14171	0.6552
26.20	13.83	935.0	6.81	2.1764	14048	0.6589
24.91	12.54	985.0	7.33	2.1302	13750	0.6773
24.02	11.65	938.0	7.35	2.0230	13059	0.6673
23.01	10.64	953.0	7.72	1.9569	12631	0.6754
22.35	9.98	960.0	7.92	1.9215	12403	0.6848
20.65	8.28	955.0	8.71	1.7381	11219	0.6801
20.20	7.83	970.0	8.99	1.7104	11041	0.6882
19.85	7.48	959.0	8.92	1.7043	11001	0.7016
17.03	4.66	961.0	11.06	1.3774	8891	0.7184
16.88	4.51	952.0	10.86	1.3896	8970	0.7367
16.62	4.25	932.0	11.02	1.3407	8654	0.7322
15.65	3.28	967.0	13.11	1.1693	7547	0.7269
15.40	3.03	983.0	13.54	1.1509	7429	0.7444
14.94	2.57	985.0	15.69	0.9952	6423	0.6989
13.55	1.18	485.0	9.24	0.8321	5371	0.8624
13.42	1.05	486.0	10.00	0.7704	4972	0.8465
13.35	0.98	497.0	10.41	0.7568	4885	0.8607
13.38	1.01	491.0	10.21	0.7623	4921	0.8540
12.90	0.53	485.0	24.54	0.3133	2022	0.4845
12.88	0.51	493.0	25.23	0.3098	1999	0.4883
12.80	0.43	412.0	46.10	0.1417	914	0.2432

TABLE 40

SINGLE ORIFICE PLATE DATA

PLATE: ST03ND	DATE:07/05/92
HOLE DIAMETER: 0.7500 IN.	LIQUID TEMPERATURE: 69 F
PLATE THICKNESS: 0.25 IN.	LIQUID DENSITY: 997.1 KG/CU.M
LIQUID: WATER	LIQUID VISCOSITY: 1.002 cp

INCREASING HEAD

ZERO POINT = 12.35 CM

MEASURED QUANTITIES				DERIVED QUANTITIES		
LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
12.80	0.45	440.0	32.55	0.2143	885	0.1596
12.82	0.47	473.0	34.77	0.2156	891	0.1571
12.95	0.60	470.0	14.61	0.5100	2107	0.3289
12.90	0.55	465.0	15.09	0.4885	2018	0.3291
13.05	0.70	473.0	9.55	0.7851	3244	0.4688
13.01	0.66	471.0	9.35	0.7985	3300	0.4911
13.45	1.10	978.0	11.66	1.3296	5494	0.6333
13.45	1.10	920.0	11.19	1.3033	5386	0.6208
13.72	1.37	915.0	9.10	1.5939	6587	0.6803
13.72	1.37	1030.0	10.12	1.6134	6668	0.6886
14.65	2.30	915.0	7.55	1.9211	7940	0.6329
14.65	2.30	968.0	8.02	1.9133	7907	0.6303
14.65	2.30	870.0	7.28	1.8944	7829	0.6240
15.22	2.87	957.0	6.50	2.3339	9645	0.6883
15.20	2.85	963.0	6.57	2.3235	9603	0.6876
15.40	3.05	944.0	6.10	2.4532	10138	0.7018
15.36	3.01	935.0	6.09	2.4338	10058	0.7008
17.05	4.70	965.0	5.13	2.9819	12323	0.6872
17.08	4.73	938.0	4.87	3.0532	12619	0.7014
17.72	5.37	935.0	4.30	3.4469	14245	0.7431
17.73	5.38	923.0	4.26	3.4346	14194	0.7398
19.68	7.33	930.0	3.80	3.8796	16033	0.7159
19.70	7.35	968.0	3.91	3.9245	16219	0.7232
21.11	8.76	972.0	3.61	4.2682	17640	0.7204
20.65	8.30	892.0	3.47	4.0749	16841	0.7066
24.50	12.15	945.0	3.02	4.9603	20500	0.7109
24.50	12.15	920.0	2.91	5.0116	20712	0.7183
24.50	12.15	980.0	3.14	4.9474	20446	0.7091

TABLE 41

SINGLE ORIFICE PLATE DATA

PLATE: ST03ND	DATE:07/05/92
HOLE DIAMETER: 0.7500IN.	LIQUID TEMPERATURE: 69 F
PLATE THICKNESS: 0.25 IN.	LIQUID DENSITY: 998.1 KG/CU.M
LIQUID: WATER	LIQUID VISCOSITY: 1.002 cp

DECREASING HEAD ZERO POINT = 12.35 CM

MEASURED QUANTITIES DERIVED QUANTITIES

LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
24.65	12.30	951.0	3.09	4.8787	20162	0.6950
24.70	12.35	980.0	3.20	4.8547	20063	0.6901
19.20	6.85	915.0	3.87	3.7480	15490	0.7154
18.95	6.60	935.0	4.10	3.6150	14940	0.7030
16.20	3.85	979.0	5.06	3.0670	12675	0.7809
15.25	2.90	979.0	5.46	2.8423	11746	0.8338
15.25	2.90	992.0	5.54	2.8385	11731	0.8327
14.30	1.95	989.0	6.56	2.3899	9876	0.8550
14.10	1.75	1010.0	6.89	2.3237	9604	0.8776
13.38	1.03	919.0	9.11	1.5991	6608	0.7872
13.38	1.03	973.0	9.67	1.5950	6592	0.7852
13.05	0.70	945.0	14.99	0.9993	4130	0.5967
13.08	0.73	480.0	8.02	0.9487	3921	0.5548
13.11	0.76	490.0	7.76	1.0010	4136	0.5736
12.90	0.55	487.0	19.54	0.3951	1632	0.2661
12.90	0.55	468.0	18.67	0.3974	1642	0.2677

TABLE 42

SINGLE ORIFICE PLATE DATA

PLATE: ST04ND
HOLE DIAMETER: 0.2504 IN.
PLATE THICKNESS: 12 GAGE
LIQUID: WATER

DATE:07/16/92
LIQUID TEMPERATURE: 68 F
LIQUID DENSITY: 998.2 KG/CU.M
LIQUID VISCOSITY: 1.026 cp

INCREASING HEAD

ZERO POINT = 12.05 CM

MEASURED QUANTITIES				DERIVED QUANTITIES		
LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
13.70	1.65	439.0	37.13	0.1874	2284	0.9111
13.70	1.65	465.0	39.76	0.1854	2259	0.9012
14.35	2.30	472.0	32.19	0.2324	2833	0.8506
14.48	2.43	470.0	31.20	0.2388	2911	0.8383
16.80	4.75	448.0	19.92	0.3565	4345	0.8040
16.81	4.76	464.0	20.38	0.3609	4399	0.8129
17.57	5.52	469.0	18.41	0.4038	4922	0.8331
17.89	5.84	464.0	17.52	0.4198	5117	0.8381
18.31	6.26	472.0	17.02	0.4396	5358	0.8432
18.49	6.44	475.0	16.77	0.4490	5473	0.8474
24.60	12.55	470.0	11.99	0.6214	7573	0.8125
24.95	12.90	464.0	11.54	0.6374	7769	0.8212
29.75	17.70	480.0	10.73	0.7091	8643	0.7731
30.90	18.85	481.0	10.19	0.7483	9120	0.7894
34.80	22.75	485.0	9.57	0.8034	9792	0.7685
35.43	23.38	478.0	9.45	0.8018	9773	0.7563
50.98	38.93	477.0	7.59	0.9962	12142	0.7231
51.97	39.92	485.0	7.64	1.0063	12265	0.7211
53.02	40.97	487.0	7.42	1.0404	12681	0.7357
54.35	42.30	497.0	7.53	1.0463	12752	0.7279
67.30	55.25	484.0	6.40	1.1988	14612	0.7281
67.57	55.52	492.0	6.54	1.1925	14535	0.7225
68.15	56.10	489.0	6.39	1.2131	14785	0.7311
70.70	58.65	499.0	6.38	1.2398	15112	0.7306
75.10	63.05	960.0	12.09	1.2587	15342	0.7150
77.10	65.05	990.0	12.44	1.2615	15376	0.7054

TABLE 43

SINGLE ORIFICE PLATE DATA

PLATE: ST04ND	DATE:07/16/92
HOLE DIAMETER: 0.2504 IN.	LIQUID TEMPERATURE: 68 F
PLATE THICKNESS: 12 GAGE	LIQUID DENSITY: 998.2 KG/CU.M
LIQUID: WATER	LIQUID VISCOSITY: 1.026 cp

DECREASING HEAD

ZERO POINT = 12.05 CM

MEASURED QUANTITIES

DERIVED QUANTITIES

LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
79.49	67.44	460.0	5.58	1.3068	15928	0.7132
80.06	68.01	481.0	5.84	1.3056	15914	0.7096
72.85	60.80	468.0	6.02	1.2323	15020	0.7083
72.91	60.86	467.0	6.00	1.2338	15038	0.7088
70.38	58.33	466.0	6.14	1.2031	14664	0.7060
69.91	57.86	482.0	6.31	1.2109	14758	0.7135
66.55	54.50	470.0	6.39	1.1660	14211	0.7079
66.10	54.05	457.0	6.18	1.1722	14287	0.7146
59.70	47.65	480.0	6.94	1.0964	13364	0.7119
58.91	46.86	475.5	6.91	1.0908	13295	0.7142
48.19	36.14	468.0	7.70	0.9635	11743	0.7183
47.75	35.70	478.0	7.83	0.9677	11795	0.7259
44.03	31.98	469.0	8.17	0.9100	11092	0.7212
43.45	31.40	467.0	8.25	0.8973	10937	0.7177
42.73	30.68	465.0	8.26	0.8924	10876	0.7221
31.65	19.60	479.0	10.20	0.7444	9073	0.7536
31.25	19.20	477.0	10.09	0.7494	9134	0.7665
26.55	14.50	467.0	10.94	0.6767	8248	0.7965
26.55	14.50	490.0	11.35	0.6844	8341	0.8055
18.40	6.35	484.0	16.64	0.4611	5620	0.8201
17.82	5.77	472.0	16.54	0.4524	5513	0.8440
17.66	5.61	478.0	17.24	0.4395	5357	0.8317
17.03	4.98	462.0	17.74	0.4128	5031	0.8291
16.50	4.45	490.0	19.70	0.3943	4805	0.8377
15.76	3.71	474.0	21.80	0.3447	4201	0.8020
15.47	3.42	465.0	21.89	0.3367	4104	0.8161
14.73	2.68	483.0	26.18	0.2925	3564	0.8007
14.65	2.60	475.0	25.92	0.2905	3540	0.8075
13.31	1.26	463.0	33.97	0.2161	2633	0.8627
13.17	1.12	482.0	36.92	0.2070	2522	0.8764
12.30	0.25	280.0	45.92	0.0967	1177	0.8664
12.30	0.25	268.0	42.55	0.0998	1216	0.8950

TABLE 44

SINGLE ORIFICE PLATE DATA

PLATE: ST05ND
HOLE DIAMETER: 0.4998 IN.
PLATE THICKNESS: 12 GAGE
LIQUID: WATER

DATE: 06/28/92
LIQUID TEMPERATURE: 70 F
LIQUID DENSITY: 998.0 KG/CU.M
LIQUID VISCOSITY: 0.988 cp

INCREASING HEAD

ZERO POINT = 11.93 CM

MEASURED QUANTITIES				DERIVED QUANTITIES		
LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
12.23	0.30	334.0	33.66	0.1573	992	0.3231
12.35	0.42	302.5	30.35	0.1580	997	0.2743
12.42	0.49	385.0	16.15	0.3779	2385	0.6073
12.43	0.50	419.0	17.98	0.3694	2332	0.5877
12.50	0.57	465.0	14.78	0.4987	3148	0.7431
12.50	0.57	450.0	14.18	0.5031	3175	0.7496
13.04	1.11	447.5	8.86	0.8007	5054	0.8549
13.00	1.07	458.0	9.24	0.7857	4960	0.8545
14.02	2.09	447.0	6.85	1.0344	6530	0.8049
14.04	2.11	460.0	7.11	1.0256	6474	0.7943
15.41	3.48	474.0	5.70	1.3182	8321	0.7949
15.45	3.52	440.0	5.56	1.2545	7919	0.7522
18.82	6.89	486.0	4.41	1.7470	11028	0.7487
18.65	6.72	819.0	7.59	1.7105	10931	0.7423
22.32	10.39	799.0	6.05	2.0935	13216	0.7306
22.25	10.32	911.5	6.80	2.1249	13414	0.7441
24.83	12.90	933.0	6.34	2.3328	14726	0.7307
24.85	12.92	895.0	6.04	2.3489	14828	0.7352
30.79	18.86	944.0	5.44	2.7508	17365	0.7126
30.88	18.95	916.0	5.27	2.7553	17394	0.7120
37.10	25.17	932.0	4.74	3.1169	19676	0.6989
37.12	25.19	870.0	4.37	3.1559	19922	0.7074
46.91	34.98	935.0	4.13	3.5888	22655	0.6826
46.54	34.61	906.0	3.93	3.6544	23070	0.6988
51.05	39.12	940.0	3.84	3.8804	24497	0.6979
49.80	37.87	872.0	3.81	3.6281	22903	0.6632
49.40	37.47	840.0	3.60	3.6988	23350	0.6798
49.50	37.57	875.0	3.63	3.8211	24122	0.7013
48.50	36.57	905.0	3.83	3.7457	23646	0.6968

TABLE 45

SINGLE ORIFICE PLATE DATA

PLATE: ST05ND	DATE:06/28/92
HOLE DIAMETER: 0.4998 IN.	LIQUID TEMPERATURE: 70 F
PLATE THICKNESS: 12 GAGE	LIQUID DENSITY: 998.0 KG/CU.M
LIQUID: WATER	LIQUID VISCOSITY: 0.988 cp

DECREASING HEAD

ZERO POINT = 11.93 CM

MEASURED QUANTITIES				DERIVED QUANTITIES		
LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
49.78	37.85	923.0	3.93	3.7230	23221	0.6808
49.17	37.24	862.0	3.62	3.7747	23543	0.6959
35.20	23.27	926.0	4.81	3.0518	19034	0.7117
35.05	23.12	869.0	4.56	3.0209	18841	0.7068
28.57	16.64	915.0	5.59	2.5947	16183	0.7156
28.49	16.56	875.0	5.27	2.6320	16416	0.7277
22.55	10.62	910.0	6.70	2.1530	13428	0.7432
22.32	10.39	950.0	7.12	2.1151	13192	0.7382
16.69	4.76	470.0	5.07	1.4695	9165	0.7577
16.62	4.69	464.0	4.82	1.5260	9517	0.7927
14.20	2.27	491.0	7.39	1.0532	6568	0.7864
14.19	2.26	456.0	6.93	1.0431	6505	0.7806
13.20	1.27	365.0	7.30	0.7926	4943	0.7912
13.11	1.18	485.0	12.24	0.6281	3917	0.6505
12.35	0.42	429.0	21.82	0.3117	1943	0.5410
12.35	0.42	438.0	22.69	0.3060	1908	0.5312

TABLE 46

SINGLE ORIFICE PLATE DATA

PLATE: ST06ND
HOLE DIAMETER: 0.7496 IN.
PLATE THICKNESS: 12 GAGE
LIQUID: WATER

DATE:07/17/92
LIQUID TEMPERATURE: 69 F
LIQUID DENSITY: 998.1 KG/CU.M
LIQUID VISCOSITY: 1.002 cp

INCREASING HEAD

ZERO POINT = 12.06 CM

MEASURED QUANTITIES				DERIVED QUANTITIES		
LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
12.42	0.36	462.0	38.84	0.1886	779	0.1572
12.45	0.39	456.0	37.02	0.1953	807	0.1564
12.55	0.49	475.0	12.92	0.5828	2410	0.4164
12.57	0.51	482.0	12.89	0.5928	2450	0.4151
12.56	0.50	488.0	12.90	0.5997	2479	0.4241
12.84	0.78	475.0	7.74	0.9728	4022	0.5509
12.80	0.74	472.0	7.31	1.0235	4232	0.5951
12.89	0.83	477.0	7.70	0.9820	4060	0.5391
13.15	1.09	465.0	5.21	1.4148	5849	0.6777
13.10	1.04	479.0	5.37	1.4140	5846	0.6934
13.91	1.85	500.0	4.30	1.8433	7621	0.6778
14.00	1.94	490.0	4.18	1.8582	7684	0.6672
13.81	1.75	495.0	4.25	1.8463	7634	0.6980
14.85	2.79	969.0	6.68	2.2995	9508	0.6885
14.36	2.30	952.0	6.59	2.2900	9469	0.7552
14.35	2.29	977.0	6.67	2.3219	9601	0.7674
15.33	3.27	941.0	5.44	2.7420	11338	0.7584
15.36	3.30	942.0	5.32	2.8069	11607	0.7728
16.49	4.43	992.0	4.88	3.2224	13324	0.7657
16.52	4.46	960.0	4.67	3.2587	13475	0.7717
19.25	7.19	978.0	3.82	4.0584	16781	0.7570
18.94	6.88	976.0	3.95	3.9168	16196	0.7468
20.01	7.95	975.0	3.59	4.3052	17802	0.7636
20.08	8.02	996.0	3.77	4.1880	17317	0.7396
24.45	12.39	953.0	3.05	4.9531	20481	0.7037
25.15	13.09	976.0	2.91	5.3167	21984	0.7349

TABLE 47

SINGLE ORIFICE PLATE DATA

PLATE:ST06ND	DATE:07/17/92
HOLE DIAMETER: 0.7496 IN.	LIQUID TEMPERATURE: 69 F
PLATE THICKNESS: 12 GAGE	LIQUID DENSITY: 998.1 KG/CU.M
LIQUID: WATER	LIQUID VISCOSITY: 1.002 cp

DECREASING HEAD

ZERO POINT = 12.06 CM

MEASURED QUANTITIES				DERIVED QUANTITIES		
LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
25.16	13.10	962.0	2.95	5.1694	21375	0.7143
25.34	13.28	961.0	2.95	5.1640	21353	0.7087
19.56	7.50	960.0	3.71	4.1019	16961	0.7491
19.63	7.57	960.0	3.75	4.0581	16780	0.7376
16.62	4.56	941.0	4.41	3.3825	13987	0.7922
16.55	4.49	986.0	4.65	3.3613	13898	0.7933
16.12	4.06	929.0	4.86	3.0301	12529	0.7521
16.08	4.02	951.0	4.97	3.0333	12542	0.7566
15.41	3.35	970.0	5.82	2.6420	10924	0.7219
15.34	3.28	966.0	5.80	2.6402	10917	0.7291
14.72	2.66	969.0	6.62	2.3203	9595	0.7115
14.70	2.64	1000.0	6.83	2.3209	9597	0.7144
14.39	2.33	960.0	7.31	2.0818	8607	0.6821
14.42	2.36	955.0	7.15	2.1173	8754	0.6893
13.60	1.54	920.0	8.41	1.7341	7170	0.6989
13.60	1.54	970.0	9.08	1.6934	7002	0.6825
13.00	0.94	950.0	11.23	1.3410	5545	0.6917
13.00	0.94	941.0	11.21	1.3307	5502	0.6864
12.71	0.65	483.0	9.52	0.8043	3326	0.4989
12.75	0.69	467.0	8.91	0.8309	3435	0.5002
12.61	0.55	489.0	12.12	0.6396	2644	0.4313
12.62	0.56	489.0	12.01	0.6454	2669	0.4313
12.63	0.57	475.0	11.66	0.6458	2670	0.4278
12.48	0.42	453.0	28.71	0.2501	1034	0.1930
12.48	0.42	475.0	30.10	0.2502	1034	0.1930
12.40	0.34	151.5	33.50	0.0717	296	0.0615
12.40	0.34	173.0	36.90	0.0743	307	0.0637

TABLE 48

SINGLE ORIFICE PLATE DATA

PLATE: ST07ND
HOLE DIAMETER: 0.2518 IN.
PLATE THICKNESS: 14 GAGE
LIQUID: WATER

DATE:08/08/92
LIQUID TEMPERATURE: 69 F
LIQUID DENSITY: 998.1 KG/CU.M
LIQUID VISCOSITY: 1.002 cp

INCREASING HEAD

ZERO POINT = 12.04 CM

MEASURED QUANTITIES				DERIVED QUANTITIES		
LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
12.47	0.43	289.0	46.86	0.0978	1203	0.6608
12.45	0.41	310.0	51.13	0.0961	1183	0.6653
13.23	1.19	423.0	35.45	0.1892	2327	0.7685
13.25	1.21	410.0	34.39	0.1890	2325	0.7615
14.71	2.67	425.0	24.24	0.2779	3421	0.7539
14.78	2.74	464.0	26.20	0.2807	3455	0.7517
16.45	4.41	450.0	20.09	0.3551	4370	0.7494
16.87	4.83	466.0	19.81	0.3729	4589	0.7520
19.49	7.45	433.0	14.67	0.4679	5759	0.7598
19.85	7.81	451.0	14.57	0.4907	6040	0.7782
24.35	12.31	437.0	11.45	0.6050	7447	0.7643
25.15	13.11	459.0	11.69	0.6224	7661	0.7619
29.41	17.37	428.0	9.64	0.7038	8663	0.7485
30.48	18.44	475.0	10.46	0.7199	8860	0.7430
37.98	25.94	462.0	8.86	0.8266	10175	0.7193
39.22	27.18	473.0	8.94	0.8387	10324	0.7130
47.71	35.67	466.0	7.85	0.9410	11584	0.6983
50.07	38.03	444.0	7.14	0.9858	12134	0.7085
65.85	53.81	465.0	6.50	1.1340	13960	0.6852
67.95	55.91	475.0	6.49	1.1602	14281	0.6877
69.56	57.52	468.0	6.27	1.1832	14565	0.6915
72.27	60.23	478.0	6.26	1.2104	14899	0.6913
73.42	61.38	475.0	6.24	1.2067	14854	0.6827

TABLE 49

SINGLE ORIFICE PLATE DATA

PLATE: ST07ND
HOLE DIAMETER: 0.2518 IN.
PLATE THICKNESS: 14 GAGE
LIQUID: WATER

DATE:08/08/92
LIQUID TEMPERATURE: 69 F
LIQUID DENSITY: 998.1 KG/CU.M
LIQUID VISCOSITY: 1.002 cp

DECREASING HEAD

ZERO POINT = 12.04 CM

MEASURED QUANTITIES				DERIVED QUANTITIES		
LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
75.50	63.46	484.0	6.17	1.2435	15307	0.6919
76.81	64.77	497.0	6.37	1.2368	15225	0.6811
72.39	60.35	461.0	6.08	1.2019	14795	0.6857
72.05	60.01	487.0	6.42	1.2025	14802	0.6880
62.10	50.06	447.0	6.44	1.1003	13544	0.6893
61.45	49.41	494.0	7.08	1.1061	13615	0.6974
51.41	39.37	453.0	7.38	0.9730	11978	0.6873
49.60	37.56	480.0	8.00	0.9511	11708	0.6878
38.79	26.75	468.0	9.07	0.8179	10069	0.7009
36.90	24.86	483.0	9.70	0.7893	9717	0.7017
31.95	19.91	490.0	10.70	0.7259	8936	0.7211
30.35	18.31	485.0	10.79	0.7125	8771	0.7380
22.89	10.85	460.0	12.77	0.5710	7029	0.7683
22.13	10.09	461.0	13.13	0.5566	6850	0.7766
19.17	7.13	460.0	15.24	0.4785	5889	0.7942
18.61	6.57	476.0	16.31	0.4626	5695	0.8000
16.49	4.45	450.0	19.52	0.3654	4498	0.7678
16.15	4.11	484.0	21.58	0.3555	4376	0.7773
15.18	3.14	453.0	23.21	0.3094	3808	0.7739
15.05	3.01	465.0	24.20	0.3046	3749	0.7781
14.59	2.55	446.0	25.01	0.2827	3479	0.7846
14.27	2.23	463.0	27.27	0.2691	3313	0.7988
12.89	0.85	409.0	35.25	0.1839	2264	0.8842
12.15	0.11	249.0	39.42	0.1001	1232	1.3381

TABLE 50

SINGLE ORIFICE PLATE DATA

PLATE: ST08ND	DATE:07/04/92
HOLE DIAMETER: 0.5008 IN.	LIQUID TEMPERATURE: 70 F
PLATE THICKNESS: 14 GAGE	LIQUID DENSITY: 998.0 KG/CU.M
LIQUID: WATER	LIQUID VISCOSITY: 0.988 cp

INCREASING HEAD

ZERO POINT = 11.88 CM

MEASURED QUANTITIES				DERIVED QUANTITIES		
LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
12.20	0.32	454.5	17.03	0.4231	2633	0.8380
12.22	0.34	440.0	17.28	0.4036	2512	0.7756
12.30	0.42	478.0	18.88	0.4013	2498	0.6939
12.49	0.61	474.0	12.36	0.6079	3784	0.8721
12.45	0.57	448.0	12.33	0.5760	3584	0.8548
13.29	1.41	466.0	8.44	0.8752	5448	0.8259
13.20	1.32	469.0	8.77	0.8477	5276	0.8267
14.24	2.36	468.5	6.84	1.0858	6758	0.7919
14.26	2.38	477.0	7.11	1.0635	6620	0.7724
15.71	3.83	468.0	5.60	1.3248	8246	0.7585
15.80	3.92	471.0	5.51	1.3550	8435	0.7669
17.80	5.92	457.0	4.50	1.6099	10020	0.7414
17.85	5.97	458.0	4.42	1.6426	10224	0.7533
21.71	9.83	948.0	7.57	1.9852	12357	0.7095
21.59	9.71	927.0	7.31	2.0102	12513	0.7228
25.77	13.89	916.0	6.17	2.3534	14649	0.7075
25.90	14.02	920.0	6.17	2.3637	14712	0.7073
31.05	19.17	931.0	5.56	2.6544	16522	0.6793
31.75	19.87	920.0	5.32	2.7413	17064	0.6891
41.70	29.82	895.0	4.39	3.2318	20117	0.6631
42.12	30.24	910.0	4.37	3.3010	20547	0.6726
54.60	42.72	820.0	3.37	3.8572	24009	0.6612
54.80	42.92	846.0	3.37	3.9795	24770	0.6806

TABLE 51

SINGLE ORIFICE PLATE DATA

PLATE: STO8ND
HOLE DIAMETER: 0.5008 IN.
PLATE THICKNESS: 14 GAGE
LIQUID: WATER

DATE:07/04/92
LIQUID TEMPERATURE: 70 F
LIQUID DENSITY: 998.0KG/CU.M
LIQUID VISCOSITY: 0.988 cp

DECREASING HEAD

ZERO POINT = 11.88 CM

MEASURED QUANTITIES				DERIVED QUANTITIES		
LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
55.42	43.54	898.0	3.62	3.9323	24478	0.6677
55.80	43.92	942.0	3.77	3.9609	24656	0.6697
43.47	31.59	886.0	4.20	3.3440	20815	0.6666
42.65	30.77	918.0	4.35	3.3453	20823	0.6757
33.96	22.08	927.0	5.13	2.8645	17830	0.6830
33.50	21.62	958.0	5.41	2.8071	17473	0.6764
29.56	17.68	996.0	6.20	2.5465	15851	0.6786
29.25	17.37	968.0	5.96	2.5746	16025	0.6922
22.82	10.94	927.0	7.09	2.0726	12901	0.7021
22.35	10.47	910.0	7.07	2.0404	12700	0.7065
17.83	5.95	940.0	9.41	1.5835	9856	0.7274
17.80	5.92	910.0	9.13	1.5800	9835	0.7276
15.57	3.69	500.0	6.16	1.2867	8009	0.7505
15.55	3.67	479.0	5.95	1.2762	7944	0.7464
14.20	2.32	473.0	7.10	1.0561	6573	0.7769
14.15	2.27	478.0	7.32	1.0351	6443	0.7698
13.23	1.35	462.0	8.68	0.8437	5251	0.8137
13.15	1.27	462.0	8.86	0.8266	5145	0.8219
12.66	0.78	449.0	10.94	0.6506	4049	0.8254
12.55	0.67	470.0	11.05	0.6742	4196	0.9230
12.56	0.68	480.0	12.04	0.6320	3933	0.8587
12.52	0.64	475.0	12.26	0.6142	3823	0.8602
12.37	0.49	467.0	14.59	0.5074	3158	0.8122
12.40	0.52	484.0	15.09	0.5084	3165	0.7900
12.10	0.22	433.0	26.10	0.2630	1636	0.6282
12.05	0.17	470.0	27.43	0.2716	1690	0.7381

TABLE 52

SINGLE ORIFICE PLATE DATA

PLATE: ST09ND
HOLE DIAMETER: 0.7506 IN.
PLATE THICKNESS: 14 GAGE
LIQUID: WATER

DATE:08/06/92
LIQUID TEMPERATURE: 71 F
LIQUID DENSITY: 997.8 KG/CU.M
LIQUID VISCOSITY: 0.975cp

INCREASING HEAD

ZERO POINT = 12.03 CM

MEASURED QUANTITIES

DERIVED QUANTITIES

LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
12.57	0.54	458.0	44.93	0.1616	681	0.1097
12.57	0.54	475.0	46.27	0.1627	685	0.1105
12.59	0.56	475.0	33.74	0.2232	940	0.1487
12.59	0.56	468.0	33.19	0.2235	941	0.1490
12.63	0.60	470.0	19.98	0.3729	1570	0.2401
12.62	0.59	478.0	20.24	0.3744	1576	0.2431
12.72	0.69	465.5	12.49	0.5908	2488	0.3548
12.72	0.69	492.0	13.26	0.5882	2477	0.3532
12.89	0.86	487.0	9.05	0.8530	3592	0.4588
12.89	0.86	488.0	9.13	0.8473	3569	0.4557
12.89	0.86	500.0	9.43	0.8405	3540	0.4521
13.09	1.06	498.0	6.52	1.2108	5099	0.5866
13.04	1.01	498.0	6.70	1.1783	4962	0.5848
13.04	1.01	479.0	6.45	1.1772	4958	0.5843
13.30	1.27	477.0	4.99	1.5153	6382	0.6707
13.30	1.27	462.0	4.80	1.5258	6426	0.6753
14.00	1.97	500.0	4.15	1.9099	8044	0.6787
13.98	1.95	497.0	4.20	1.8758	7900	0.6700
14.01	1.98	498.0	4.17	1.8931	7974	0.6711
14.00	1.97	483.0	4.06	1.8858	7943	0.6702
13.99	1.96	500.0	4.16	1.9053	8024	0.6788
14.50	2.47	928.0	6.74	2.1826	9193	0.6927
14.53	2.50	947.0	6.75	2.2240	9366	0.7016
15.22	3.19	979.0	6.07	2.5567	10768	0.7140
15.23	3.20	985.0	6.08	2.5681	10816	0.7161
16.19	4.16	950.0	5.27	2.8576	12035	0.6988
16.10	4.07	942.0	5.16	2.8939	12189	0.7155
16.15	4.12	980.0	5.44	2.8557	12027	0.7017
17.15	5.12	960.0	4.51	3.3743	14212	0.7438
17.14	5.11	940.0	4.46	3.3410	14072	0.7372
16.85	4.82	943.0	4.64	3.2216	13569	0.7319
20.11	8.08	974.0	3.85	4.0104	16891	0.7037
19.86	7.83	971.0	3.96	3.8869	16371	0.6929
23.66	11.63	929.0	3.14	4.6900	19754	0.6860
23.99	11.96	962.0	3.17	4.8106	20262	0.6938
24.11	12.08	969.0	3.24	4.7409	19968	0.6804
24.28	12.25	970.0	3.24	4.7458	19989	0.6763
24.24	12.21	938.0	3.09	4.8120	20268	0.6869
27.83	15.80	929.0	2.74	5.3746	22637	0.6744
28.29	16.26	941.0	2.74	5.4441	22929	0.6734

TABLE 53

SINGLE ORIFICE PLATE DATA

PLATE: ST09ND
HOLE DIAMETER: 0.7506 IN.
PLATE THICKNESS: 14 GAGE
LIQUID: WATER

DATE:08/06/92
LIQUID TEMPERATURE: 71 F
LIQUID DENSITY: 997.8 KG/CU.M
LIQUID VISCOSITY: 0.975 cp

DECREASING HEAD

ZERO POINT = 12.03 CM

MEASURED QUANTITIES				DERIVED QUANTITIES		
LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
28.46	16.43	945.0	2.68	5.5896	23369	0.6878
28.64	16.61	891.0	2.52	5.6048	23433	0.6859
24.15	12.12	911.0	2.97	4.8623	20329	0.6966
23.68	11.65	964.0	3.25	4.7019	19659	0.6871
21.05	9.02	951.0	3.63	4.1530	17363	0.6897
21.01	8.98	952.0	3.61	4.1804	17477	0.6958
20.96	8.93	943.0	3.61	4.1408	17312	0.6912
17.79	5.76	960.0	4.38	3.4744	14526	0.7221
17.71	5.68	932.0	4.27	3.4600	14466	0.7241
16.59	4.56	943.0	4.81	3.1078	12993	0.7259
16.60	4.57	980.0	5.08	3.0581	12785	0.7135
15.01	2.98	949.0	6.30	2.3879	9983	0.6899
15.02	2.99	950.0	6.27	2.4018	10041	0.6928
14.20	2.17	930.0	7.53	1.9578	8185	0.6629
14.18	2.15	878.0	7.20	1.9331	8081	0.6576
13.24	1.21	467.0	5.11	1.4487	6057	0.6569
13.31	1.28	482.0	5.01	1.5251	6376	0.6724
13.32	1.29	475.0	4.93	1.5273	6385	0.6707
13.02	0.99	455.0	6.24	1.1559	4832	0.5794
13.01	0.98	469.0	6.43	1.1562	4833	0.5826
12.91	0.88	473.0	8.27	0.9067	3790	0.4821
12.93	0.90	462.0	7.93	0.9235	3860	0.4856
12.93	0.90	466.0	8.13	0.9086	3798	0.4777
12.79	0.76	465.0	10.78	0.6838	2858	0.3912
12.80	0.77	460.0	10.54	0.6918	2892	0.3933
12.73	0.70	445.0	12.04	0.5859	2449	0.3493
12.78	0.75	440.0	11.83	0.5896	2465	0.3396
12.63	0.60	455.0	19.85	0.3634	1519	0.2340
12.62	0.59	475.0	21.55	0.3494	1460	0.2269
12.60	0.57	460.0	26.55	0.2746	1148	0.1814
12.60	0.57	465.0	27.43	0.2687	1123	0.1775
12.60	0.57	465.0	27.43	0.2687	1123	0.1775
12.59	0.56	300.0	33.68	0.1412	590	0.0937
12.59	0.56	291.0	32.86	0.1404	586	0.0932

TABLE 54

SINGLE ORIFICE PLATE DATA

PLATE: B04ND
HOLE DIAMETER: 0.2496 IN.
PLATE THICKNESS: 12GAGE
LIQUID: WATER

DATE:08/08/92
LIQUID TEMPERATURE: 68 F
LIQUID DENSITY: 998.2 KG/CU.M
LIQUID VISCOSITY: 1.026cp

INCREASING HEAD

ZERO POINT = 12.09 CM

MEASURED QUANTITIES				DERIVED QUANTITIES		
LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
12.49	0.40	282.0	48.82	0.0916	1118	0.6515
12.45	0.36	273.0	46.54	0.093	1136	0.6974
13.02	0.93	385.0	33.73	0.1809	2209	0.8443
13.10	1.01	433.0	35.86	0.1914	2337	0.8570
15.75	3.66	440.0	20.96	0.3328	4064	0.7827
16.00	3.91	441.0	20.04	0.3488	4260	0.7938
17.90	5.81	450.0	16.22	0.4398	5371	0.8210
18.40	6.31	479.0	16.60	0.4574	5586	0.8194
21.19	9.10	456.0	13.34	0.5419	6617	0.8083
22.52	10.43	487.0	13.30	0.5804	7088	0.8088
28.02	15.93	434.0	10.32	0.6666	8141	0.7516
28.69	16.60	471.0	10.91	0.6844	8357	0.7558
37.72	25.63	457.0	8.84	0.8195	10008	0.7284
40.50	28.41	495.0	9.17	0.8557	10450	0.7224
44.37	32.28	480.0	8.46	0.8994	10984	0.7123
47.17	35.08	472.0	8.05	0.9295	11352	0.7062
51.81	39.72	480.0	7.75	0.9818	11990	0.7010
52.90	40.81	480.0	7.71	0.9869	12053	0.6952
57.71	45.62	458.0	6.94	1.0461	12776	0.6970
58.97	46.88	470.0	6.99	1.0659	13017	0.7005
64.15	52.06	470.0	6.72	1.1087	13540	0.6914
65.45	53.36	489.0	6.81	1.1383	13902	0.7012
69.70	57.61	480.0	6.51	1.1688	14274	0.6929
72.10	60.01	485.0	6.49	1.1846	14467	0.6881

TABLE 55

SINGLE ORIFICE PLATE DATA

PLATE: B04ND
HOLE DIAMETER: 0.2496 IN.
PLATE THICKNESS: 12 GAGE
LIQUID: WATER

DATE:08/08/92
LIQUID TEMPERATURE: 68 F
LIQUID DENSITY: 998.2 KG/CU.M
LIQUID VISCOSITY: 1.026 cp

DECREASING HEAD

ZERO POINT = 12.09 CM

MEASURED QUANTITIES				DERIVED QUANTITIES		
LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
72.67	60.58	477.0	6.38	1.1852	14491	0.6868
73.51	61.42	500.0	6.55	1.2101	14796	0.6965
64.25	52.16	455.0	6.52	1.1062	13526	0.6909
63.30	51.21	497.0	7.17	1.0988	13435	0.6926
50.11	38.02	468.0	7.75	0.9573	11705	0.7003
48.35	36.26	494.0	8.31	0.9423	11522	0.7059
42.44	30.35	450.0	8.24	0.8657	10586	0.7088
40.89	28.80	487.0	9.16	0.8428	10305	0.7084
31.37	19.28	459.0	10.16	0.7161	8757	0.7357
29.97	17.88	475.0	10.62	0.7090	8669	0.7563
24.42	12.33	445.0	11.52	0.6123	7487	0.7866
23.71	11.62	465.0	12.15	0.6067	7418	0.8028
19.52	7.43	466.0	14.95	0.4941	6041	0.8177
18.95	6.86	441.0	14.62	0.4782	5846	0.8235
17.14	5.05	435.0	16.84	0.4095	5006	0.8219
16.75	4.66	458.0	18.59	0.3905	4775	0.8161
15.60	3.51	453.0	21.38	0.3359	4107	0.8087
15.15	3.06	414.0	21.23	0.3091	3779	0.7971
14.10	2.01	454.0	28.77	0.2501	3058	0.7959
13.70	1.61	427.0	30.09	0.2250	2750	0.7997
13.13	1.04	437.0	37.27	0.1859	2272	0.8221
13.00	0.91	325.0	29.81	0.1728	2113	0.8172
12.49	0.40	322.0	46.80	0.1091	1333	0.7779
12.47	0.38	307.0	47.00	0.1035	1266	0.7577

TABLE 56

SINGLE ORIFICE PLATE DATA

PLATE: B14ND
HOLE DIAMETER: 0.2496 IN.
PLATE THICKNESS: 12 GAGE
LIQUID: WATER

DATE:08/09/92
LIQUID TEMPERATURE: 69 F
LIQUID DENSITY: 998.1 KG/CU.M
LIQUID VISCOSITY: 1.002 cp

INCREASING HEAD

ZERO POINT = 12.13 CM

MEASURED QUANTITIES				DERIVED QUANTITIES		
LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
12.20	0.07	200.0	51.19	0.0619	769	1.0559
12.20	0.07	203.0	51.61	0.0624	774	1.0630
13.10	0.97	445.0	35.99	0.1960	2434	0.8977
13.20	1.07	420.0	33.09	0.2012	2498	0.8774
14.25	2.12	440.0	26.57	0.2625	3259	0.8132
14.44	2.31	438.0	25.24	0.2751	3416	0.8164
18.00	5.87	475.0	17.15	0.4390	5452	0.8174
22.55	10.42	450.0	13.26	0.5380	6680	0.7517
22.78	10.65	472.0	13.69	0.5465	6787	0.7554
25.15	13.02	443.0	11.99	0.5857	7273	0.7322
26.42	14.29	478.0	12.50	0.6062	7527	0.7233
31.91	19.78	435.0	10.08	0.6841	8494	0.6938
32.57	20.44	469.0	10.59	0.7020	8718	0.7004
42.93	30.80	467.0	8.92	0.8299	10306	0.6745
45.21	33.08	479.0	8.91	0.8522	10583	0.6683
64.55	52.42	463.0	6.91	1.0622	13190	0.6617
67.25	55.12	460.0	6.64	1.0982	13637	0.6672
69.68	57.55	465.0	6.63	1.1118	13806	0.6611
73.21	61.08	472.0	6.58	1.1371	14121	0.6563

TABLE 57

SINGLE ORIFICE PLATE DATA

PLATE: B14ND	DATE:08/09/92
HOLE DIAMETER: 0.2496 IN.	LIQUID TEMPERATURE: 69 F
PLATE THICKNESS: 12 GAGE	LIQUID DENSITY: 998.1 KG/CU.M
LIQUID: WATER	LIQUID VISCOSITY: 1.002 cp
DECREASING HEAD	ZERO POINT = 12.13 CM
MEASURED QUANTITIES	DERIVED QUANTITIES

LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
75.00	62.87	480.0	6.41	1.1870	14741	0.6753
76.95	64.82	480.0	6.22	1.2233	15191	0.6854
72.08	59.95	480.0	6.70	1.1357	14103	0.6616
70.67	58.54	475.0	6.71	1.1222	13935	0.6616
63.61	51.48	475.0	7.20	1.0458	12987	0.6575
61.95	49.82	494.0	7.44	1.0525	13071	0.6726
54.44	42.31	446.0	7.40	0.9554	11865	0.6625
52.45	40.32	488.0	8.16	0.9480	11772	0.6734
44.51	32.38	459.0	8.60	0.8461	10506	0.6707
41.95	29.82	490.0	9.48	0.8194	10175	0.6768
36.79	24.66	454.0	9.64	0.7466	9270	0.6781
35.32	23.19	497.0	10.70	0.7363	9143	0.6897
30.03	17.90	447.0	10.86	0.6525	8102	0.6956
27.97	15.84	496.0	12.52	0.6280	7798	0.7117
20.35	8.22	482.0	15.17	0.5037	6254	0.7924
19.49	7.36	469.0	16.13	0.4609	5723	0.7663
16.37	4.24	474.0	20.47	0.3671	4558	0.8041
15.75	3.62	450.0	21.25	0.3357	4168	0.7958
13.90	1.77	436.0	29.02	0.2382	2957	0.8075
13.05	0.92	424.0	35.38	0.1900	2358	0.8934
12.90	0.77	454.0	40.48	0.1778	2207	0.9139
12.42	0.29	366.0	43.60	0.1331	1652	1.1146
12.36	0.23	290.0	41.35	0.1112	1380	1.0456
12.20	0.07	288.0	46.52	0.0981	1218	1.6731

APPENDIX D

SAMPLE CALCULATION

The equations used for finding the values of the Reynolds number and the orifice coefficient are given in Chapter 5. They are:

$$\mathrm{Re} = \frac{dV_o\rho}{\mu} \qquad \text{(D-1)}$$

and

$$C_o = \frac{V_o}{\sqrt{2gh}} \qquad \text{(D-2)}$$

The velocity term, V_o is obtained as follows.

$$V_o = \frac{\text{Volumetric flow rate}}{\text{orifice cross-sectional area}} \qquad \text{(D-3)}$$

Consider the case, when the conditions observed are as follows:

Plate : ST05ND

Run # : 11

Orifice diameter (nominal) : 0.5 in.

Measured diameter : 0.4998 in.

Head in level indicator : 18.65 cm.

Zero point : 11.93 cm.

Volume of water collected : 819 ml.

Collection time : 7.59 sec.

Water temperature : 70°F

The head is (18.65-11.93) = 6.72 cm. The corresponding flow rate is $\frac{819}{7.59} = 107.91$ ml/sec. This can be converted to any desired unit.

For the Reynolds number vs. orifice coefficient relation, the Reynolds number is found by Equation (D-1).

Here, $V_0 = \dfrac{107.91 \text{ ml / sec}}{\frac{\pi}{4} d^2 \text{ cm}^2} = 85.25 \text{ cm / sec}$

Also at 70°F, the density and viscosity of water are approximately 998.0 kg/m3 and 0.988 cp. respectively. Substituting in D-1, we get, $\text{Re} \cong 10{,}931$.

Similarly, applying to equation D-2, we get, $C_0 = 0.7424$.

All other readings are reduced to the desired quantities (Reynolds number and orifice coefficient) in a similar manner.

APPENDIX E

ERROR ANALYSIS

The error associated due to experimental errors can propagate in the derived quantities. To estimate the error in derived quantities such as the Reynolds number and the orifice coefficient, I used the approach given by Lyon [57]. (Another approach is suggested by Gasem [58].)

$$\text{If } u = Cx^l y^m z^n .....$$

where C is a constant and l, m, n,... are any real numbers and if the relative error in x, y, z, .. are $\frac{E_X}{X}$, $\frac{E_Y}{Y}$, $\frac{E_Z}{Z}$,... respectively, then the relative error in u, $\frac{E_U}{U}$, can be evaluated as

$$\frac{E_U}{|U|} = \left| l\frac{E_X}{X} \right| + \left| m\frac{E_Y}{Y} \right| + \left| n\frac{E_Z}{Z} \right| + \ldots \qquad \text{(E-1)}$$

For our case, the measurable quantities are -

- the volume of water collected, V (ml)
- time interval, t (sec)
- head, h (cm)
- water temperature, T(°F)

The maximum relative error in terms of these quantities can be evaluated as follows. Here, Case 1 is for low heads (< 5 cm), Case 2 is for medium heads (< 30 cm) and Case 3 is for high heads (> 30 cm). Also, E_m is the maximum error involved in the quantity (estimated), M is the maximum value of the quantity for that case and E_m/M is the relative error involved for that quantity.

TABLE 58

THE RELATIVE ERRORS IN THE MEASURED QUANTITIES.

	V, ml			t, sec			Head, mm		
	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3
E_m	5	10	20	0.3	0.3	0.3	3	5	7
M	300	450	900	30	15	8	40	200	600
E_m/M	1.6 %	2.2 %	2.2 %	1.0 %	2.0 %	2.7 %	7.5 %	2.5 %	1.1 %

Also,

$$\mathrm{Re} = \frac{dV_o\rho}{\mu} \tag{E-2}$$

$$C_o = \frac{V_o}{\sqrt{2gh}} \tag{E-3}$$

Here, the velocity term, V_o is obtained as follows.

$$V_o = \frac{\text{Volumetric flow rate}}{\text{orifice cross - sectional area}} \tag{E-4}$$

In Equation E-2, since some uncertainty is associated with d, ρ and μ, the relative error in Re can be obtained from Equation E-1 as

$$\frac{E_{\mathrm{Re}}}{\mathrm{Re}} = \frac{E_{V_o}}{V_o} + \frac{E_d}{d} + \frac{E_\rho}{\rho} + \frac{E_\mu}{\mu}. \tag{E-5}$$

Similarly,

$$\frac{E_{C_o}}{C_o} = \frac{E_{V_o}}{V_o} + \frac{1}{2}\frac{E_h}{h} \tag{E-6}$$

and since orifice cross-sectional area depends on the square of the orifice diameter,

$$\frac{E_{V_o}}{V_o} = \frac{E_Q}{Q} + 2\frac{E_d}{d} \qquad \text{(E-7)}$$

where Q is the volumetric flow rate. Now, q = V/t. Hence,

$$\frac{E_Q}{Q} = \frac{E_V}{V} + \frac{E_t}{t} \qquad \text{(E-8)}$$

Considering the maximum relative uncertainty in d as 0.05 %, ρ as 0.2 % and μ as 2.5 %(which are attributed to the uncertainty in the measurement of the liquid temperature), the maximum relative error for the Reynolds number and orifice coefficient from Equation E-5, E-6, E-7 and E-8 can be calculated as under.

TABLE 59

THE RELATIVE ERRORS IN THE DERIVED QUANTITIES.

	Case 1	Case 2	Case 3
Reynolds number	5.6 %	7.2 %	7.9 %
Orifice coefficient	6.45 %	5.55 %	5.45 %

Hence, we can say that the error associated with the orifice coefficient is 5.75 %. and with the Reynolds number is 6.8 %. This translates into a error band as shown in Fig. 32. The error band explains almost all the points in the region of interest.

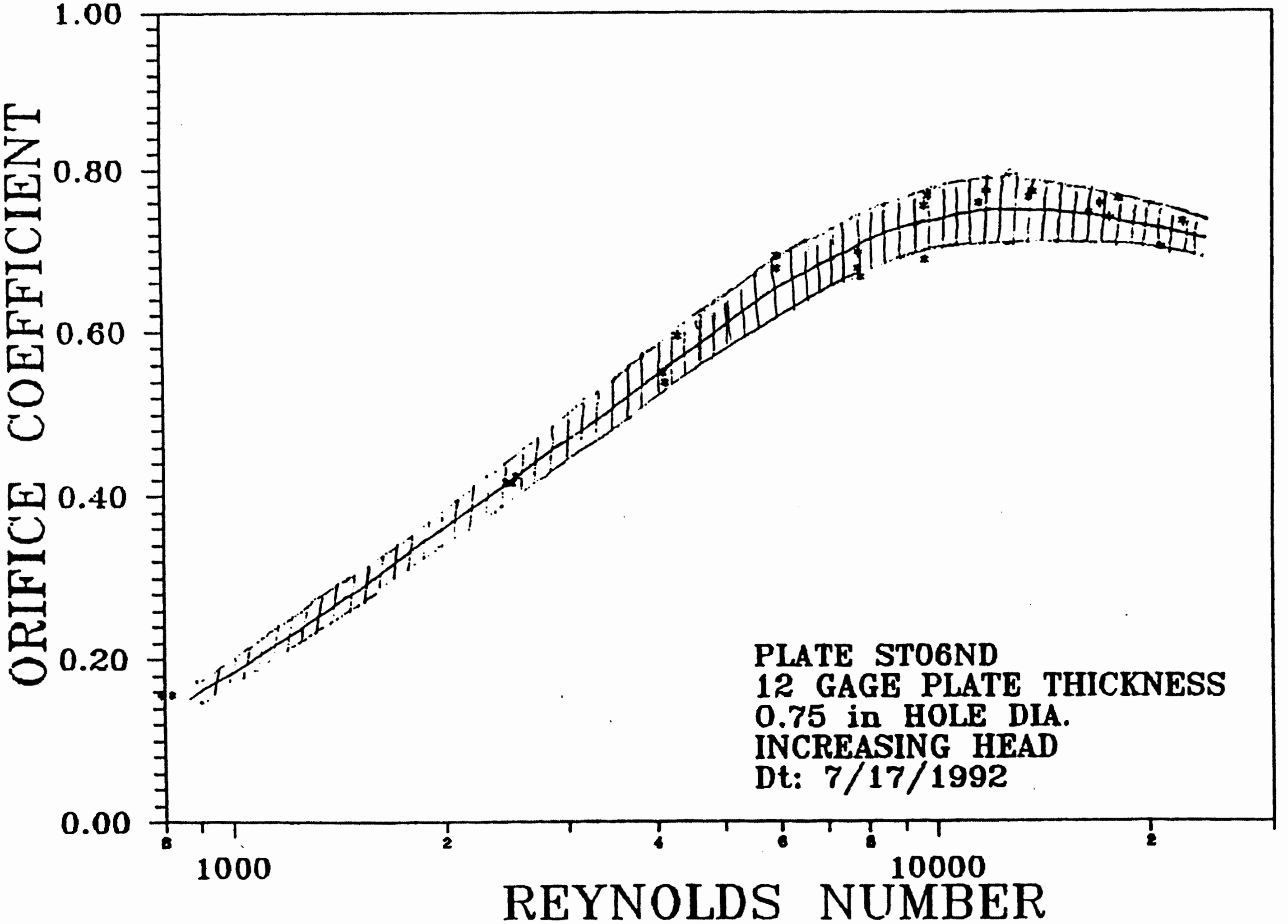

Figure 32. The Error bands with 5 % uncertainity

VITA

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