ANALYSIS OF FLUID FLOW THROUGH SIDE ORIFICES AND ITS APPLICATION TO LIQUID DISTRIBUTORS

By

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NOMENCLATURE

a - width of lateral outlet, ft or m.

$(A_j)_{min}$ - area of the jet at the minimum cross-sectional area, ft^2 or m^2.

$A_o = \pi d_o^2/4$ - cross sectional area of the orifice, ft^2 or m^2.

A_T - cross section of the stream, ft^2 or m^2.

C_o or C_d - orifice coefficient or discharge coefficient.

C_v - coefficient of variation.

d_o or D_B - orifice diameter, ft or m.

D_p - diameter of packing, ft or m.

g - acceleration due to gravity, ft/s^2 or m/s^2.

h - height of liquid above orifice or head, ft, m.

K - barrier inclination parameter

l - thickness of orifice plate, ft or m.

N - number of holes in the trough.

p - pressure, lb_f/ft^2 or N/m^2.

Q - volumetric flow rate through each orifice, ft^3/s or m^3/s.

Q_r - ratio of outflow through each lateral orifice-weir unit to inflow in main channel.

$R_A = A_T/W_P$ - radius at station A, ft or m.

Re - orifice Reynolds number = $dv_o\rho/\mu$.

T - temperature of the liquid, ^oK.

U_h - gas velocity through hole in sieve tray, ft/s or m/s.

V_1 - flow velocity at the upstream edge of a lateral outlet, ft/s or m/s.

V_2 - flow velocity at the downstream edge of a lateral outlet, ft/s or m/s.

V_j - jet velocity, ft/s or m/s.

V_o or v_o or v - velocity through orifice, ft/s or m/s.

W_P - wetted perimeter, ft or m.

X- mole fraction of light key in liquid phase.

Z - elevation, ft or m.

α - kinetic energy correction factor(in orifice coefficient derivation).

ρ - density of liquid, lb/ft^3 or kg/m^3.

η - jet velocity ratio = V_1/V_j.

β - NA_0/A_T

μ - viscosity of liquid, lb/ft-s or kg/m-s.

η - viscosity of the liquid , cp.(when used in correlation for calculating water viscosity)

CHAPTER I

INTRODUCTION

Separation processes are central to the petroleum, chemical, petrochemical, pulp, pharmaceutical, mineral and other industries. A large portion of the capital and operating costs is associated with separation costs; consequently, the impact of separation process technology on corporate profitability is greatest in these industries. Some of the operations used in these industries are distillation, gas absorption, dehumidification, liquid extraction and stripping. The efficiency of separation is dependent on the extent to which liquid and vapors mix. These operations are done either in tray or packed columns. Packed columns use either random or structured packings depending on factors like efficiency and costs. Tray columns have been used conventionally, but packed columns are attracting more attention because of lower pressure drops and costs associated with them. A general guideline is required to make the right choice in selecting a contacting device.

Criteria For Selecting Contacting Device

The selection of optimum device is a tough task considering the fact that, in addition to trays, a number of different packing materials can be used for contacting devices. Fair (Rousseau, 1987) presents several criteria that should be considered both for new designs and for analysis of new equipment. The criteria for selection of a contacting device are: a) Vapor handling capacity, b) Liquid handling capacity, c) Flexibility, d) Pressure drop, e) Cost and f) Design background. The criteria with explanations are given in Table 1-1.

Chen (1989) discusses design constraints a design engineer should consider before selecting a new contacting device in a distillation column. According to him, a design engineer should calculate four parameters; capacity, pressure drop, mass transfer efficiency and holdup of the new contacting device. With a knowledge of physical properties and equations of state, the engineer can develop reliable generalized models for capacity, pressure drop, mass transfer efficiency and holdup.

Packings

The most important parts of a composite packed tower with associated internals (Figure 1-1) are the distributor and the packings. The main reason why packings have gained so much importance is because of savings in the energy costs due to lower pressure drops. Also, for the same column height, a packed column has more number of stages when compared to a conventional tray column. Packings are classified as random or structured depending on the way they are placed. When the packings are placed in a random fashion, as by dumping they are called random packings. Random packings are further classified into two types according to their resistance to the flows of liquid and vapor. The older packings like Raschig rings, Berl Saddles and Ceramic Intalox Saddles (Figure 1-2) require that liquids flow around them, thus causing pressure loss both by form drag and skin friction. The newer packings like Nutter's rings and Norton's IMTP permit fluids to flow through them, with greatly reduced form drag and consequently offer low pressure drops and high efficiencies.

Table 1-1 Criteria for selecting contacting device (Fair, in Rousseau, 1987)

	General
Vapor-handling capacity	The device must permit reasonable volumetric flow of vapor without excessive entrainment of liquid or, at the maximum vapor rate, flooding.
Liquid-handling capacity	There must be channels for liquid flow that will be non-constructive, otherwise the column will flood due to excessive liquid backup.
Flexibility	The device should allow for variations in vapor and liquid flow, to accommodate those periods when demand for production fluctuates.
Pressure drop	For situations when pressure drop can be costly, the device should maximize the ratio of efficiency to pressure drop.
Cost	The device should not be excessively complex, and therefore costly to manufacture
Design background	The designer should work with a device in which he or she has confidence and an understanding of the physical principles by which the device will operate.

Special

1. Possible fouling should be considered; some devices resist fouling better others.
2. Potential corrosion problems place limitations of the type of material and the techniques for fabricating the device to be used.
3. If foaming is expected, some devices can provide a built-in foam breaking capability.

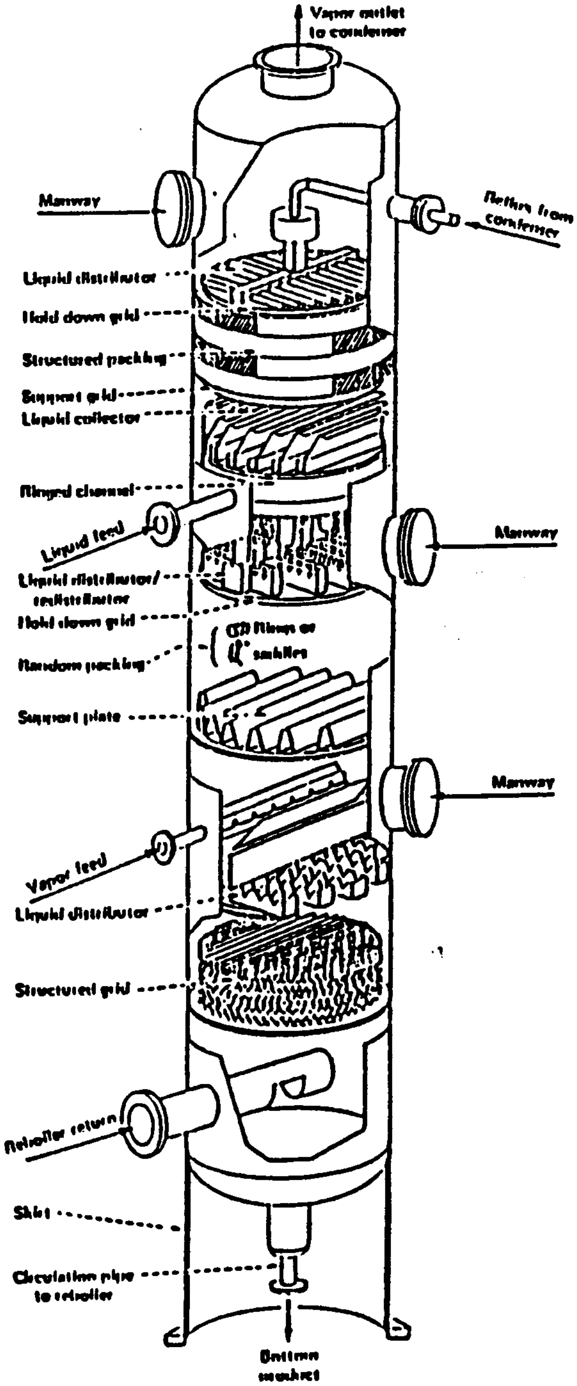


Figure 1-1 Packed tower with associated internals.(Rousseau,1987)

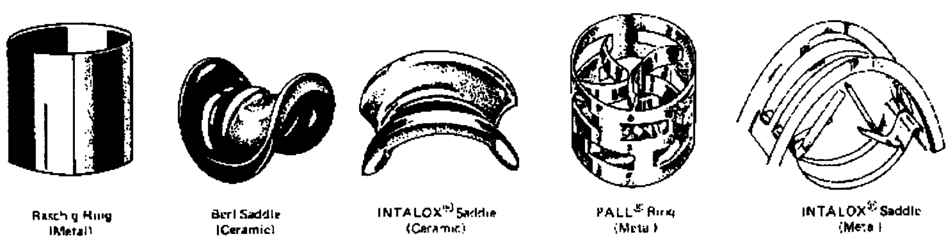


Figure 1-2 Random Packings. (Rousseau,1987)

Structured packings also offer low pressure drops, high surface area and high efficiency. They have well-defined geometry and within a distillation column, the angle of arrangement and shape of flow channels can be confidently predicted. These features allow a chemical engineer to apply principles of similarity, dimensional analysis and fluid mechanics (Chen, 1989). These packings may be stacked as individual elements or they may be fashioned as rigid meshes or multiple plates and inserted carefully in the column. A few structured packings are shown in Figure 1-3. These packings are in various dimensions and are available in a number of materials of construction. The packing elements are made from sheets of corrugated sheet metal or gauze and the sheets are perforated. Furthermore, the sheet metal has been given a special treatment to aid in the spreading of the liquid film and thus to emulate the gauze surface, which by capillary action promotes liquid spreading (Fair, in Rousseau, 1987). But, proper liquid distribution is the key to achieving optimum performance with any high efficiency random or structured packing. Further, initial liquid distribution is critical to packed column efficiency (Perry, 1990).

Liquid Distributors

A liquid distributor is a device to spread the liquid evenly in a packed column. The distributor is the most important part of a packed column with associated internals. Distributors are broadly classified as a) Pressure b) Gravity and c) Flashing types depending on the way the liquid is introduced.(Chen, 1984)

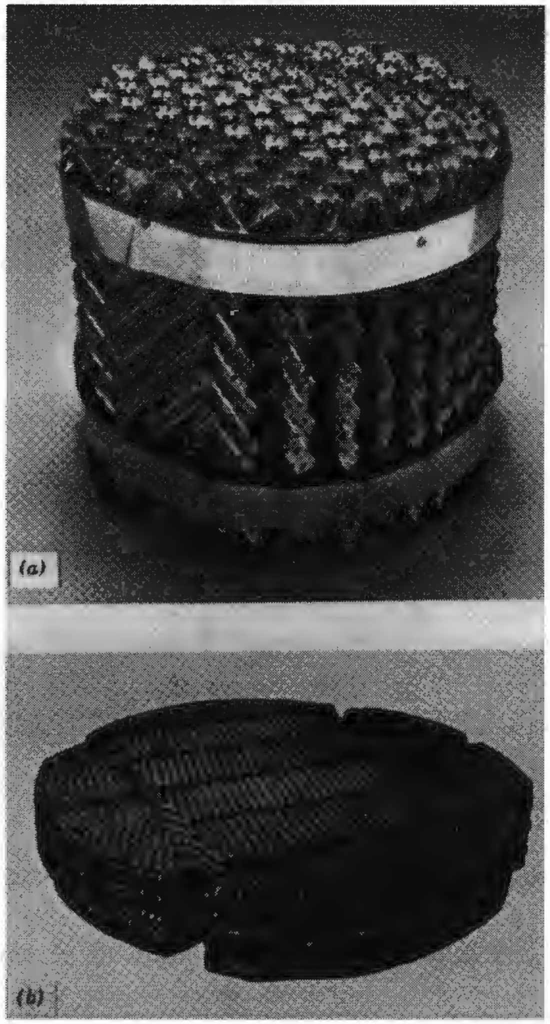


Figure 1-3 Structured Packings. (Rousseau, 1987)

a) Pressure Distributors: In general, pressure distributors provide more open area for vapor flow and tend to be less expensive, lighter, less robust and require smaller lead-up piping than gravity distributors. Their disadvantages are high operating costs (because of liquid pressure drop), susceptibility to plugging and corrosion, entrainment and a relatively inferior quality of liquid distribution. The common pressure distributors include the perforated-pipe type and the spray nozzle type. These distributors are used for heat transfer and vapor washing, where no significant degree of fractionation is required.

1) Perforated-Pipe Distributors (Figure 1-4): Perforated-pipe distributors are normally of the ladder type or the perforated-ring type. Perforations are located on the underside of the pipes. The ladder type is usually easier to fabricate and therefore less expensive than the perforated-ring type. The quality of distribution achieved with perforated-pipe distributors is generally somewhat inferior to that achievable with orifice type distributors. The higher liquid pressure drop available in perforated-pipe distributors (compared to gravity orifice-type distributors) induces a greater liquid flow per unit area; this in turn restricts the numbers of drip points. If it is practical to provide a sufficient number of evenly spaced drip points per unit of column cross-sectional area, the perforated-pipe distributor can provide a distribution as good as orifice-type distributors.

2) Spray Distributors (Figure 1-4): Spray distributors are pipe headers with spray nozzles fitted on the underside of the pipes. They are most popular in heat transfer and scrubbing services and are infrequently used in fractionation. Spray distributors are commonly used in refinery crude towers, FCC main fractionators, and refinery vacuum

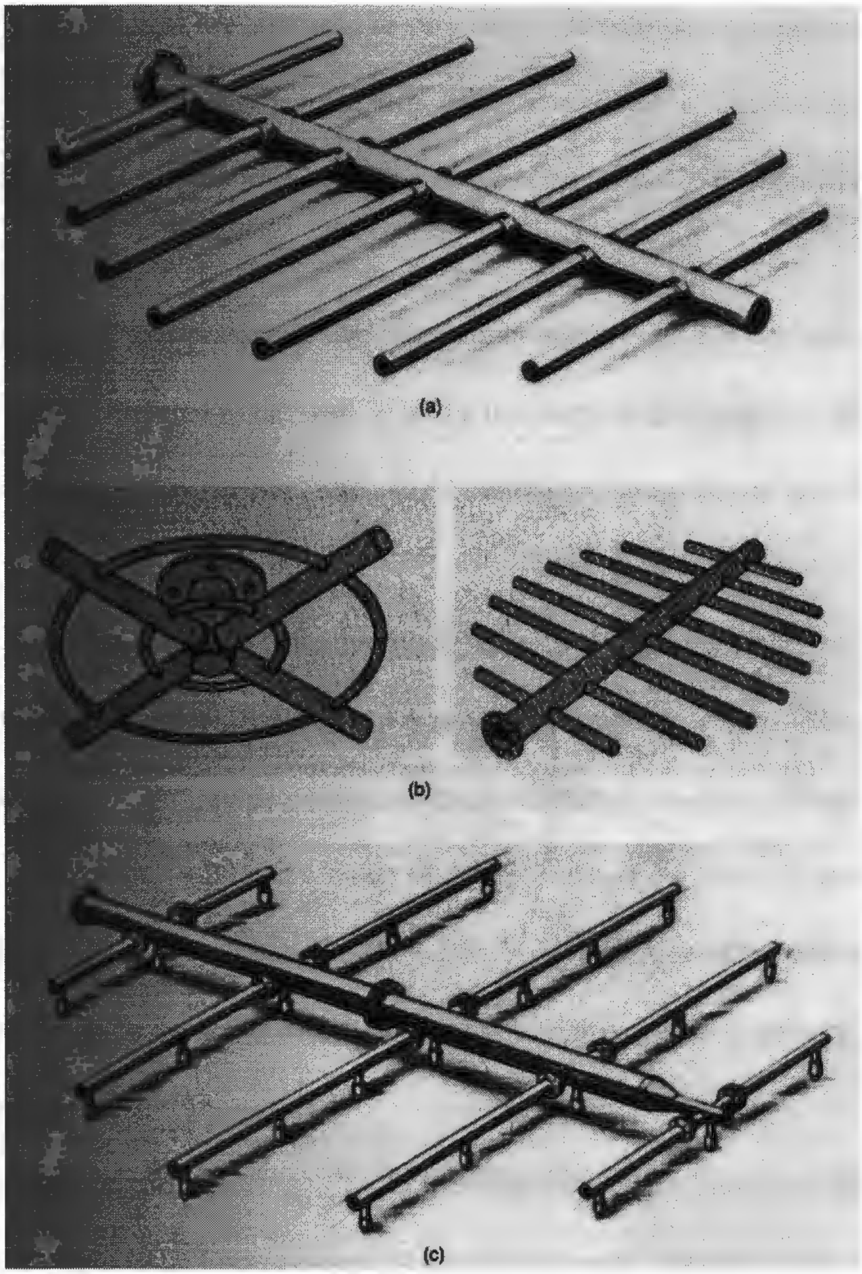


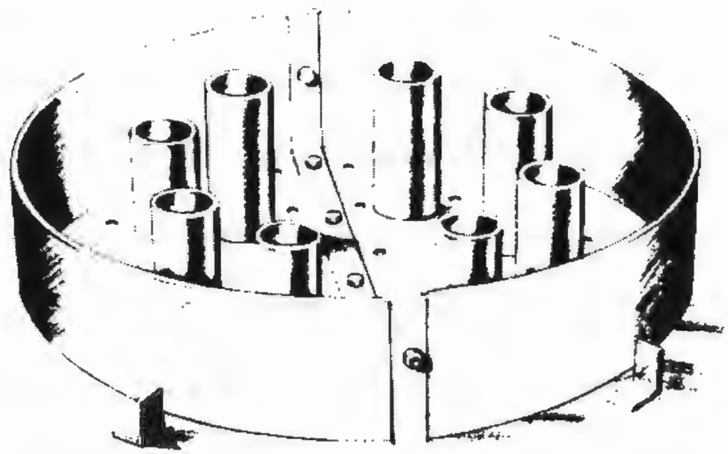
Figure 1-4 Pressure Distributors: a) Ladder Distributor, b) Perforated ring Distributor, c) Spray Distributors. (Kister, 1990)

towers. Spray distributors are also used in very small columns, and in applications where a large vapor-handling capacity is most important. The quality of distribution provided by a spray distributor may be inferior to any of the others because the spray cones create areas

of uneven irrigation, the spray cones are often nonhomogeneous and because a significant amount of liquid is directed to the wall. Factors like spray angle, height of spray nozzles above the bed, nozzle construction, and nozzle pattern set the quality of distribution.

b) Gravity Distributors: The common gravity distributors are the weir type (trough type) and the orifice type. Both types can handle large liquid flow rates. The weir type is generally one of the least troublesome distributors and has an excellent turndown, but it can usually provide only a limited number of drip points and is extremely sensitive to levelness and liquid surface agitation. The orifice type may suffer from corrosion and plugging, but it can be designed with a large number of drip points to provide superior liquid distribution.

1) Orifice Distributors (Fig 1-5): Orifice distributors are usually of the pan type or of the tunnel type. The former type is best suited for small diameter columns (<4 ft., Kister, 1990), while the latter is used in large diameter columns. An orifice pan distributor consists of a pan equipped with circular or rectangular risers for vapor flow and perforations in the pan floor for liquid flow. The pan may rest on a support ring; alternately, it may be supported on lugs in a manner that provides annular space for vapor



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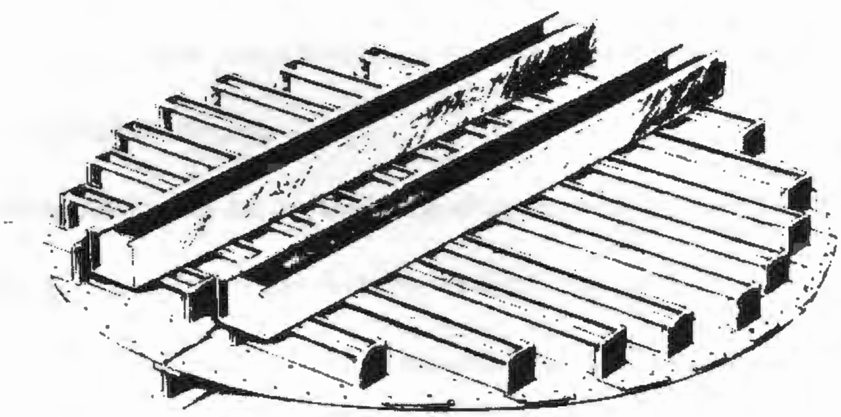


(e)

Figure 1-5 Orifice Distributors. (Kister, 1990) rise between the distributor and the column wall. Orifice tunnel distributors consist of parallel troughs with perforations for liquid flow in the trough floors. The troughs are often interconnected by cross channels that equalize liquid levels in different troughs. Level-equalizing channels are most important in columns greater than 10 feet in diameter.

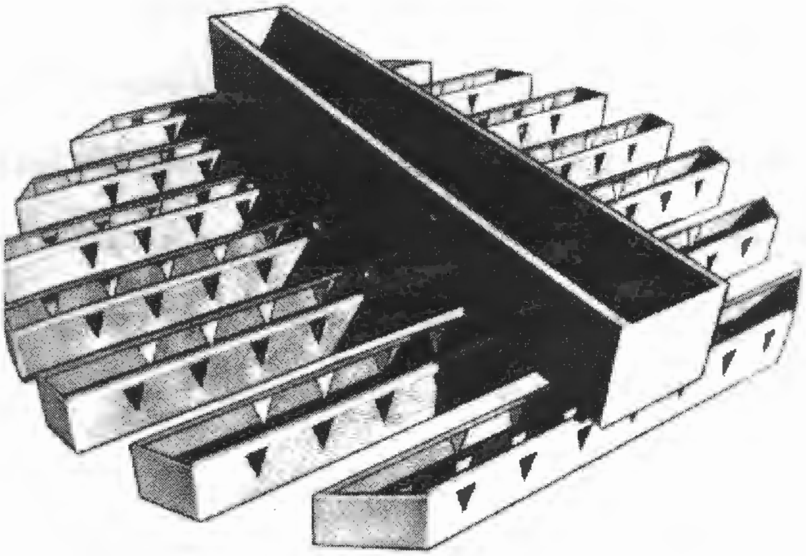
Orifice distributors can incorporate a large number of drip points and therefore have the potential of providing better liquid distribution than most other distributor types. This better liquid distribution is not always achieved, the main restricting factors being difficulty in irrigating areas beneath vapor passages and supports, a high sensitivity to plugging and construction irregularities. In some high performance designs, side orifices and deflection baffles are used.

Orifice distributors are capable of handling high liquid loads, with standard orifice pan distributors and orifice tunnel distributors delivering up to 30 and 50 to 70 gpm per square foot of bed, respectively. The open area for vapor flow is relatively low in orifice distributors.

Orifice distributors are also generally larger, more expensive, consume more vertical space, and are more difficult to support than most other distributors. Tunnel orifice distributors provide greater open areas for vapor flow, are easier to support, and are more suitable for large-diameter columns than pan distributors.

2) Weir Distributors (Fig 1-6): Weir distributors are usually of the weir riser type or the notched-trough type. The former type is commonly used in small-diameter columns (<4 ft.), while the latter is used in larger-diameter columns (>3 ft.), but can also be used in smaller columns.

a) Narrow Trough Distributor (Nutter Bulletin TI-1, Nutter Engineering, Tulsa,OK, 1987)



b) V-Notch Distributor. (Chen, 1984)

Figure 1-6 Weir Distributors.

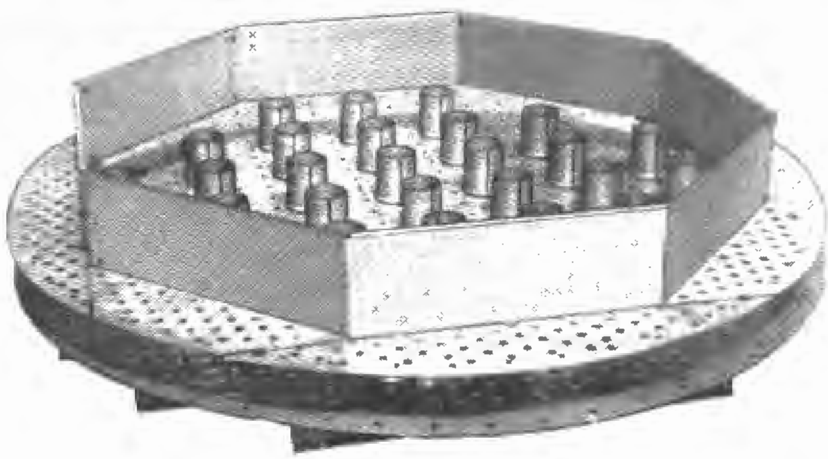
A weir riser distributor consists of a pan equipped with cylindrical risers with a V-notch cut in each riser. The V-notch allows liquid to descend countercurrently to the rising vapor. A major disadvantage that renders the weir riser distributor unpopular is the interdependence of maximum vapor and maximum liquid flow rates.Notched-trough distributors consist of parallel troughs with V-notches cut in their sides for liquid flow. Vapor rises through the space between the troughs. The quality of distribution provided by notched-trough distributors is generally somewhat inferior to orifice-type distributors. With notched-type distributors, it is generally difficult to incorporate more than three to four drip points per square-foot of cross-sectional area.

c) Flashing Feed Distributors (Fig 1-7): As the name suggests, these distributors deal with feeds under flash conditions. The kinetic energy of the feed is absorbed by the distributor and then the liquid and vapor are made to disengage completely and finally the liquid is distributed to the packed bed. There are two types of flashing feed distributors; baffle type and gallery type.

The baffle type consists of a pan type distributor on which an impingement baffle is mounted. The feed is sent via slotted piping against the baffle and the two phases are separated. They are recommended for small-diameter columns and two phase feeds are involved.

The gallery type distributor has a perimeter gallery mounted on the surface of the pan. The feed is discharged into the gallery where complete disengagement of the two phases occurs before the liquid falls into the distributor below.

a) Baffle Type Flashing Feed Distributor. (Chen, 1984)



a) Gallery Type Flashing Feed Distributor. (Chen, 1984)

Figure 1-7 Flashing Feed Distributors.

Performance Evaluation of Packings and Distributors

The performance evaluation of packings or distributors are is a very important design aspect. One way of doing this is to plot log[X/(1-X)] versus bed height, where X is the molar concentration of the light key in the liquid (Fig. 1-8).The slope of the line thus obtained is directly proportional to the efficiency of the packing and is related to the performance of the bed and the distributor. If constant relative volatility is assumed, then a straight line (Curve **c**, Fig. 1-8) would mean a constant slope which in turn would imply constant efficiency. This would mean that the initial liquid distribution is sufficient for the desired separation. If the line is initially curved and then straightens out (Curve **b**, Figure-8), it means that the slope is increasing down the length of the bed. The initial curved portion represents poor initial distribution. The increase in slope down the bed would suggest that the packing efficiency is improving as the packing succeeds in spreading the liquid. Curve **a** in Figure 1-8 illustrates the case where a good initial liquid distribution deteriorates because of vapor maldistribution or excessively deep beds (Bonilla 1993).

Guidelines for Distributor Selection and Operation

A general set of guidelines for distributor design, selection, construction and operation are presented below (Kister,1990).

1) A liquid distributor(or redistributor) should be used in any location in a packed column where an external liquid stream is introduced.

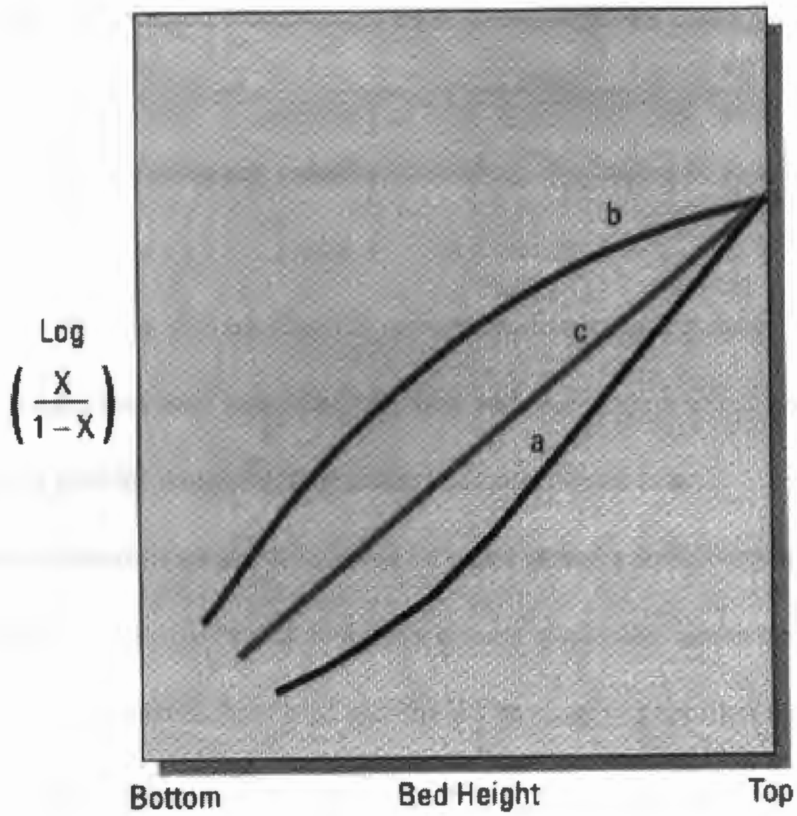


Figure 1-8 Graph for Performance Evaluation of Packings and Distributors. (Bonilla, 1993)

2) It is best to have the packing manufacturer specify and supply the distributor. The user should critically examine and carefully troubleshoot the manufacturer's recommendation and design.

3) In order for manufacturers to specify or design a distributor correctly, they must be provided with concise information on the service: its plugging, corrosive, erosive and foaming tendencies; and of any requirements which may affect distributor selection or design.

4) Fabrication irregularities may lead to severe maldistribution and loss of performance in the tower. All perforations should be punched with the smooth edge of the hole facing the liquid, and that the rough edge is ground smooth free of burrs.

5) Distributor performance should always be water tested prior to startup. The piping supplying liquid to the distributor should be closely duplicated at the test rig.

6) The irrigation pattern at the top of bed should be closely examined to identify areas of large scale maldistribution. This should be carried out at the design stage and also checked in the water test.

7) To counteract the tendency of liquid flow toward the wall, a large percentage of the total liquid should not enter at the tower wall or within 5 to 10 percent of the tower diameter from the wall. At the same time, it is important to ensure that some liquid get to the wall.

8) A minimum of 9 drip points per square foot works well for most sizes of random and structured packings (Perry,1990).

9) The drip points should be evenly spread. Zonal maldistribution is detrimental to column efficiency.

10) The distributor should be located at least 6 to 12 inches above the packing to permit vapor disengagement from the bed before passing through the distributor

11) The plugging potential of a service should not be underestimated.

12) If the service contains solids, or the liquid is close to freezing point, a weir type distributor is the best choice. If it is still desired to use a perforated-pipe, spray or orifice distributor, a filter should be installed upstream to remove particles that can block the perforations or spray nozzles. The filters should be installed in an accessible location as close to the column as possible. Typical good locations are close to the foot of the vertical rise of liquid feed or reflux, or just upstream of the flashing control valve for flashing feeds. The line downstream of the filter should be adequately flushed or blown to shake free and remove loose rust particles prior to the startup. Orifice distributors with bottom perforations should be avoided in plugging services, even when filters are installed.

13) Perforation diameters smaller than 0.25 inch should be avoided in order to prevent plugging; 0.5 inch perforations are preferred. If the service is perfectly clean and noncorrosive, some designers advocate using holes as small as 0.125 inch. Corrosion, erosion, and plugging also tend to change perforation diameter to a greater extent when perforation diameter is small. On the other hand, the larger the perforation diameter, the lower the number of drip points that can be incorporated in the distributor.

14) In slightly corrosive services it may pay to use a stainless steel distributor even when carbon steel is satisfactory as the packing material. Successful applications have been reported. Alternatively, a distributor that is insensitive to corrosion such as the notched trough type can be used.

15) When a high liquid flow rate is required, notched trough, orifice type, or spray type distributors are the best selections.

16) The vapor risers or channels offer resistance to vapor flow. If vapor pressure drop across the risers becomes equal to the liquid head above the distributor, the distributor will flood. It is therefore important to allow sufficient open area for vapor flow. This open area must be distributed evenly and in a manner that prevents formation of poorly irrigated regions directly beneath the vapor passages.

17) When a high rate of vapor flow is required, the orifice pan and the weir riser distributors are best avoided.

18) The area directly beneath wide troughs with no bottom perforations should be closely examined to ensure absence of unirrigated regions.

19) Column turndown is commonly set by the turndown of the liquid distributor. Distributor turndown, therefore, is a most important consideration.

20) For good turndown, weir type or some orifice type distributors are the best selections. Alternatively, the turndown of perforated-pipe, spray, and some orifice-trough distributors can be enhanced by using a dual liquid distributor arrangement. This arrangement consists of two distributors, mounted one above the other. The upper distributor is designed for a higher range of liquid flow rates than the lower distributor.

At low liquid flow rate, only the lower distributor is operated; at medium liquid flow rates, only the upper distributor is operated; and at high liquid flow rates, both distributors are operated.

21) Distributor levelness affects the quality of distribution, especially under turned-down conditions, when liquid head is low. Careful design and inspection are required to ensure that the distributors are leveled. Inspection with level gages is strongly recommended for weir type distributors. Weir type distributors should be specified with leveling screws to enable in situ level adjustment.

22) Leakage of liquid from the distributor or the flanges on the pipes leading to the distributor may cause maldistribution. This is most severe in low liquid flow rate applications.

23) Distributor fans and troughs should be deep enough to avoid liquid overflow.

Scope of This Work

The work done so far in this project involved single orifice experiments and multi-hole tests for vertical flow. Derasari (1993) has covered most of the experimental part of single orifice experiments. Mendes (1994) collected further data for single orifice experiments and also worked on multi-hole tests. The present study involved study of flow through side orifices by collecting orifice coefficient data. Comparisons were made between the data obtained in this study and the data for vertical flow.

CHAPTER II

LITERATURE REVIEW

Orifice flow is a very commonly observed phenomenon in industries and it has been extensively studied by many researchers. Orifice flow through pipelines has been more extensively studied, and has been used for orifice meter applications. Flow through an orifice in a pipeline is in a closed channel. There is not much data available for orifice flow through distributors. Orifice flow through distributors is in an open channel. The literature is broadly classified into the following sections:

1) Closed channel flow

2) Open channel flow

Closed Channel Flow

A detailed literature study on closed channel flow was done by Derasari (1993). The bibliography he cites on closed channel flow includes orifice coefficient data, contraction coefficient, and correlations.

Orifice Coefficients and Reynolds Numbers: Judd and King (1908) experimentally measured the relation between flow rate and liquid head. They predicted the average value of discharge coefficient to be around 0.6066. They also estimated the contraction coefficient to be around 0.6117. Tuve and Sprenkle (1933) studied the flow of viscous fluid through orifices. They discussed the advantages and disadvantages of using Reynolds number as the independent variable. They experimentally proved that same coefficients were obtained for the same value of Reynolds number though the parameters contributing to Reynolds number, that is, diameter, velocity of flow and viscosity were changed. They also quantified that error due to geometric uncertainty is only 1.5%.

Contraction Coefficient: The reduction in cross-sectional area at the orifice results in the fluid streamlines converging, reducing the jet diameter. Hence, the inertial forces dominate the viscous forces. This results in a vena contracta formation a few pipe diameters downstream of the orifice as shown in figure 2-2. The contraction coefficient is defined as the ratio of the area of the jet at the minimum cross-section to the orifice cross-sectional area.

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. They determined the coefficient to be around 0.611 which is in good agreement with some experimental results.

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

Jet Behavior: A free falling jet issuing from an orifice under the influence of gravity 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.

Studies on jet hydrodynamics have been extensively done. 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 and Reynolds numbers.

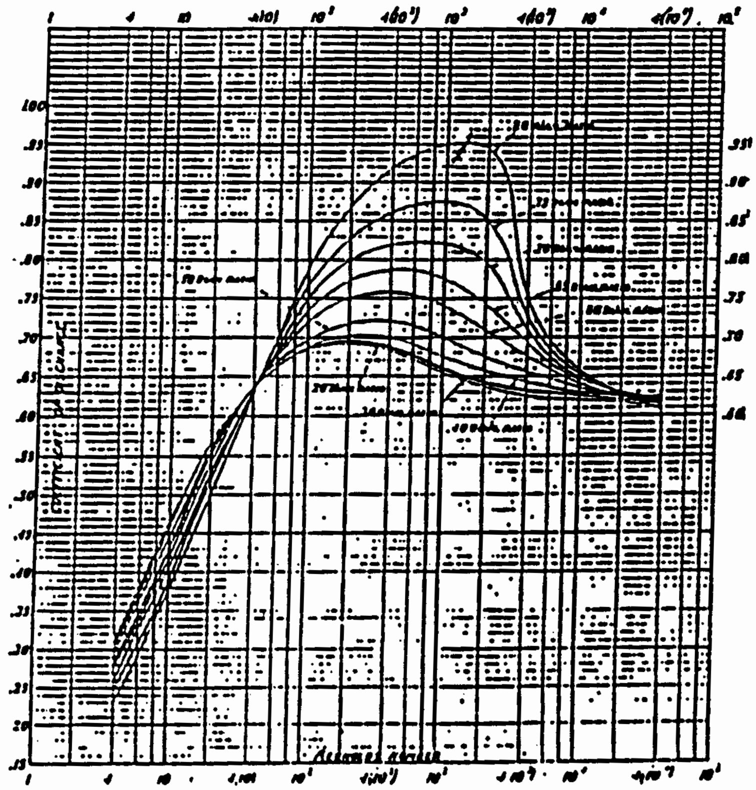


Figure 2-1 Orifice Coefficient Data (Tuve and Sprenkle, 1933)

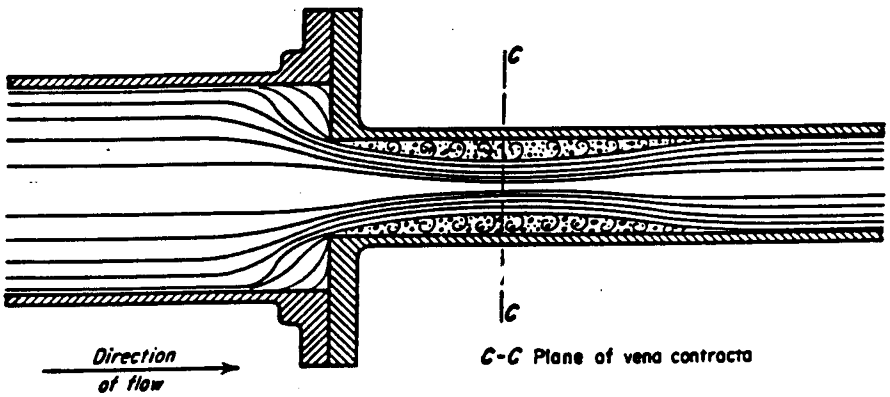


Figure 2-2. Vena Contracta Formation (Mccabe, 1976)

The character of the jet, laminar or turbulent, is also an important criterion for studying the effect of jet hydrodynamics. When drag is sufficient, the disturbances grow along the jet length resulting in sinuous breakup and atomization. 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 that jet structure is characterized by Reynolds number. They have also concluded that Reynolds number alone is not sufficient for describing the jet behavior.

Available Correlation: Several empirical correlations have been developed by researchers over the years for predicting the discharge coefficients. Two most widely used equations are the ISO-Stolz equation and the ASME-AGA equation for a beta ratio less than 0.75. The Stolz equation (1975,1977) is given as

$$C = 0.5959 + 0.03112\beta^{2.1} - 0.184\beta^{8} + 0.0029\beta^{2.5}\left[\frac{10^{6}}{R_{D}}\right]^{0.75} \tag{2-1}$$

This equation was developed for upstream and downstream tap locations. Because of the uncomplicated formulation and overall accuracy, this equation is preferred. The uncertainty in the orifice coefficient is ±1%. The reader is referred to Derasari (1993) for further study on these topics.

Open Channel Flow

There is very little data and study on the actual distributor studies. Most of the work on distributors has been carried out by FRI (Kunesh et al.(1985,1987)) and by the Delft Technical University, Holland (Zuiderweig et al.(1978,1987)) and by Albright(1984). Mendes (1994) has done a detailed review on distributor studies and classified on the basis of maldistribution.

Conclusions pertaining to maldistribution in distribution equipment practices are listed in Kister (1990).These conclusions are a detailed study on the nature and effects of maldistribution and they are as follows:

1)Packing efficiency may decrease by a factor as high as 2 to 3 due to maldistribution.

2) A packed column has reasonable tolerance for a uniform or smooth variation in liquid distribution and for a variation that is totally random ("Small scale maldistribution"). However, the impact of discontinuities or zonal flow ("Large scale Maldistribution") is much more severe.

3) The necessity of uniform distribution sharply increases with the number of theoretical stages per packed bed. A corollary is that beds consisting if small packings or structured packings, which develop more theoretical stages per bed, are substantially more sensitive to maldistribution than equal-depth beds of larger random packings.

4) A packed bed appears to have a "natural distribution," which is an inherent and stable property of the packings. An initial distribution that is better than natural will rapidly degrade to it, and one that is worse will finally achieve it, but sometimes at very slow rate. If the rate is very slow, recovery from a maldistributed pattern may not be observed in practice.

5) Three factors appear to set the effect of maldistribution on efficiency:

a) Maldistribution delivers less liquid to some areas than to others. In these areas the liquid to vapor ratio is relatively low, causing a composition pinch. The pinched areas contribute little to mass transfer. Vapor leaving these areas is rich with the less volatile components, which contaminate the vapor rising from the bed. Similarly, lights-rich liquid leaving these areas contaminates the liquid descending from the rest of the bed. The pinches also create non-uniform liquid and vapor composition profiles along the cross-section of the column. This is referred to as the pinching effect.

b) Packing particles deflect both liquid and vapor laterally. This promotes mixing of vapor and liquid and counteracts the pinching effect in (a) above. This is referred to as the lateral mixing effect.

c) Liquid flow through the packing is uneven. Directly under the distributor, the column wall area is poorly irrigated. In the bed, the liquid tends to flow toward the wall. After some depth, the liquid flow in the wall region exceeds the average flow through the bed.

6) At small tower to packing diameter ratios (<10), the effect of lateral mixing outweighs the pinching effect, and a greater degree of maldistribution can be tolerated without a serious efficiency loss. At high ratios of column to packing diameter (>40), the lateral mixing effect becomes too small to counteract the pinching effect. This implies that the effects of maldistribution on efficiency are most severe on large diameter columns and with small diameter packings.

7) Either a shortage or an excess of liquid near the wall causes large scale maldistribution and can substantially lower packing efficiency. If the wall zone is poorly irrigated at the top of the bed, it may take several feet of packing before a reasonable amount of liquid reaches the wall region. This effect is most severe with small packings, where liquid spread toward the wall is slow. On the other hand, buildup of excessive wall flow further down in the bed is most severe with larger packings, where the liquid spread toward the wall is rapid.

8) In the presence of large-scale maldistribution, packing efficiency decreases as packing height increases. This is due to the composition non-uniformity generated by pinching and to the development of wall flow. With small packings, the above may occur even in the absence of initial distribution.

9) Liquid distribution tends to lower packing turndown.

10) Maldistribution tends to be a greater problem at low liquid flow rates than at high liquid flow rates.

11) Vapor is easier to distribute than liquid, but vapor maldistribution can also be troublesome. Vapor flow through packing tends to be uniform if the initial liquid and vapor distribution to the packing is uniform. Vapor maldistribution may also be induced by liquid maldistribution when vapor flows are high. Areas of high liquid holdup will impede vapor rise and will channel the vapor into lighter-loaded regions. Since liquid tends to accumulate near the wall, vapor will tend to channel through the center.

Gunn and Al-Saffar (1993) conducted studies on liquid redistribution in columns packed with stainless-steel IMTP, stainless-steel Nutter rings, and plastic pall rings and super Intalox saddles. Quantitative changes in liquid distribution for all packings were closely described by a recent theory for anisotropic redistribution that was a development of the same theory given for isotropic redistribution. They found that enhancement of liquid flow in regions of packing close to the wall was similar for all packings, but the increase in wall flow with axial distances from the top of the column was less rapid because radial redistribution in the high voidage packings was much weaker than redistribution observed in ceramic packings.

Stoter and Olujic (1991) developed a simulation model to study the effect of irregularities in distributor design and operation on the uniformity of liquid distribution. They found that the sensitivity to unlevelness increases with decreasing liquid load and increasing length of liquid flow path, and depends on the position of liquid level with respect to vertically placed holes. They also conclude that if properly fabricated and installed (leveled) the narrow trough distributors with drip pipes and holes can ensure uniform distribution over a wide range of liquid loads. Malperformance will be reduced to minimum if holes are large enough and liquid level adjusted to be in between two rows of holes. However, for higher turndowns considerably high troughs (liquid levels) are needed.

Fan (1994) in his report on vertical orifice flow in the fully turbulent regime made the following conclusions for single orifice plate studies:

1) In vertical down orifice flow and turbulent flow regime, the liquid head above the orifice plate rather than the Reynolds number is the critical parameter to determine the orifice coefficient. With the increase of the liquid head, the orifice coefficient will decrease and finally approach a limit value around 0.7.

2) The vertical orifice flow becomes unstable in the low liquid head region. The instability occurs when the liquid head is below 1 inch and disappears when the liquid head is above 3 inches.

3) Both the orifice diameter and the orifice plate thickness have some influence on the orifice coefficient. When the ratio of orifice diameter to orifice plate thickness is equal to 3, the orifice coefficient reaches a maximum. However, when the ratio of the orifice diameter to the orifice plate thickness is approaching 1, the orifice coefficient decreases significantly, Which possibly indicates a transition from the orifice flow to short tube flow.

4)A simple correlation for orifice coefficients in fully developed turbulent flow regime was developed by regressing data over different orifice plates and different physical properties of the working fluid. This correlation can be used for engineering design with high accuracy and reliability but should not be extrapolated outside the range of the current data base.

Further, on the multi-hole trough tests with Fan (1994) draws the following conclusions:

1) For a multi-hole trough the liquid can be fed behind a weir, using the weir to break the liquid momentum from the feed pipeline . This can improve the liquid distribution through the holes compared with feeding the liquid directly into the trough.

2) For the multi-hole trough studied in the program the discharge coefficient is slightly less than that of a single orifice. Such a difference is possibly a complex function of trough geometry and system properties.

CHAPTER III

DESCRIPTION OF EXPERIMENTAL APPARATUS

A pilot plant scale recirculating loop designed and constructed by Derasari and Chatorikar (Derasari, 1993) was used for all the experimental work. The platform for the trough was constructed by Chatorikar, Ramamurthy and Kottarvedu. The loop uses a constant head tank which stabilizes the fluid flow from the pump. For other details of the recirculating loop the reader is referred to Derasari (1993) and Mendes (1994). A brief description of the recirculating loop and the side orifice trough are given in the following sections.

Recirculating Loop

This experimental facility (Fig. 3-1) was designed primarily to test different liquid distributors. In this study it was used to obtain data on a side orifice trough. The basic components of the system are:

1) Feed Tank

2) Pumps

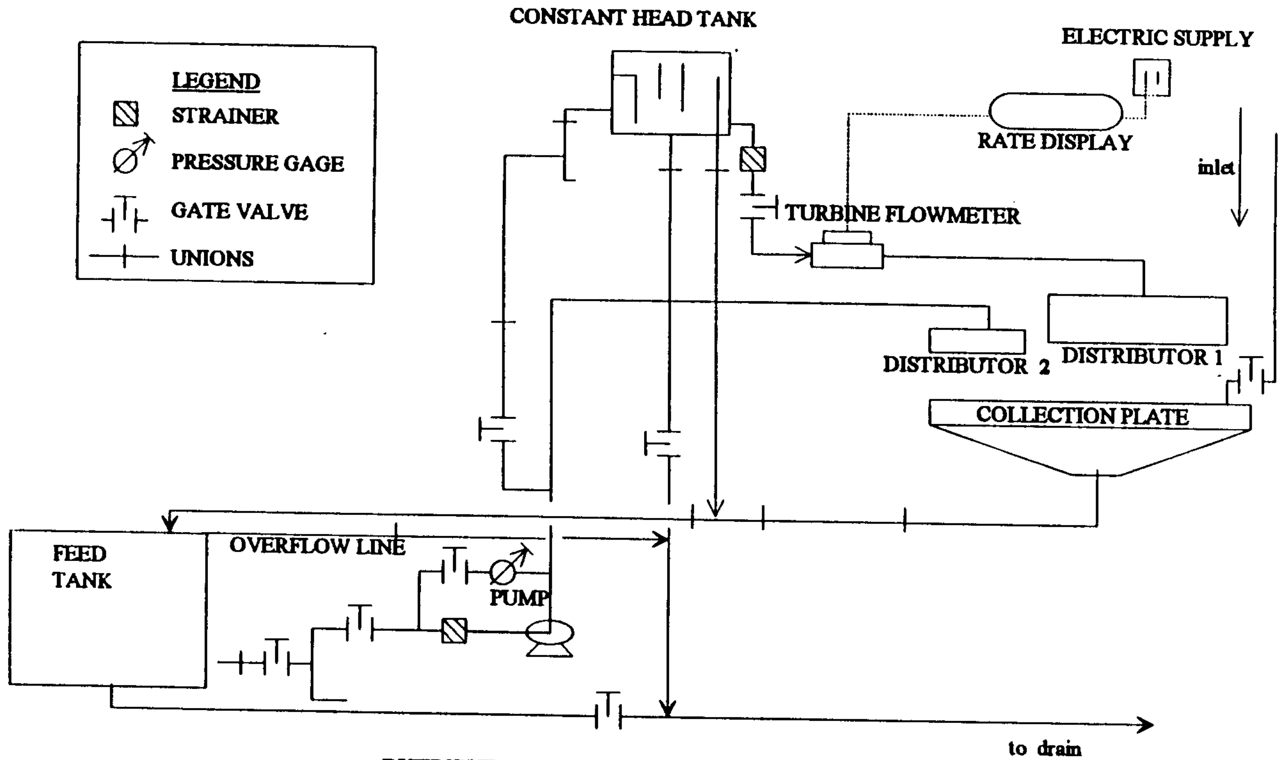
3) Constant Head Tank

4) Flow Meters

5) Collection Trough

6) Associated Piping, Supporting Structures, Electrical Connections

The feed tank was first filled with water, which was used as the test liquid. From the feed



DISTRIBUTOR 1 : SIDE ORIFICE TROUGH
DISTRIBUTOR 2 : HORIZONTAL VELOCTIY TROUGH

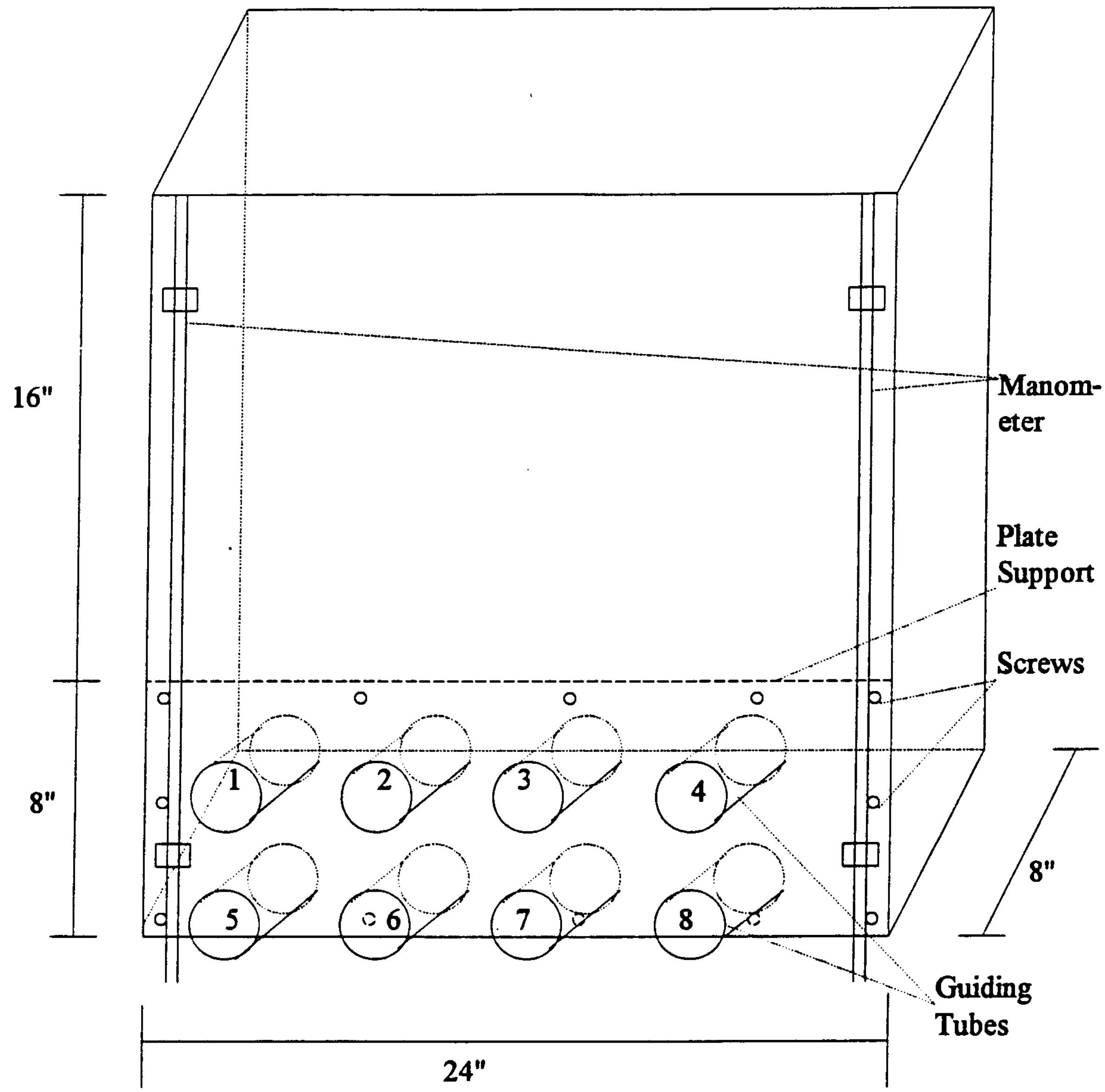
Figure 3-1 Schematic Diagram of the Recirculating Loop.

tank the water was pumped to the constant head tank, which was mounted 10 ft above floor level. Globe valves were used to give a controlled output flow from the constant head tank. Turbine flow meters were used to measure this flow rate. The water was then discharged into the distributor trough. The collection trough, mounted below the distributor, collects the water and returns it to the feed tank.

Side Orifice Trough

A Plexiglas trough (Fig. 3-2) constructed at the O.S.U. Physics shop was used to study the flow through a side orifice type distributor. The inside dimensions of the trough were as follows: 24 inches long, 8 inches wide, and 24 inches high. It had a uniform wall thickness of 1/2 inch. Eight holes, each of 2 inch diameter were made on the front side of the trough to provide flow through the orifice. Cylindrical guiding tubes made out of Plexiglas and fitting into the 2 inch holes were glued to the front side. These were used to guide the fluid flow and make the measurements easier. The guiding tubes at the top were 4 inches long while the ones at the bottom were 3 inches long. An aluminum bracket with tightening screws was used to hold the orifice plate to the trough wall (from inside). Three manometers made out of Plexiglas, two located at the front corners and one located at the rear corner were provided for leveling and head measurement purposes.

A total of five plates (Fig 3-3 -- Fig 3-4) was supplied by Nutter Engineering, Tulsa, OK. Each plate had four holes in the bottom and four holes in the top, making a total of eight holes. Plate 1 (12 gage) had 0.125 inch, 0.25 inch, 0.5 inch and 0.75 inch diameter holes in that order from left to right as one faces the trough. Plate 2 (12 gage) had 0.125 inch, 0.125 inch, 0.75 inch and 0.5 inch diameter holes in that order from left

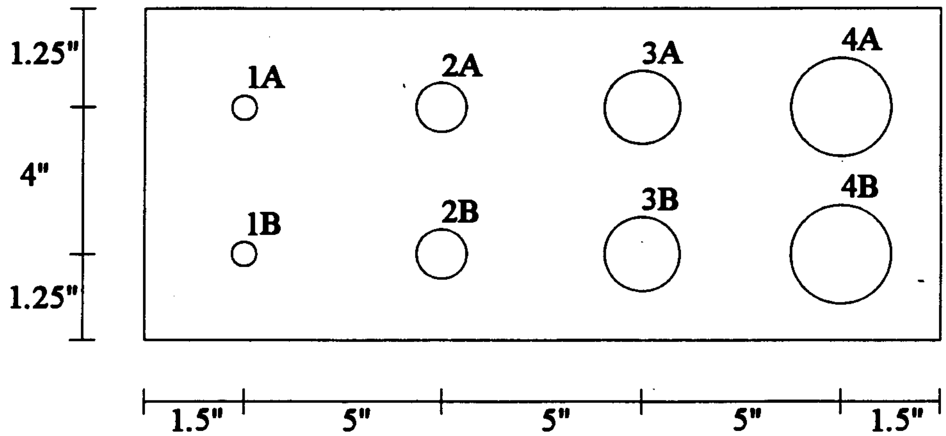


GUIDING TUBES 1,2,3&4: 2"ID ,4"LONG

GUIDING TUBES 5,6,7&8: 2"ID,3"LONG

TROUGH THICKNESS: 0.5"

Figure 3-2 Side Orifice Trough Diagram.



Holes 1A&1B : 0.125"diameter; Holes 2A&2B : 0.25"diameter;

Holes 3A&3B : 0.50"diameter; Holes 4A&4B : 0.75"diameter

Inlet pipe inside diameter: 1.53 in.

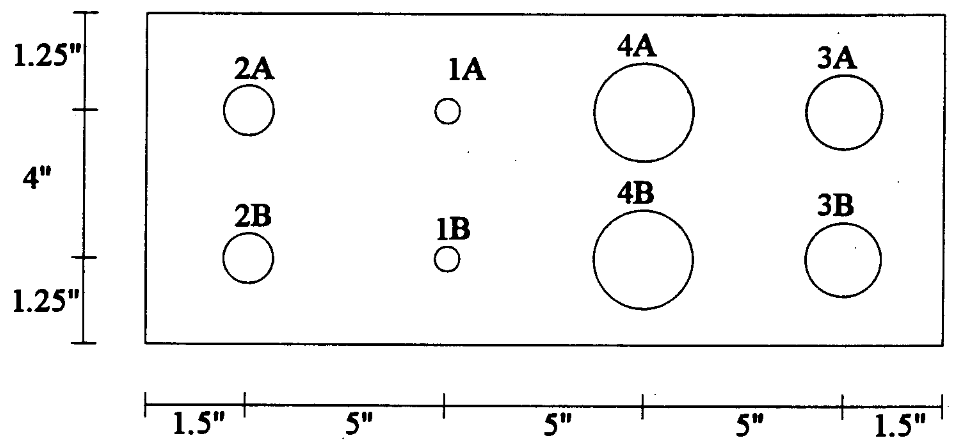
Inlet pipe pipe position 1.75 in from bottom of trough, at center, and adjacent to the wall opposite to orifice plate wall.

⊕ : Blocked holes

Holes deburred: 2A, 2B

Plate thickness: 12 gage (Plate 1), 14 gage (Plate 3).

Figure 3-3 Orifice Plate Diagram. (Arrangement 1)



Holes 1A&1B : 0.125"diameter; Holes 2A&2B : 0.25"diameter;

Holes 3A&3B : 0.50"diameter; Holes 4A&4B : 0.75"diameter

Inlet pipe inside diameter: 1.53 in.

Inlet pipe pipe position: 1.75 in from bottom of trough, at center, and adjacent to the wall opposite to orfice plate wall.

⊕ : Blocked holes

Holes deburred: 2A,2B

Plate thickness: 10 gage (Plate 5), 12 gage (Plate 2), 14 gage (Plate 4).

Figure 3-4 Orifice Plate Diagram (Arrangement 2).

to right as one faces the trough. Plates 4 and 5 were similar to Plate 2 in terms of hole configuration but were of 14 gage and 10 gage thickness respectively. Plate 3 was similar to Plate 1 except that it was of 14 gage thickness. A total of 10 readings was taken for diameter measurements for each hole. A total of 5 readings was taken for measuring thickness of each plate. The diameter and plate thickness measurements are tabulated in Appendix 1.

CHAPTER IV

EXPERIMENTAL PROCEDURES AND DATA ANALYSIS

The basic operation involved opening the valve in the feed line to the trough until a desired flow rate was achieved and then measuring the flow rate and liquid level at steady state. Flow rates were measured by volume as well as weight. In some cases the turbine flow meter was used with appropriate calibration. Calibration check was done during the experiment. For net head measurements, the liquid level was noted from the manometer reading. As the zero point measurements were found unreliable because of possible surface tension effects, a new procedure was adopted. The trough was filled with water approximately to a depth of 1 inch. The manometer reading was noted. Then the actual reading was measured using a scale. These readings were called as the base line readings. When a liquid level is noted (manometer reading) ,the net head is calculated as follows:

Net Head = (Liquid elevation - Center line) + (Base line manometer reading - Actual base line reading)

where,

Center line = Height from the bottom of the trough to the center of orifice.

The Center line is 2 inches for the bottom set of holes and 6 inches for the top set of holes.

The following general procedures are used for conducting an experiment: (Derasari, 1993)

Startup:

1) The drain valves of the feed and constant head tank are closed. Also, the outlet valve downstream of the constant head tank is closed.

2) The feed tank is filled by opening the valve in the main water supply line.

3) The valve upstream of the pump is opened.

4) The valves in the bypass line around the pump and rotameter are opened to reduce stress on the equipment. The valve upstream of the rotameter is closed at this time.

5) The pump is started and the constant head tank is filled.

6) The bypass valve around the rotameter is gradually closed and the upstream valve simultaneously opened.

7) The flowmeter is switched on.

8) The valve downstream of the constant head tank is gradually opened until the desired flow rate is achieved.

9) The flow is allowed to stabilize until an approximate steady state is achieved. This is manifested by a more or less stable liquid level and also an approximately constant flow meter reading.

10) Once steady state is achieved, the orifice flow rates are measured using a measuring cylinder and stopwatch. The corresponding liquid level in the level indicator is noted.

11) The surface of the water in the trough is examined for any aberrations or abnormal phenomena such as local vortex formations, excessive rippling, etc. Also, the jets are checked for continuity, smoothness and straightness and qualitative observations are recorded.

12) The flow rate is changed until a new steady state is achieved.

13) Steps 10 - 13 are repeated.

Shutdown:

1) The valve in the rotameter bypass line is opened and simultaneously the ones in the main line closed.
2) The pump and flow meter are switched off.
3) The outlet valve from the constant head tank is gradually closed to avoid damaging the bearings in the flowmeter.
4) The valve upstream of the pump is closed.
5) The feed tank is drained.
6) The constant head tank is drained and the drain valve from the feed tank is closed.

Precautions:

1) Make sure the trough is leveled before starting the experiment. Check leveling in all directions. If the trough is not leveled, maldistribution effects will be manifested as significant variations in orifice flow rates, especially at the ends of the trough.
2) Always open and close the outlet valve from the constant head tank slowly to prevent a sudden surge from occurring, which could damage the turbine flowmeter.
3) Sufficient time should be allowed for the system to reach steady state.
4) At least three temperature readings should be taken at different times for each run. In these experiments, the viscosity and density were calculated at the average temperature because it was found that there weren't any significant temperature variations during each run. The maximum temperature variation was around 8^{o}F.

Data Interpretation

The experiments were done using a side orifice trough. For further reading on data interpretation, the reader is referred to Mendes (1994). The measured variables in the experiments were the liquid level or head and the flow rate. The liquid level was measured in centimeters and the flow rate in cc/s. When weight measurements were used, they were appropriately converted to cc/s. When the flow meter was used to measure the flow rate, the readings were obtained in gpm. These readings were then converted to consistent units and used to calculate an orifice coefficient (Eqn 4-2) and a Reynolds number (Eqn. 4-1). This was done because it is believed that a more general correlation can be obtained between the orifice coefficient and the Reynolds number which can be used to determine head-flow rate relationships for any liquid with known physical properties.

The orifice Reynolds number and the orifice coefficient are defined as follows:

Orifice Reynolds Number: (Re)

This parameter is defined by the following equation:

$Re = dv\rho/\mu$ ....(4-1)

where,

d = hole diameter, m or ft

v = velocity of water through the orifice assuming constant flow, m/s or ft/s

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

μ = viscosity of the liquid, kg/m-s or lb_m/ft-s

The density of water was obtained from Perry (1988). The densities for the temperature range in which these experiments were run are tabulated in Appendix 8. Viscosity is calculated using the correlation shown in Appendix 7.

<u>Orifice Coefficient:</u> (C_o)

The orifice coefficient is calculated using Eqn 4-2.

$C_o = v/(2gh)^{1/2}$ ....(4-2)

where,

g = gravitational acceleration, m/s^2 or ft/s^2

h = height of liquid above the center line of the orifice, m or ft

v = velocity of water through the orifice assuming constant flow, m/s or ft/s

The derivation of this equation is presented in Appendix 3. It is similar to that derived by Derasari for the down flow single orifice case.

After calculating the orifice Reynolds number and the orifice coefficients, the data was plotted in terms of head vs. flow rate, head vs. orifice coefficient and Reynolds number vs. orifice coefficient. Earlier in this project, data interpretation was done mainly in terms of Reynolds number vs. orifice coefficient. But when the parameters on which the Reynolds number depends, namely, viscosity and density were changed, the orifice coefficients obtained were different for the same Reynolds number. It was decided that the head-orifice coefficient relationship would be more appropriate for correlation purposes. Hence, the data interpretation was done mainly in terms of head vs. orifice coefficient.

CHAPTER V

RESULTS AND DISCUSSION

This chapter will mainly deal with the experimental results obtained and analyze these in detail. The diameters ranged from 0.125 inch to 0.75 inch. There were two sets of holes located at top and bottom, when the plate was fitted into the trough. As mentioned earlier, a total of five plates was tested. The results of these plates were compared with down flow data previously obtained by Derasari.

The effects of hysteresis, hole position, side wall effect, two hole interactions, and plate thickness were checked by running experiments separately for each of these cases. In the case of hysteresis, there were four runs for increasing and decreasing heads. Two runs each of increasing and decreasing heads was done. In the case of hole position three sets of runs were performed for three sets of top and bottom holes. The effect of side wall was checked by performing experiments for two different plates for the 0.75 inch hole. All these runs were single orifice experiments. Runs were done to see the if there was any effect when two holes were run simultaneously. Three plates of different thickness, 14 gage, 12 gage, and 10 gage were used to check the effect of plate thickness. The data was analyzed in terms of head vs. flow rate, head vs. orifice coefficient, and orifice coefficient vs. Reynolds number. All the data for this work are tabulated in Appendix 4.

Effect of Hysteresis

A total of 6 runs was done to see the effect of hysteresis. Values of orifice coefficient and Reynolds number were found from equations(4-1) and (4-2) respectively. The effect is shown in figures 5-1 and 5-2. The average value of orifice coefficient for heads above 2 inches is used as a measure for each case study considered here. The following points can be concluded from these figures.

- The curves for increasing and decreasing heads follow each other very closely
- The difference in the value of average orifice coefficient between the increasing head and decreasing head is 0.28 %.. There is negligible hysteresis effect.
- This behavior is expected if the trough is leveled properly and the water flow is stable.

Effect of Hole Position

The location of a hole is a very important design consideration for a distributor having holes in the side. Two sets of holes were located at 2 inches and 6 inches from the bottom. Experiments were done for the 0.75 inch holes and 0.5 inch hole at the top and bottom. These experiments were done for plates 1 and 2 (both were of 12 gage thickness). The results are as shown in figures 5-3 and 5-4. The following points can be concluded from the figures.

- There is essentially no difference between the top and bottom hole results for the 0.75 inch and 0.5 inch holes. The average orifice coefficients differ by 0.28 %.
- This result is expected if the trough is properly installed and leveled.
- This conclusion is important for design considerations.
- This conclusion can be generalized for the smaller diameter holes.

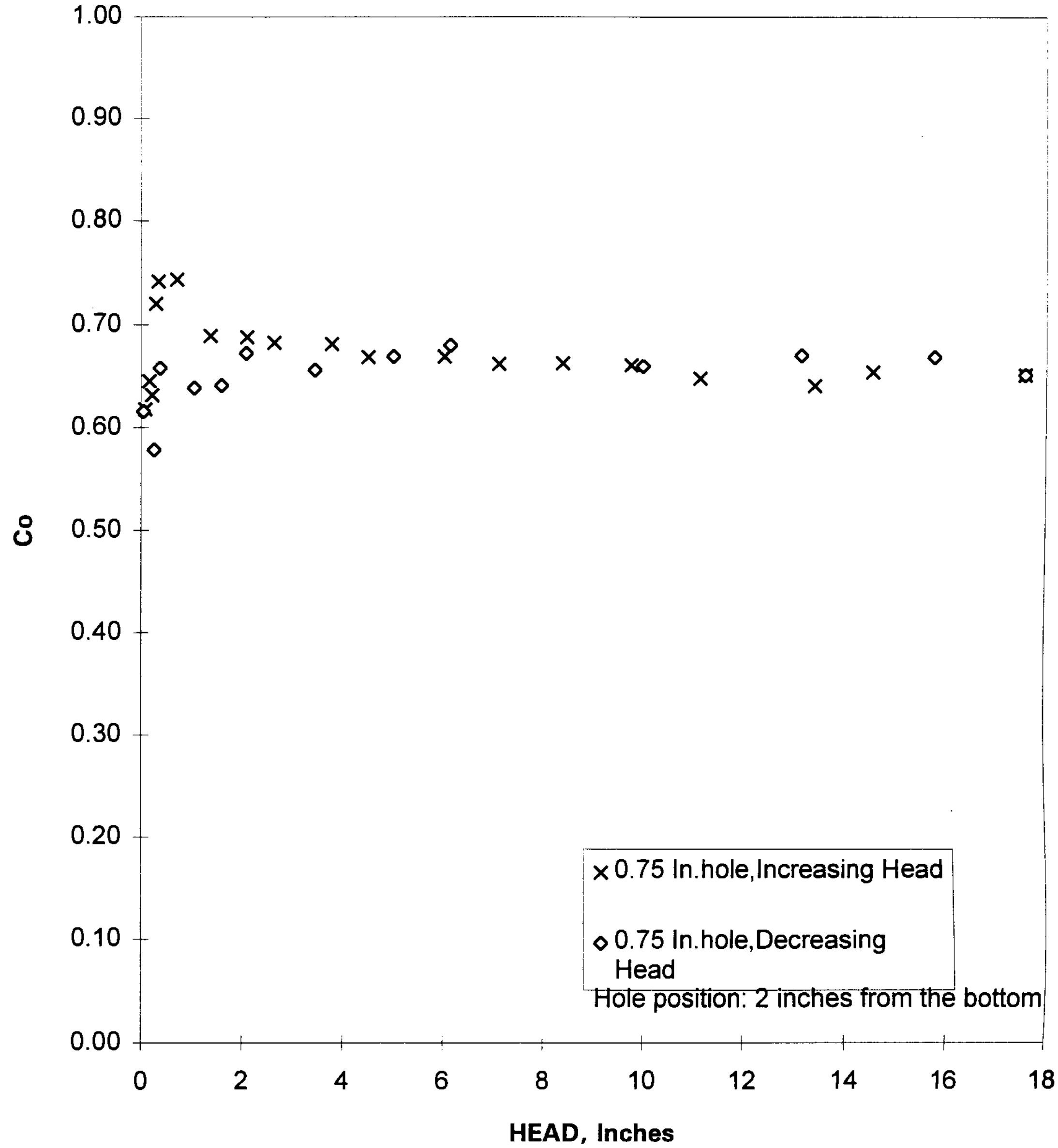


Figure 5-1. Effect of hysteresis.

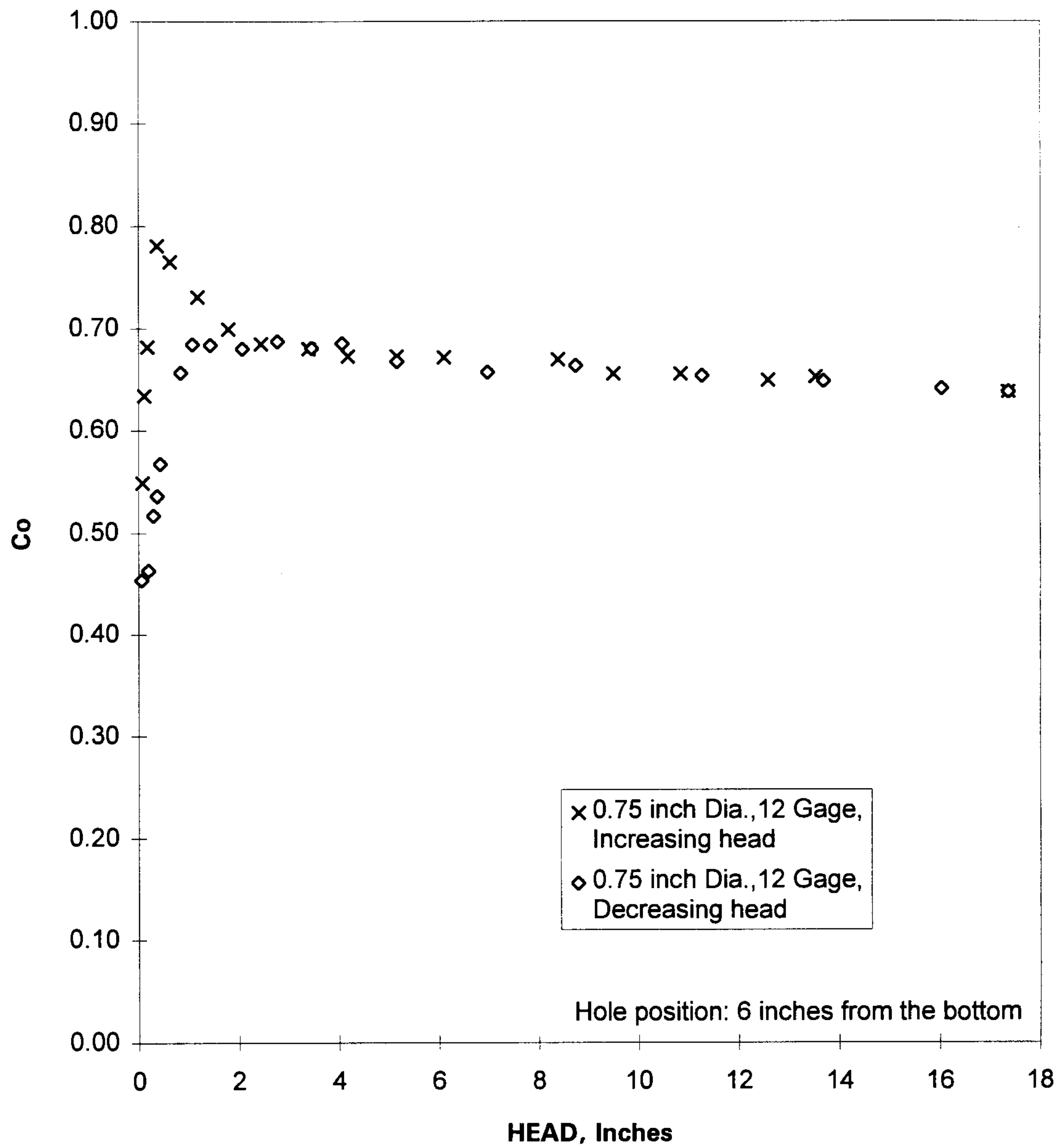


Figure 5-2 Effect of hysteresis.

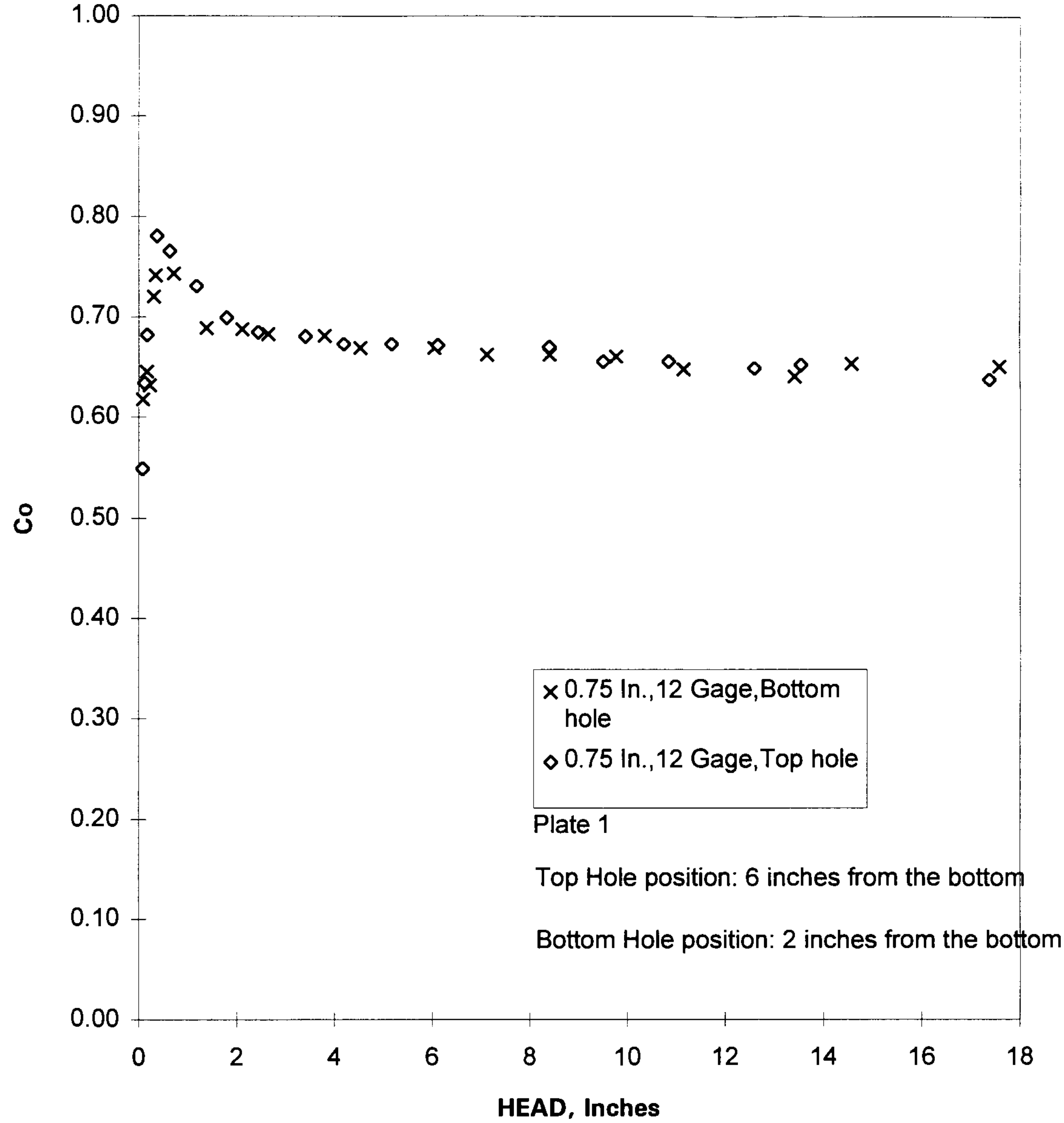


Figure 5-3 Effect of hole position.

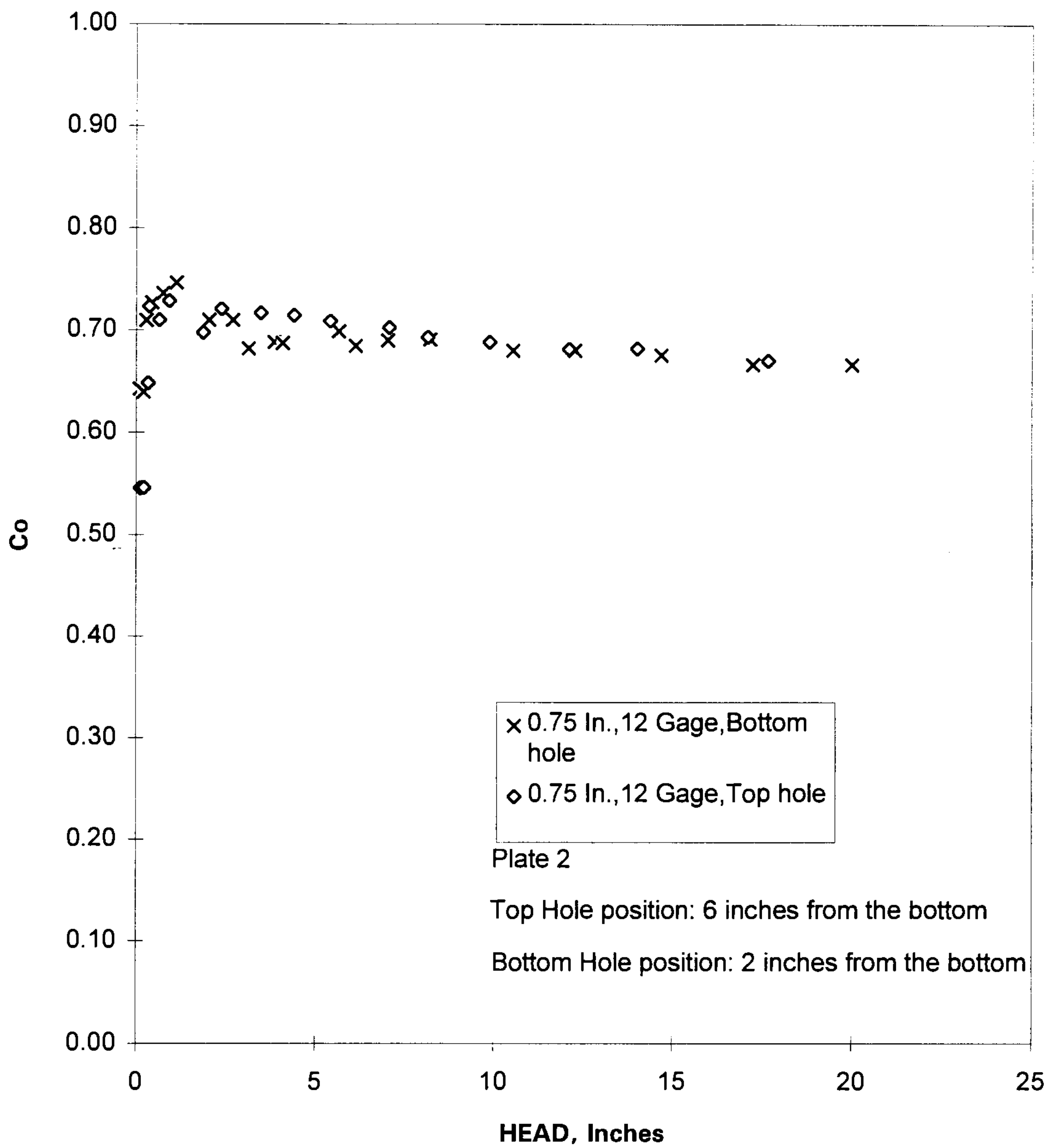


Figure 5-4 Effect of hole position.

- This conclusion can also be generalized for different plate thickness.

Effects of Side Wall

There was a concern regarding the side wall affecting the flow pattern through the 0.75 inch hole which was 1 inch away from the side wall. The term "side wall" here means the aluminum bracket that covers and holds the orifice plates. This bracket was half inch thick and could possibly affect the flow through the 0.75 inch hole, which was about 1 inch away. Hence, plate 2 which had a different configuration of holes was used to see if there was any effect whatsoever, due to the side wall. In plate 2, the 0.75 inch hole was 6 inches away from the side wall. The main objective behind checking this effect was to see if there was any interference from the side wall. The following points can be concluded from figures 5-5 and 5-6.

- There is a noticeable offset in the two curves. There is a difference of around 5 % in the value of the average orifice coefficients.
- The holes farther from the side wall had higher orifice coefficients, indicating the interference of side wall. These coefficients were considered more reliable.

Effects of Two Hole Interactions

The main objective behind doing the two hole tests was to do the experiments simultaneously and finish the experiments in a fast and more efficient manner. A total of three runs was performed for this case. The first run was for the 0.75 inch hole and 0.5 inch hole of plate 1 at the bottom. The second run was for the 0.75 inch hole and 0.5 inch hole of plate 1 at the top. The third run was for the 0.75 inch hole at the bottom and 0.5 inch hole at the top. The results were compared to the previously done single orifice

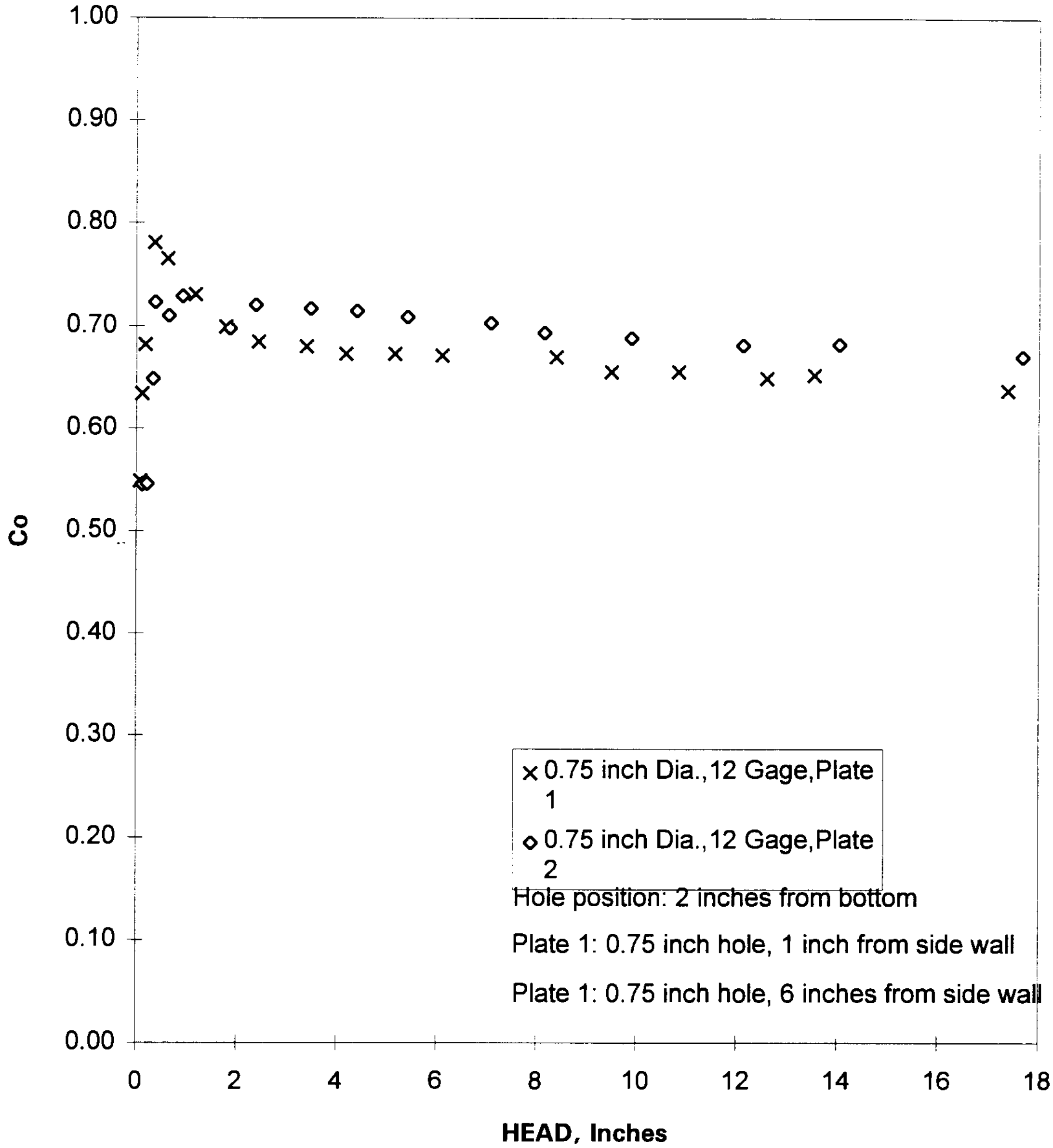


Figure 5-5 Effect of side wall on 0.75 inch hole.

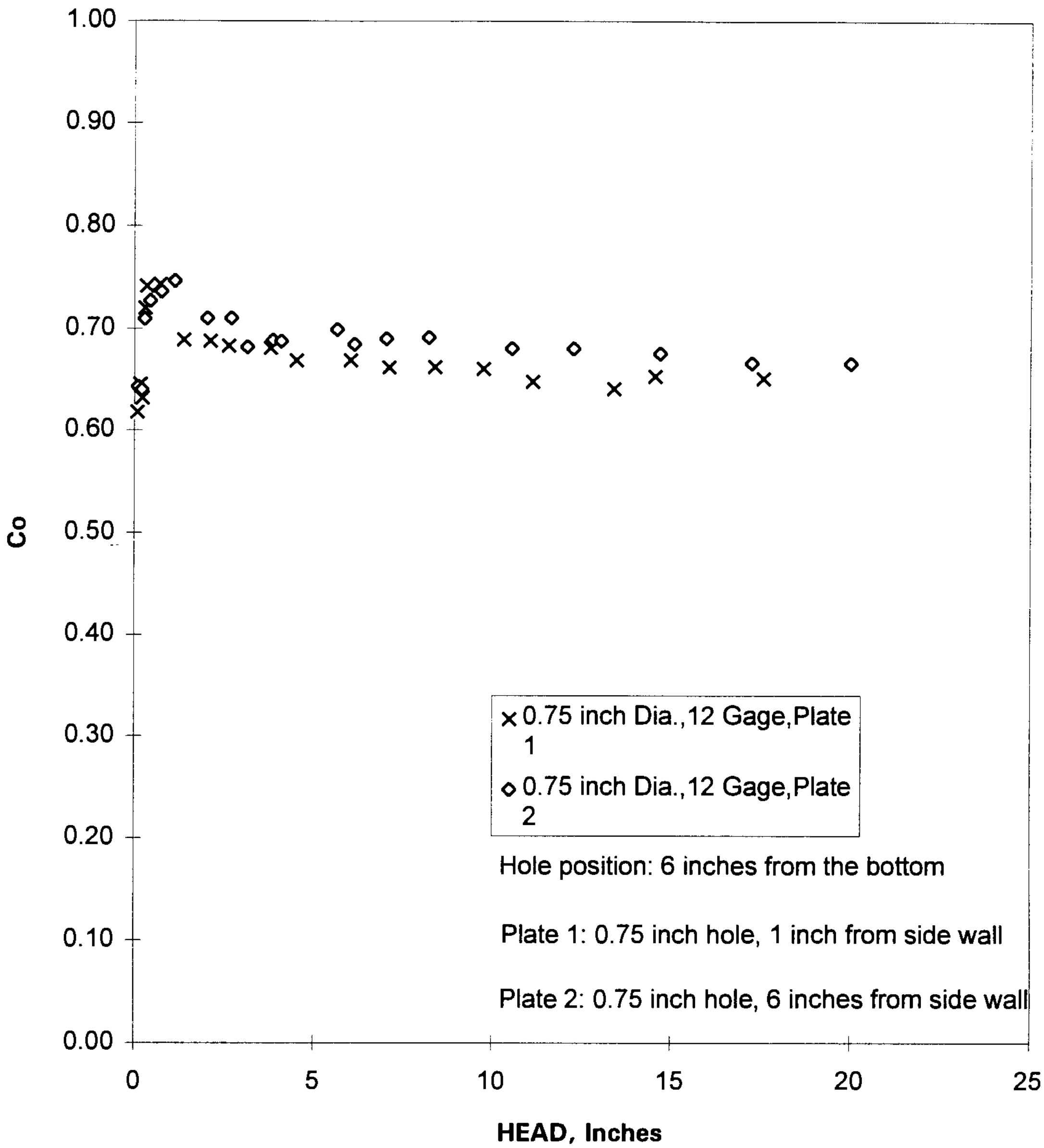


Figure 5-6 Effect of side wall on 0.75 inch hole.

experiments. The results are shown in figures 5-7 and 5-8. The following points can be observed.

- The 0.75 inch hole shows a slight difference in the curves attributable to experimental errors involving weight measurements. The difference between the average orifice coefficient values is around 2 %.
- The 0.5 inch hole shows a very negligible effect.
- The slight difference for the 0.75 inch hole prompted the idea of running further experiments with the holes separated by a further distance and running a 0.25 inch hole or 0.125 inch hole with a 0.75 inch hole.
- These experiments cut down the experimental work in half.

Effect of Plate Thickness

Plate thickness is an important parameter affecting the orifice coefficient. It is an essential parameter for correlation in the form of the l/d ratio. Three plate thickness; 14 gage, 12 gage, and 10 gage were experimented for the 0.125 inch, 0.25 inch, 0.5 inch and 0.75 inch holes. Comparisons are shown in figures 5-9, 5-10, 5-11 and 5-12. The following points can be observed from the figures.

- For the 12 gage and 14 gage plate thickness the curves closely follow each other and there is no significant difference.
- The 10 gage plate shows lower orifice coefficient values.
- The orifice coefficients decrease as the plate thickness increases. For the 0.75 inch hole, the average orifice coefficient value decreases by 3 % as the plate thickness decreases from 10 gage to 14 gage. For the 0.125 inch hole, the average orifice coefficient value decreases by 9 % as the plate thickness decreases from 10 gage to 14 gage.
- This trend is exactly opposite to the trend observed in down flow.

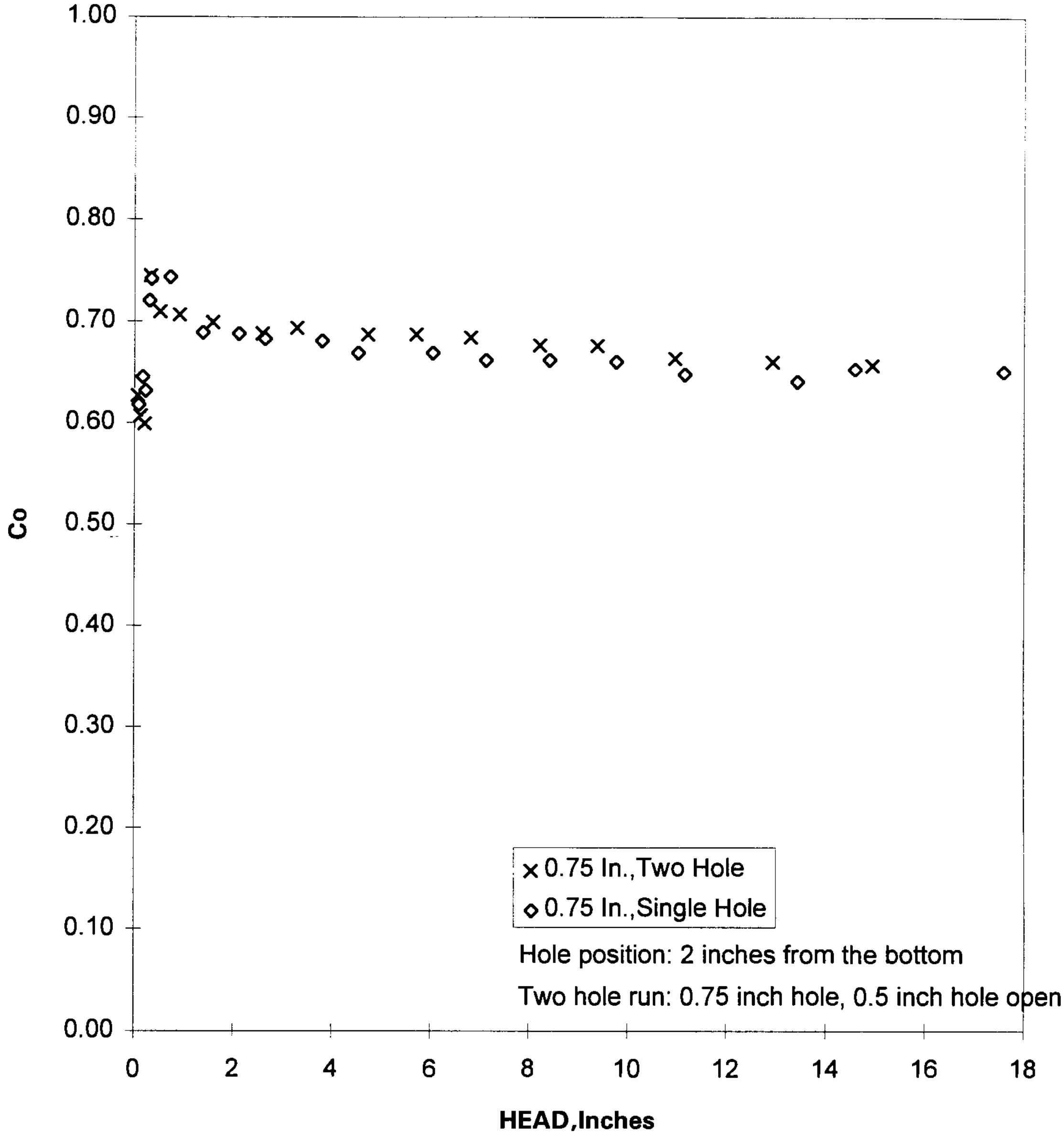


Fig 5-7 Effect of two hole interactions.

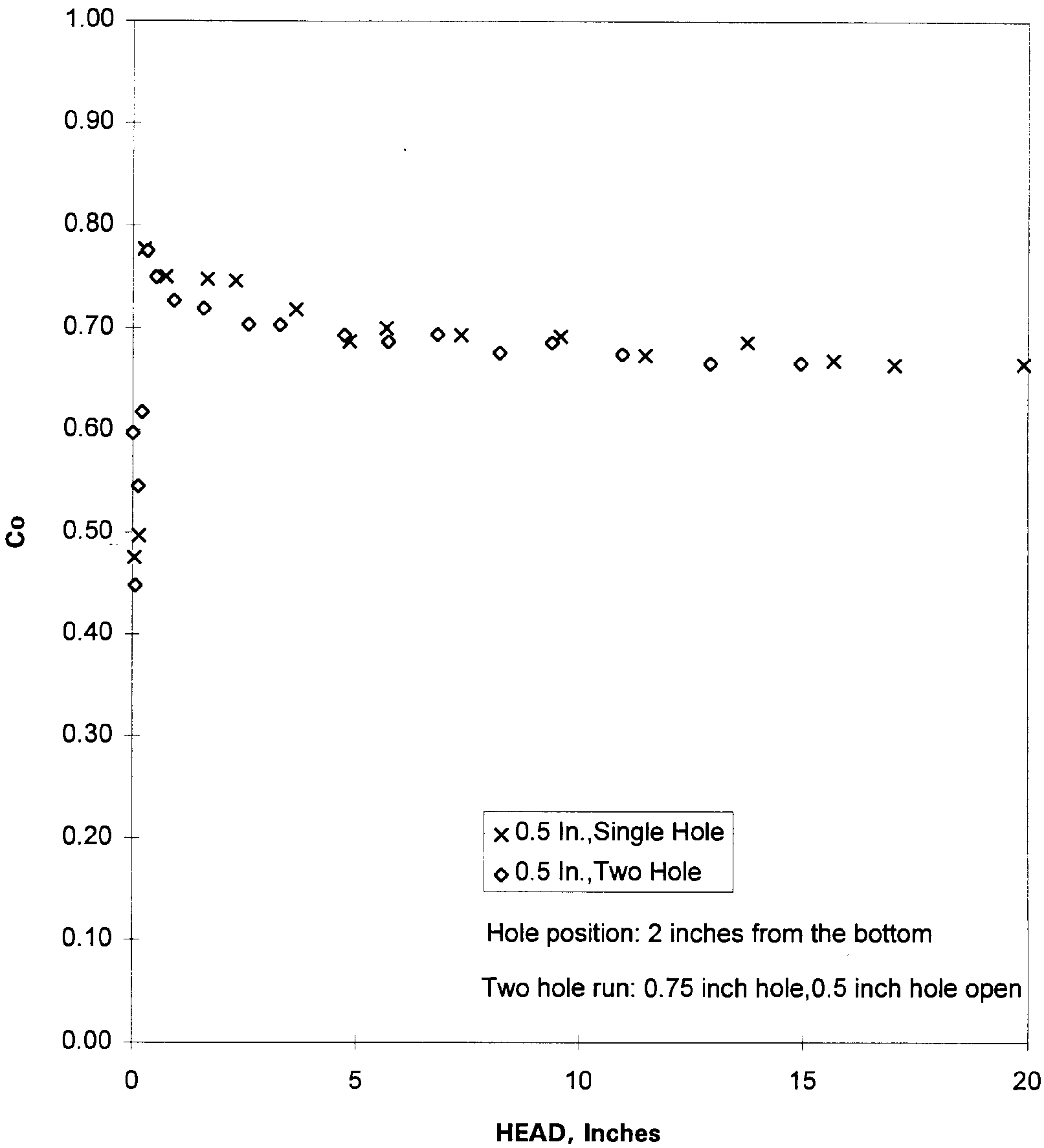


Figure 5-8 Effect of two hole interactions.

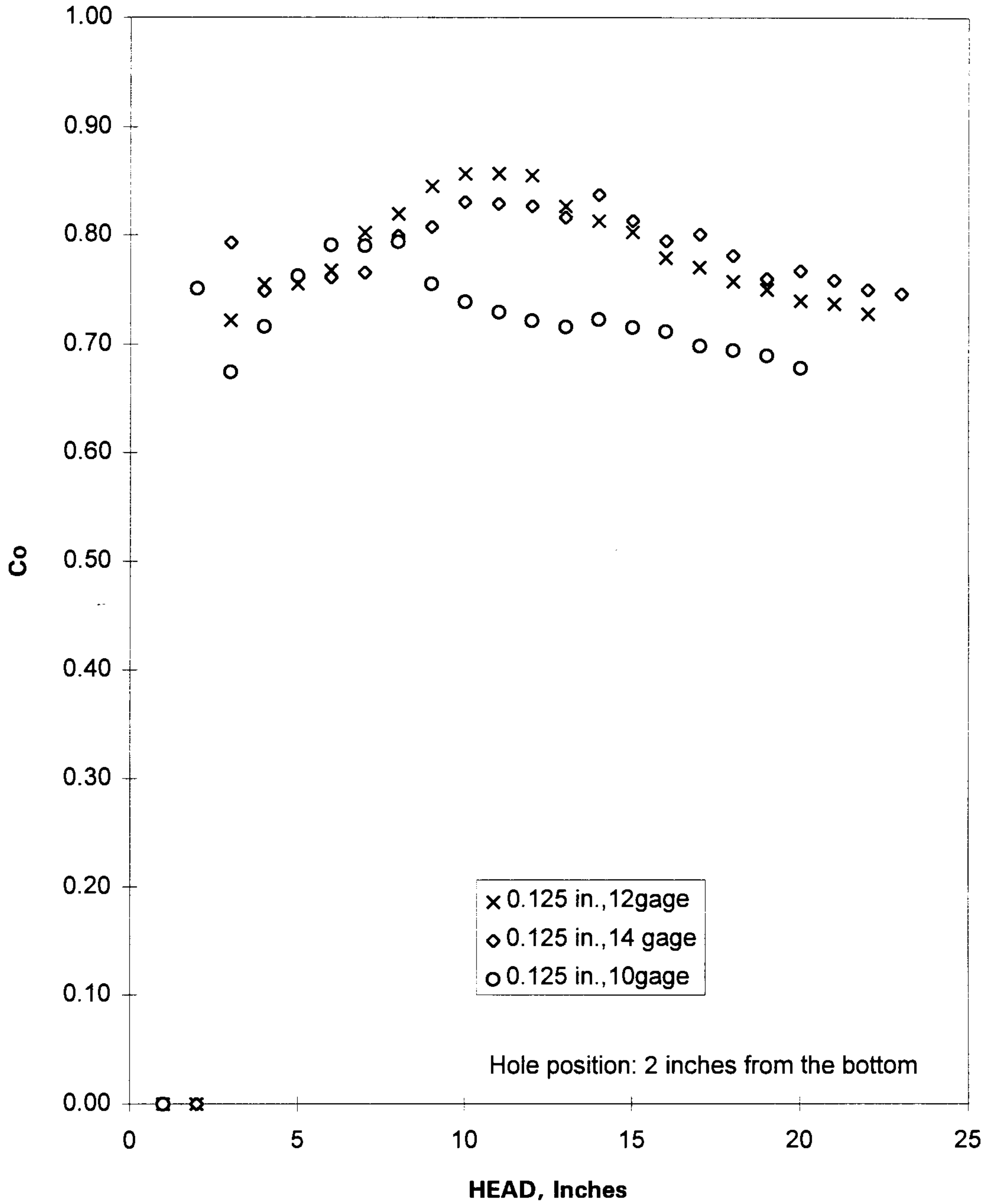


Figure 5-9 Effect of plate thickness.

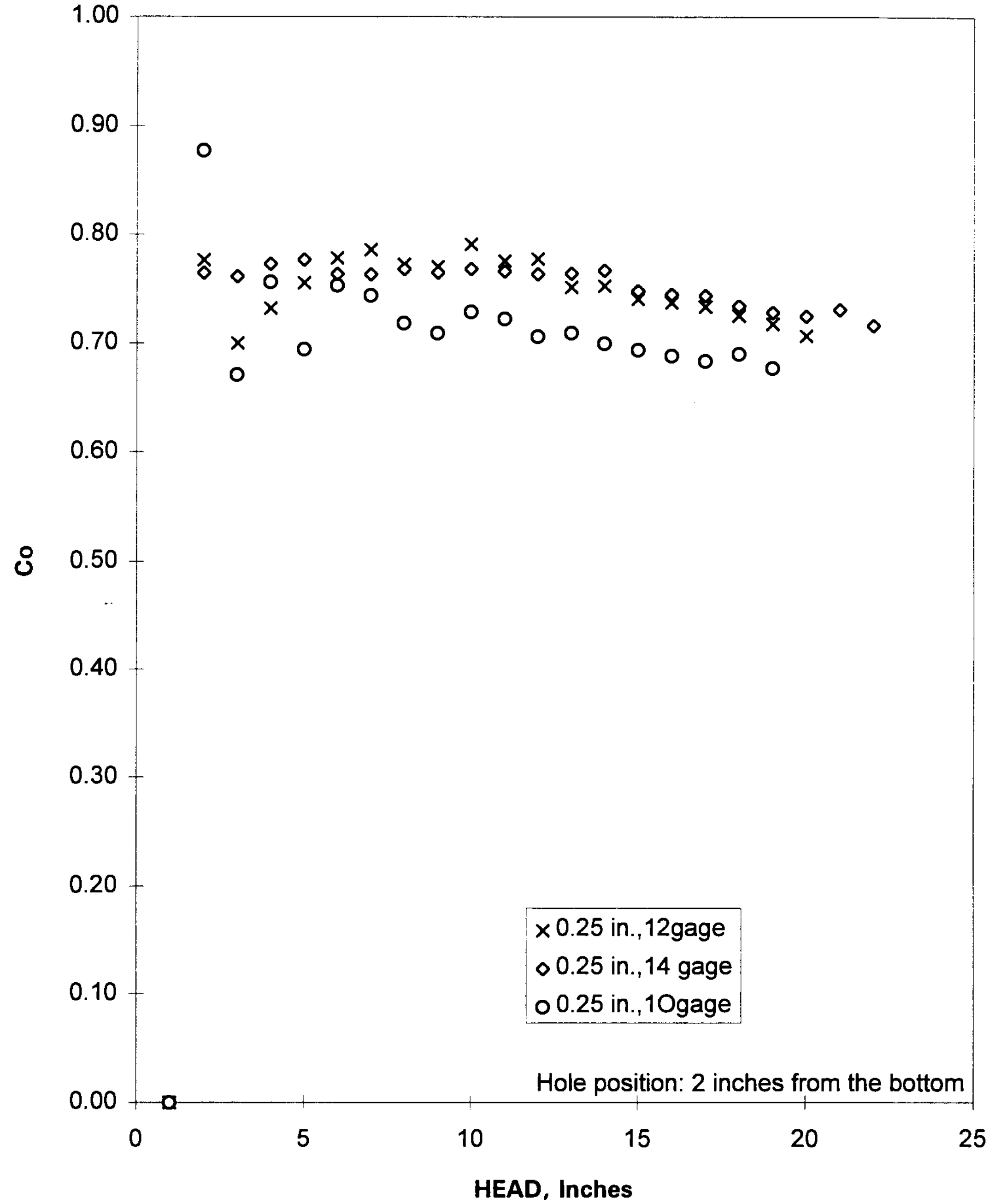


Figure 5-10 Effect of plate thickness.

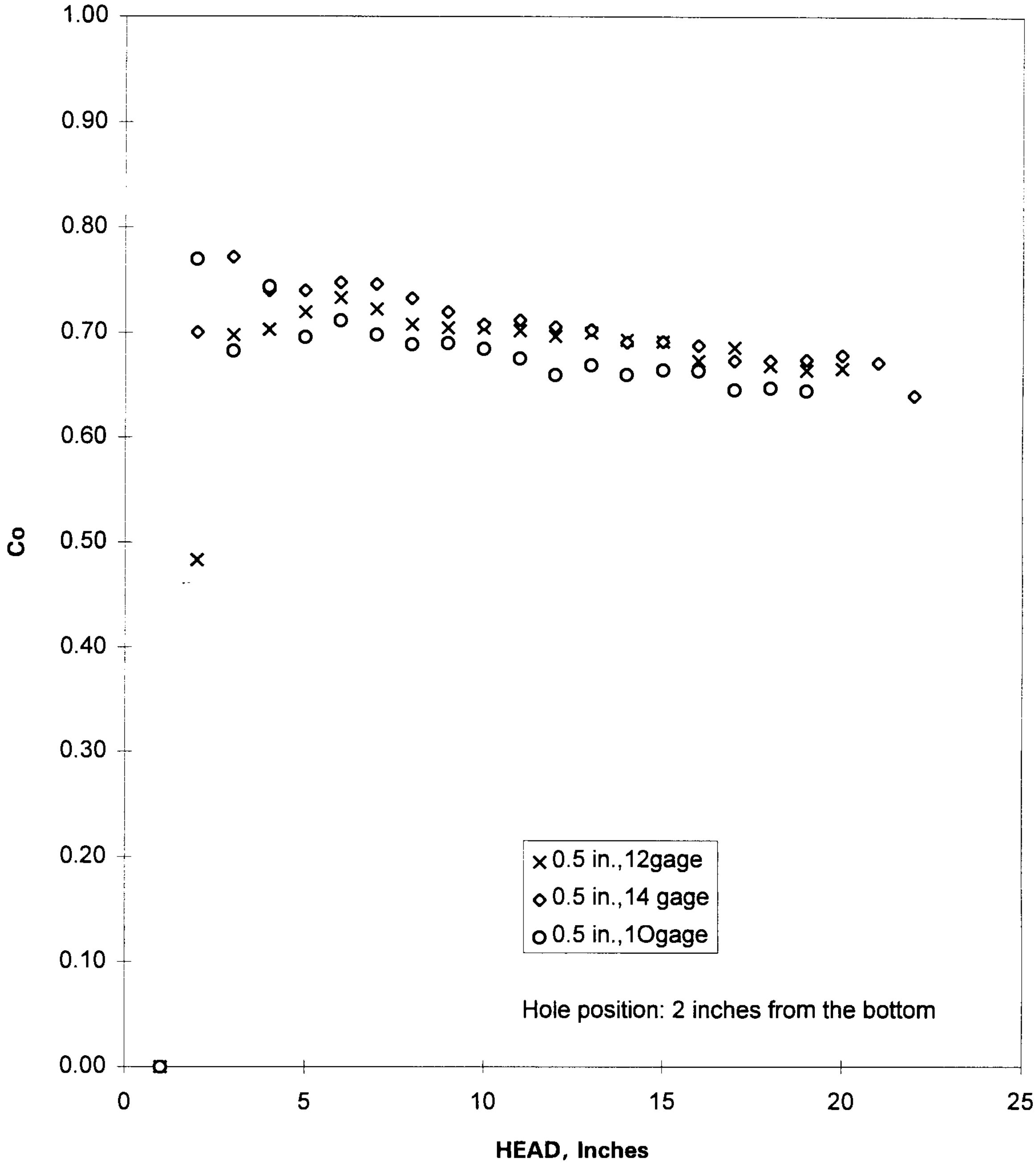


Figure 5-11 Effect of plate thickness.

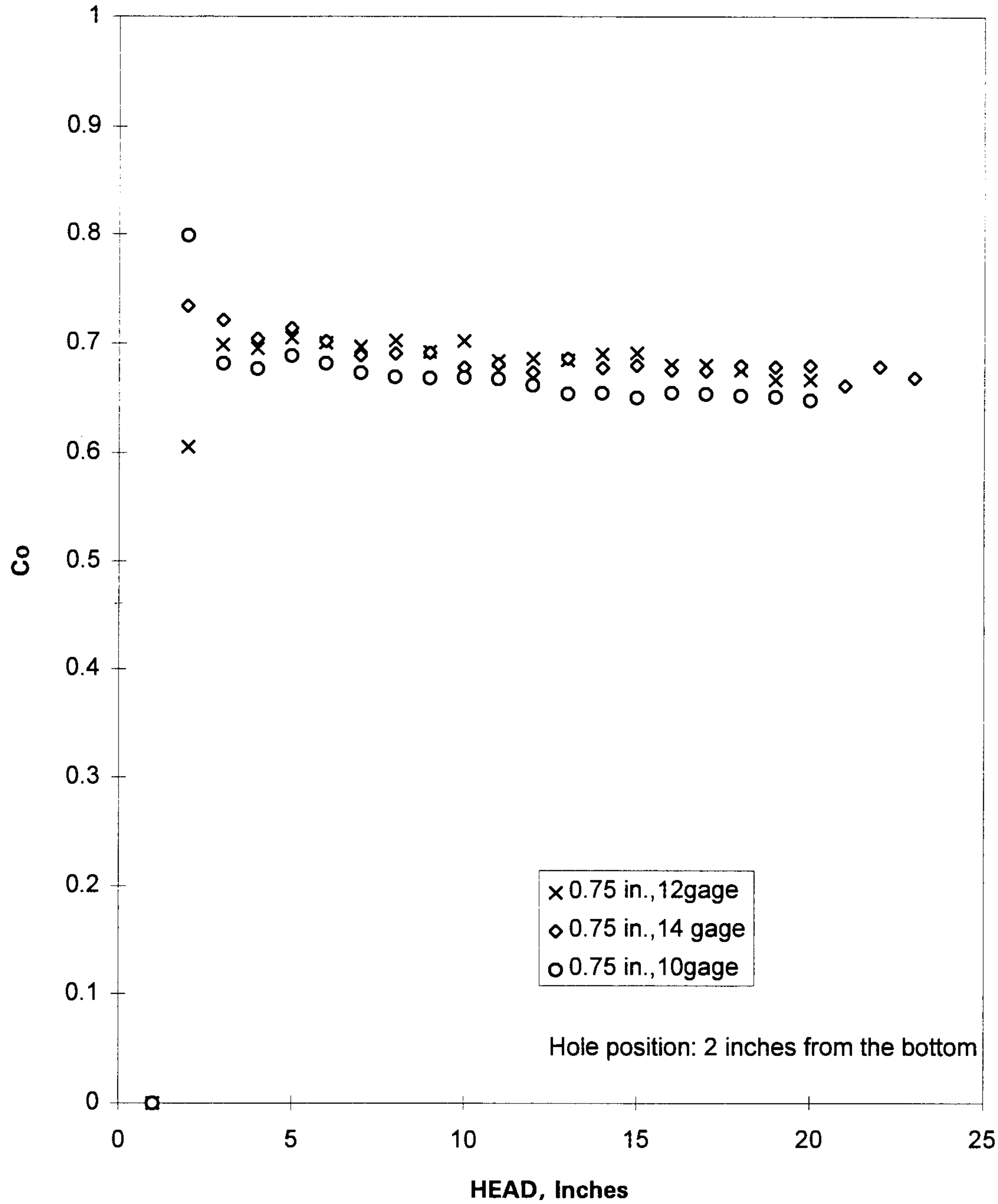


Figure 5-12 Effect of plate thickness.

- The difference in the orifice coefficient values between the 14 gage, 12 gage and 10 gage decreases as the hole diameter increases.

Comparison of side orifice flow to vertical down flow

Comparisons were done for side flow and down flow for both 12 gage and 14 gage thickness. The down flow data was for a cylindrical trough from previous single orifice experiments for circular troughs done by Derasari (1993). Except for the 0.125 inch hole, it is observed that the orifice coefficient values for side flow are always lower than down flow and they approach the down flow values as the head increases. Further, the curves merge for lower heads as the hole diameter increases. The comparisons are shown in figures 5-13 through 5-19.

Effect of Hole Diameter

The hole diameter is the most important factor influencing the orifice coefficient. Comparisons of data for 4 different diameters and for 3 different plate thickness are shown in figures 5-20, 5-21 and 5-22. The following points can be observed.

- The orifice coefficient decreases as diameter increases for all the three plate thicknesses.
- The average orifice coefficient value decreases by about 10.5 % for the 10 gage plate as the diameter decreases from 0.75 inch to 0.125 inch. For the 14 gage plate, the average orifice coefficient value decreases by about 16.7 % as the diameter decreases from 0.75 inch to 0.125 inch.
- The orifice coefficient value decreases with decreasing thickness.

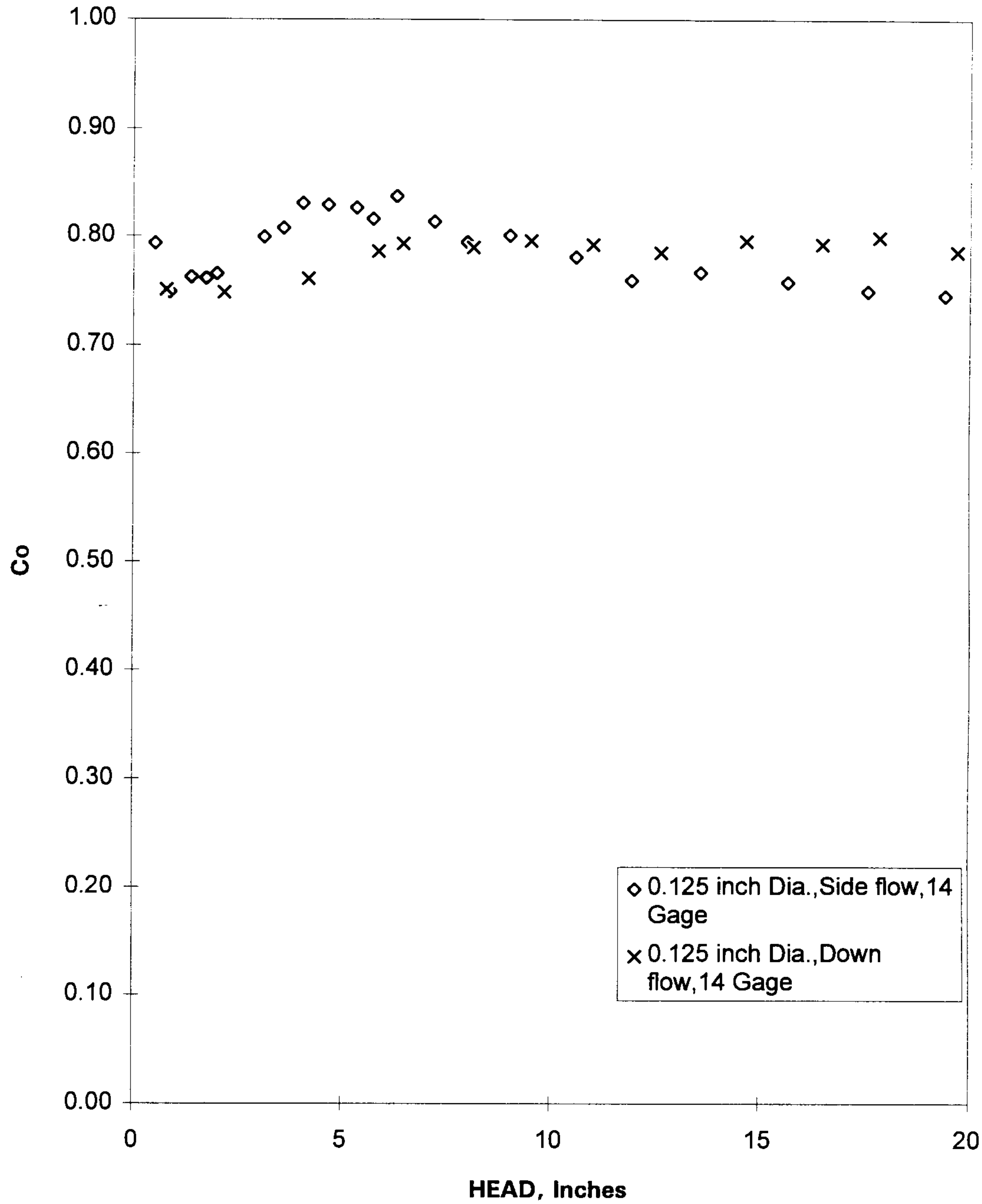


Figure 5-13 Comparison of side flow to down flow.

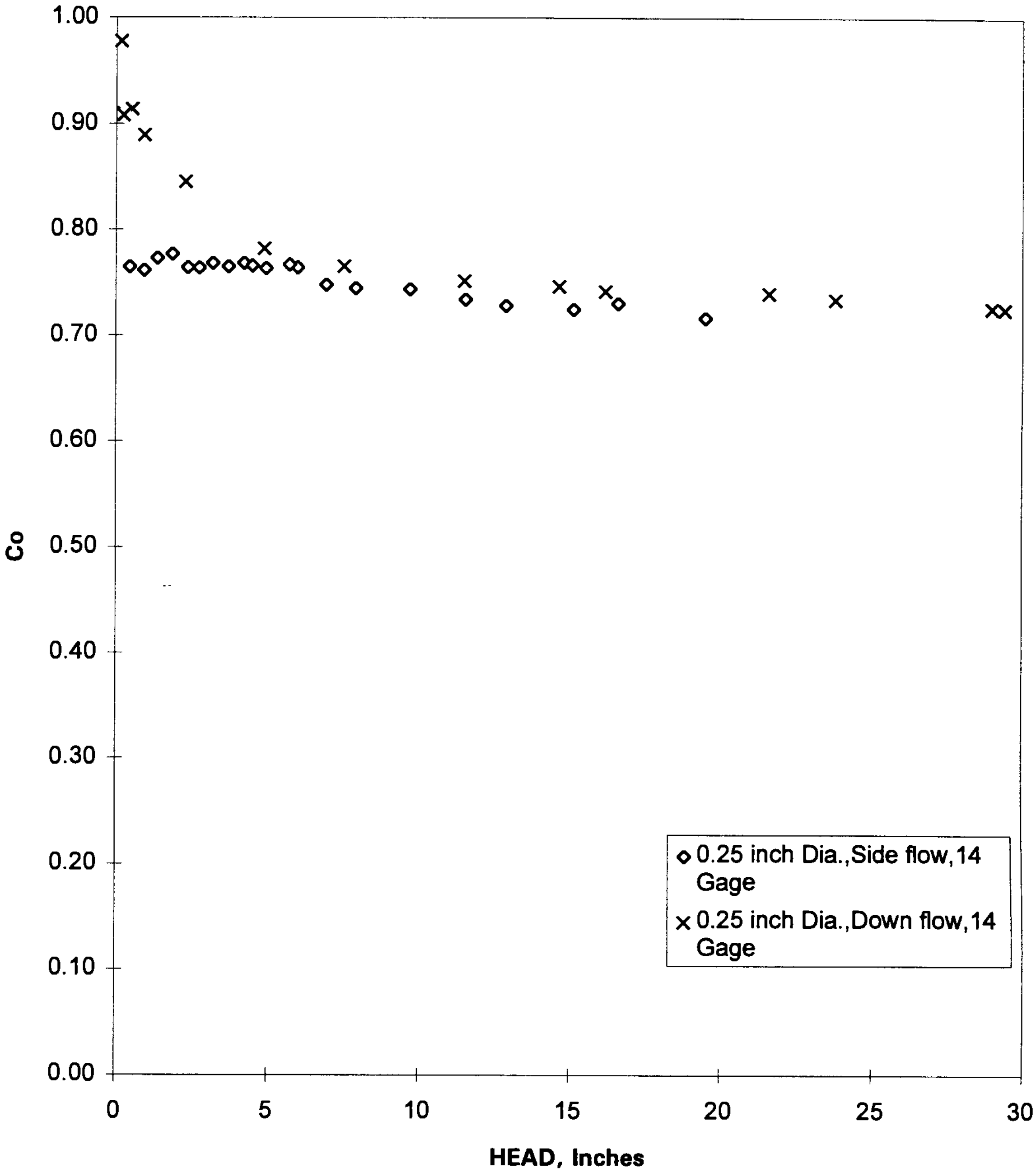


Figure 5-14 Comparison of side flow to down flow.

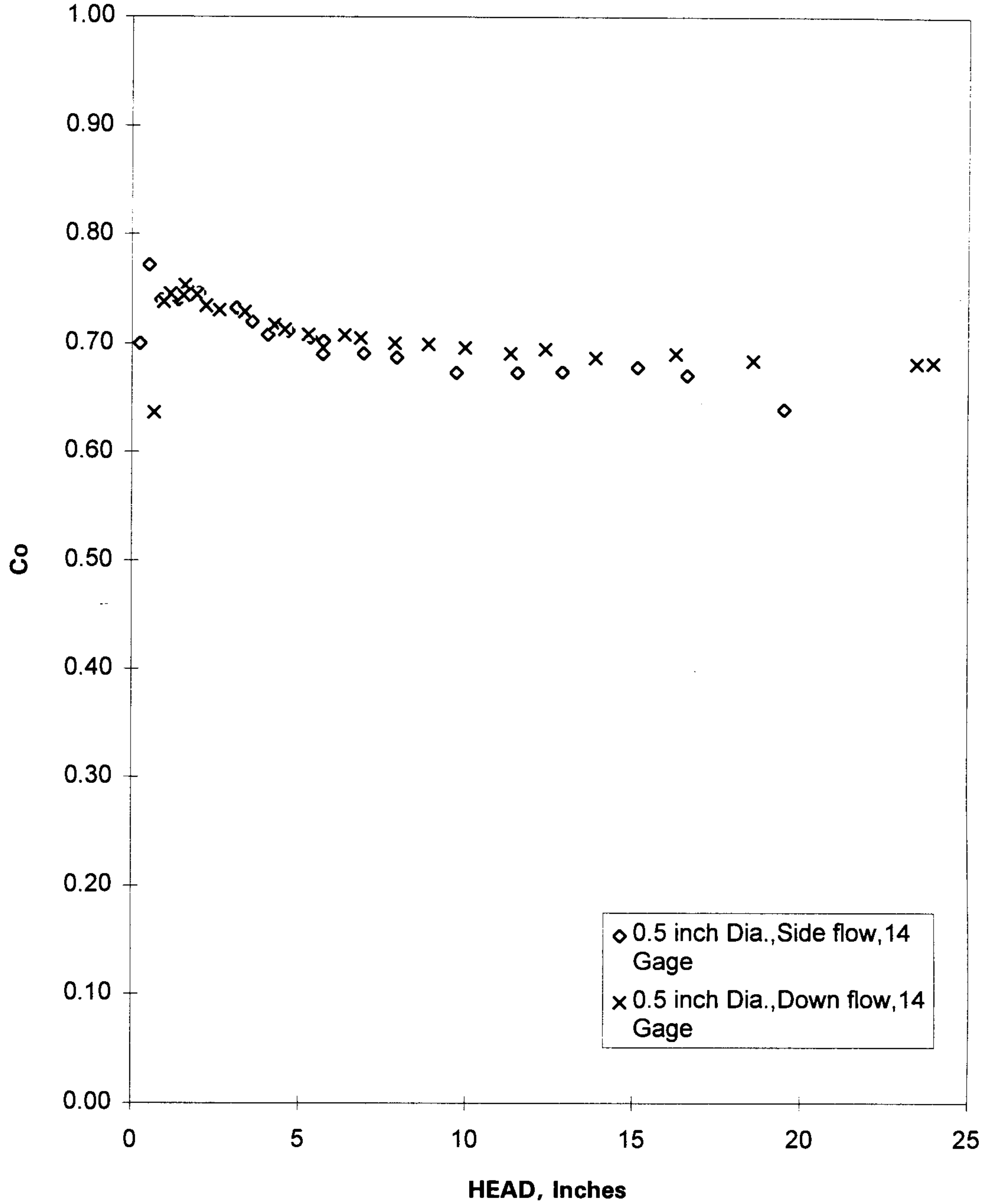


Figure 5-15 Comparison of side flow to down flow.

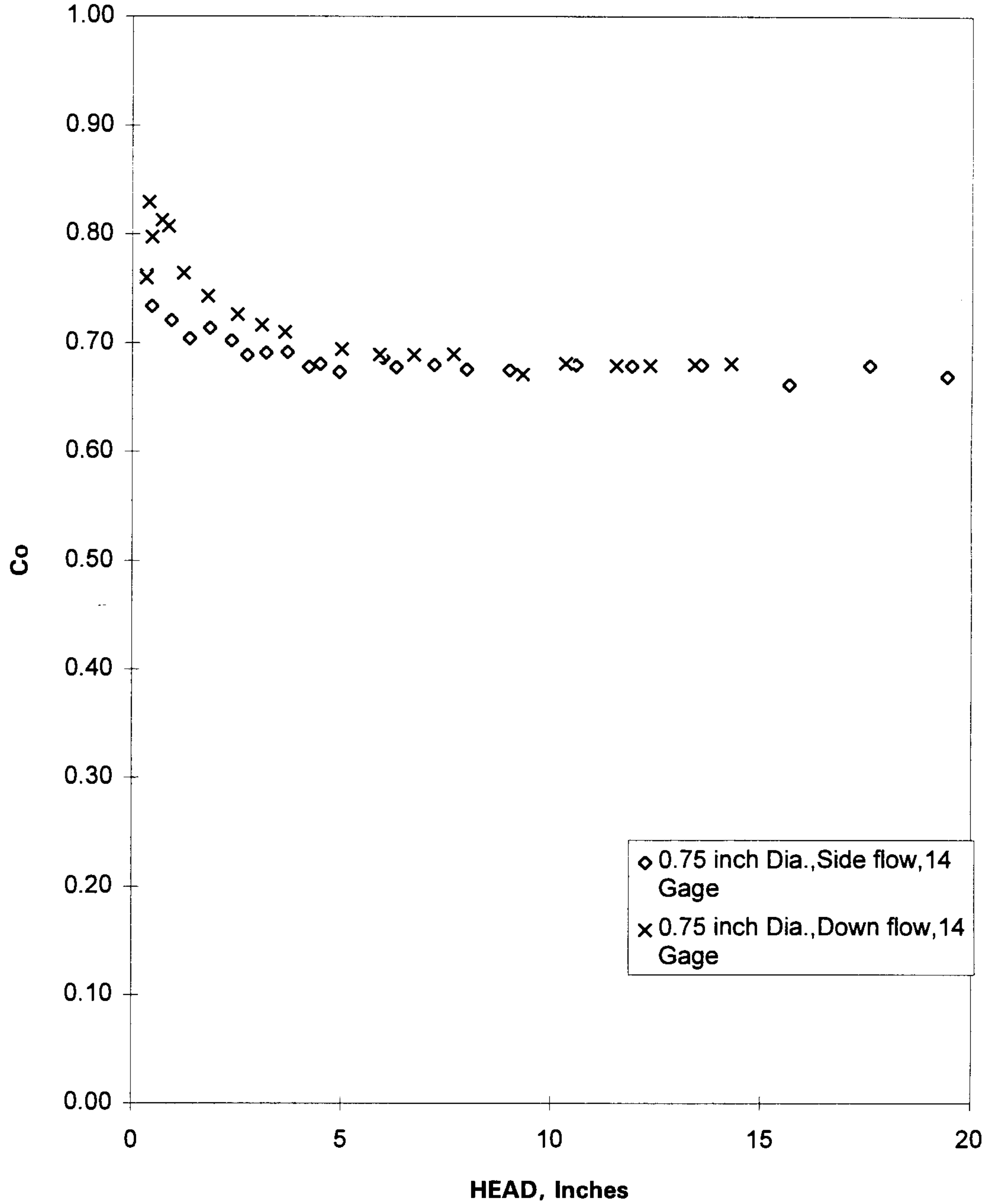


Figure 5-16 Comparison of side flow to down flow.

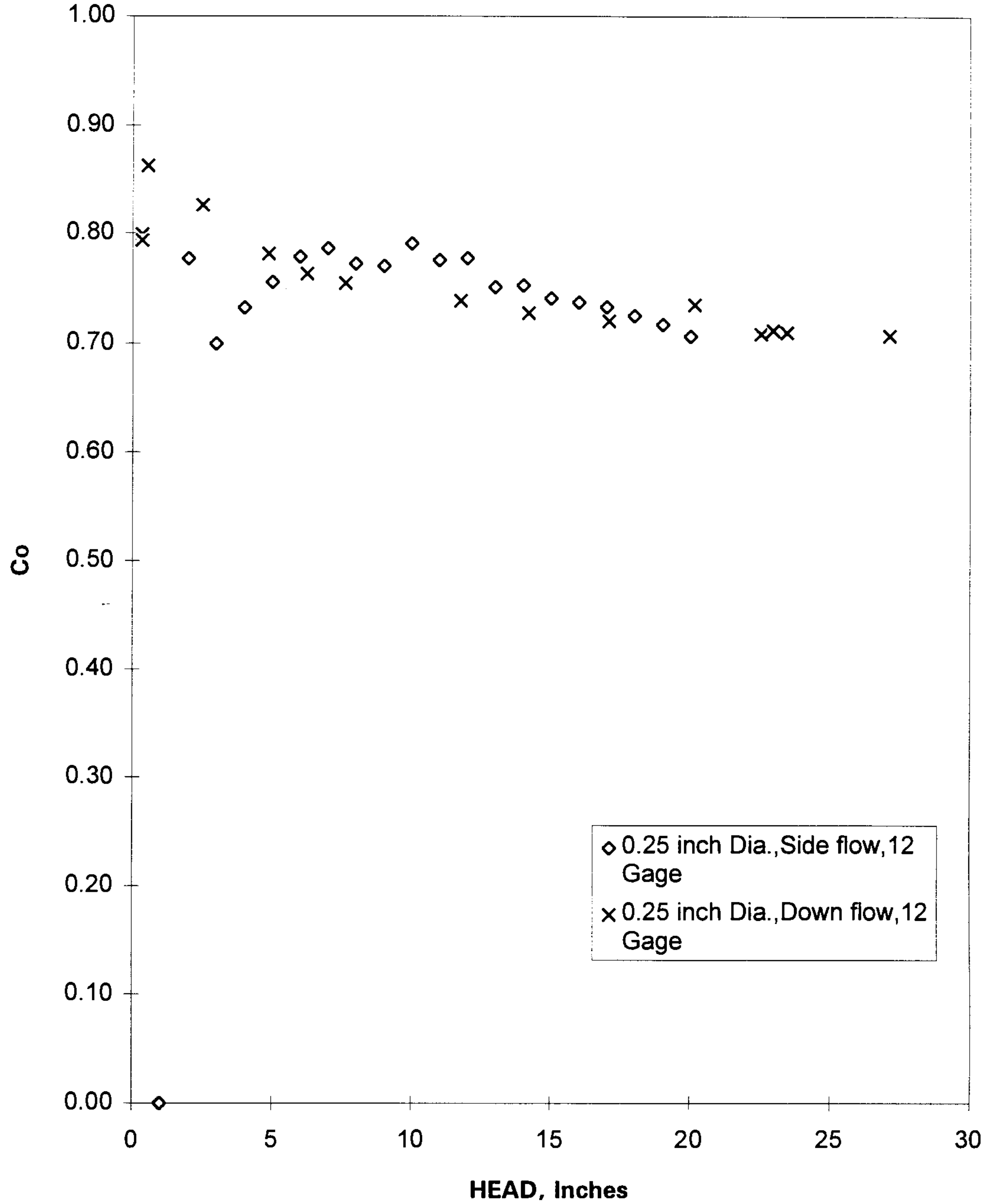


Figure 5-17 Comparison of side flow to down flow.

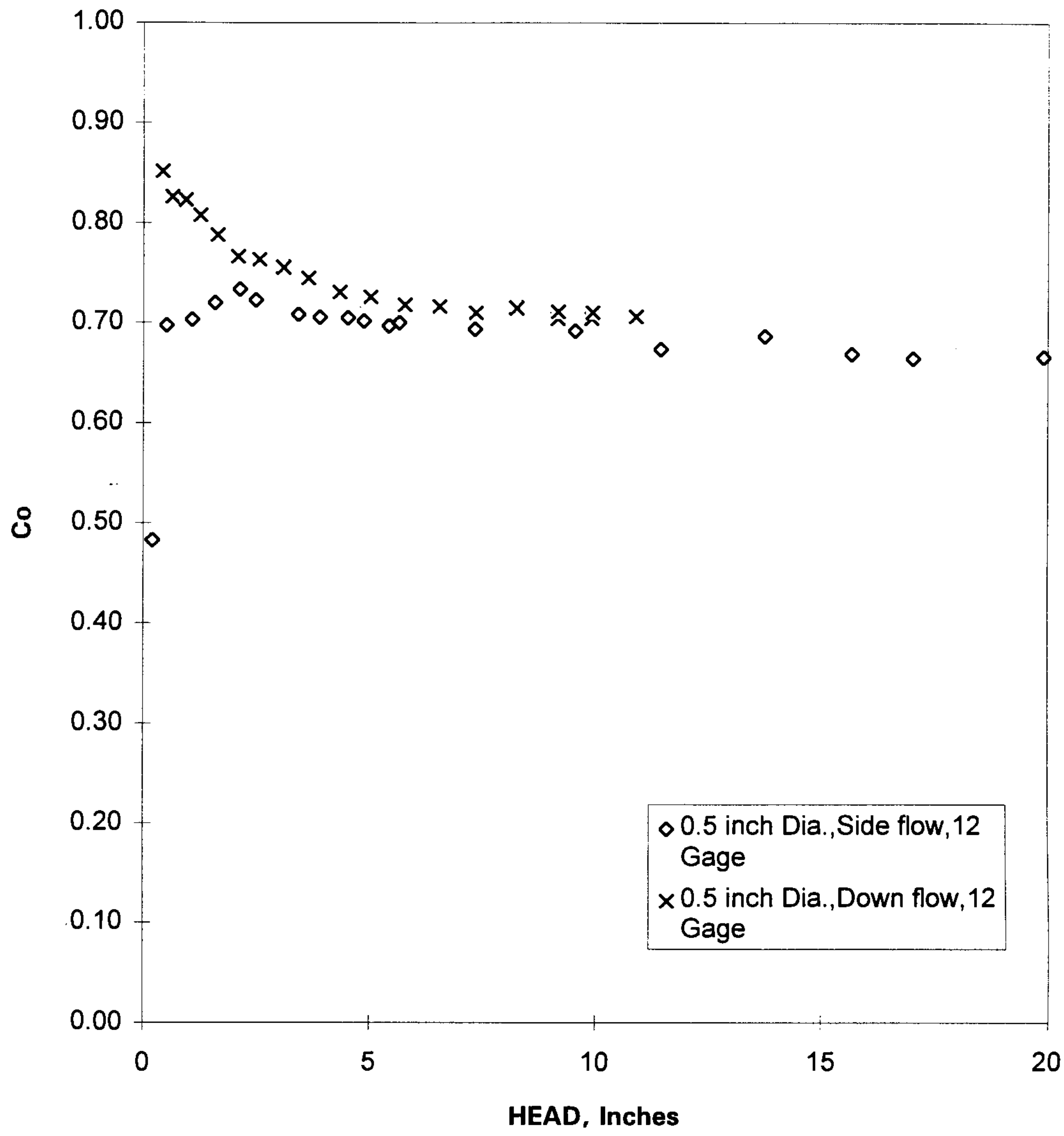


Figure 5-18 Comparison of side flow to down flow.

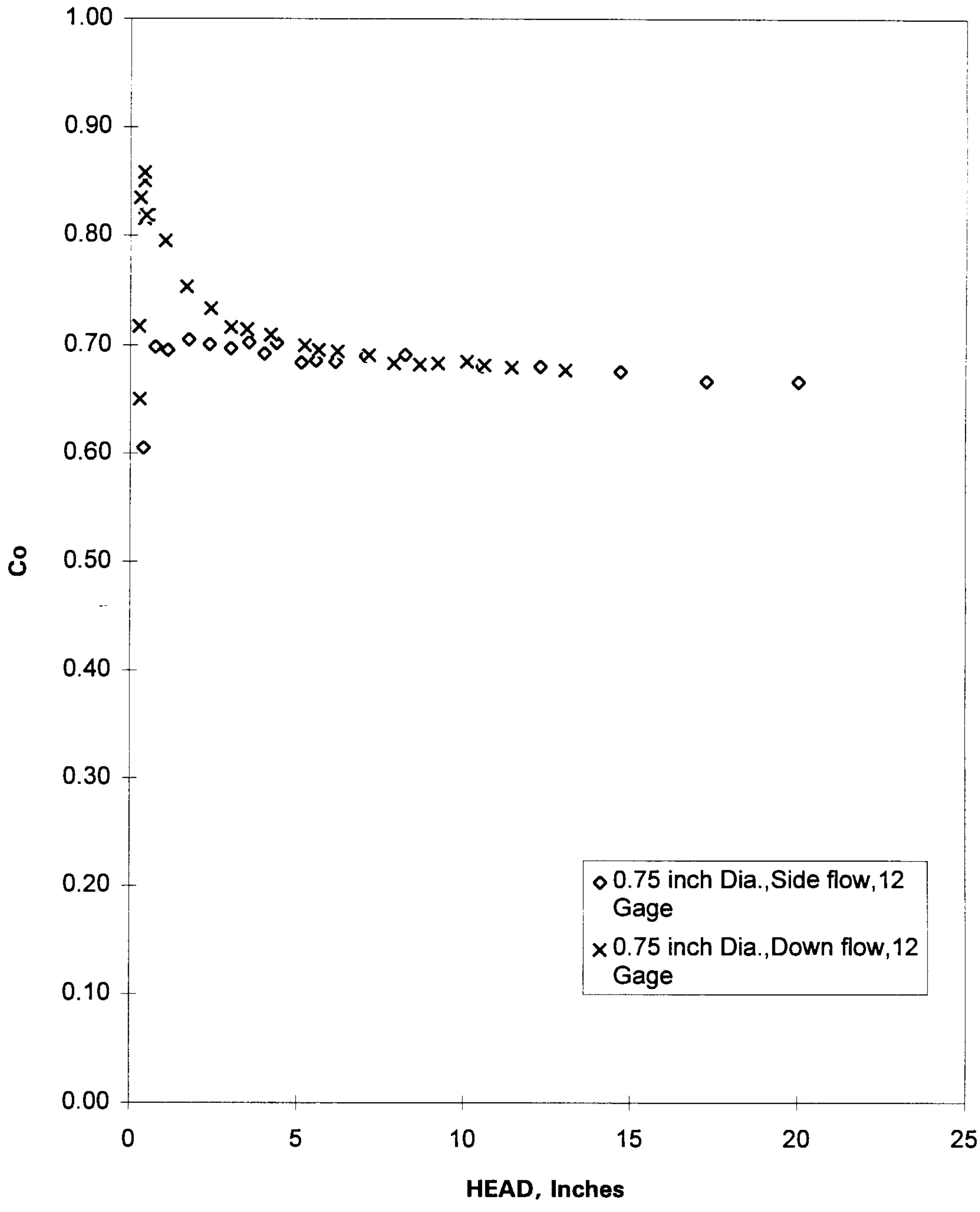


Figure 5-19 Comparison of side flow to down flow.

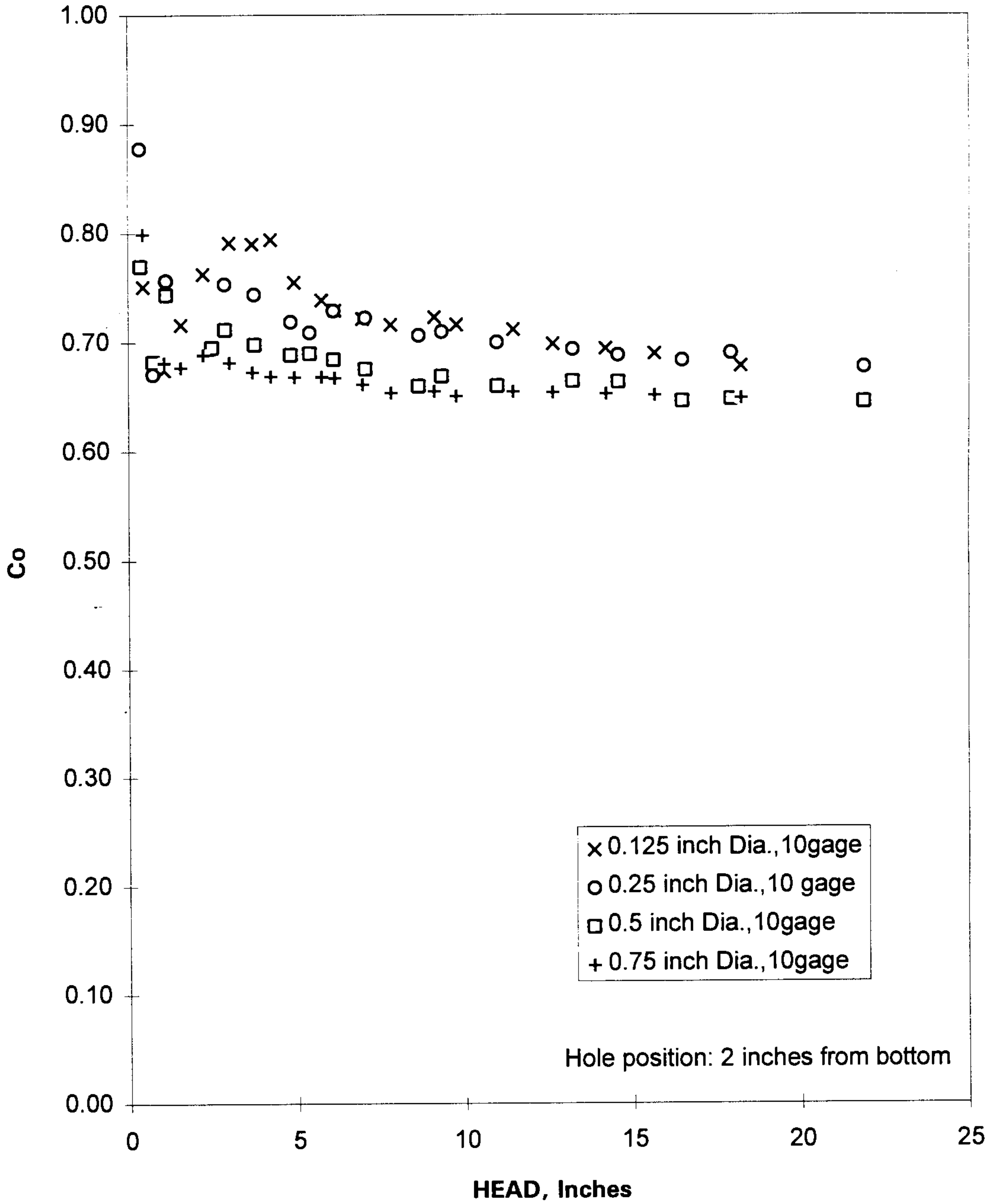


Figure 5-20 Effect of hole diameter.

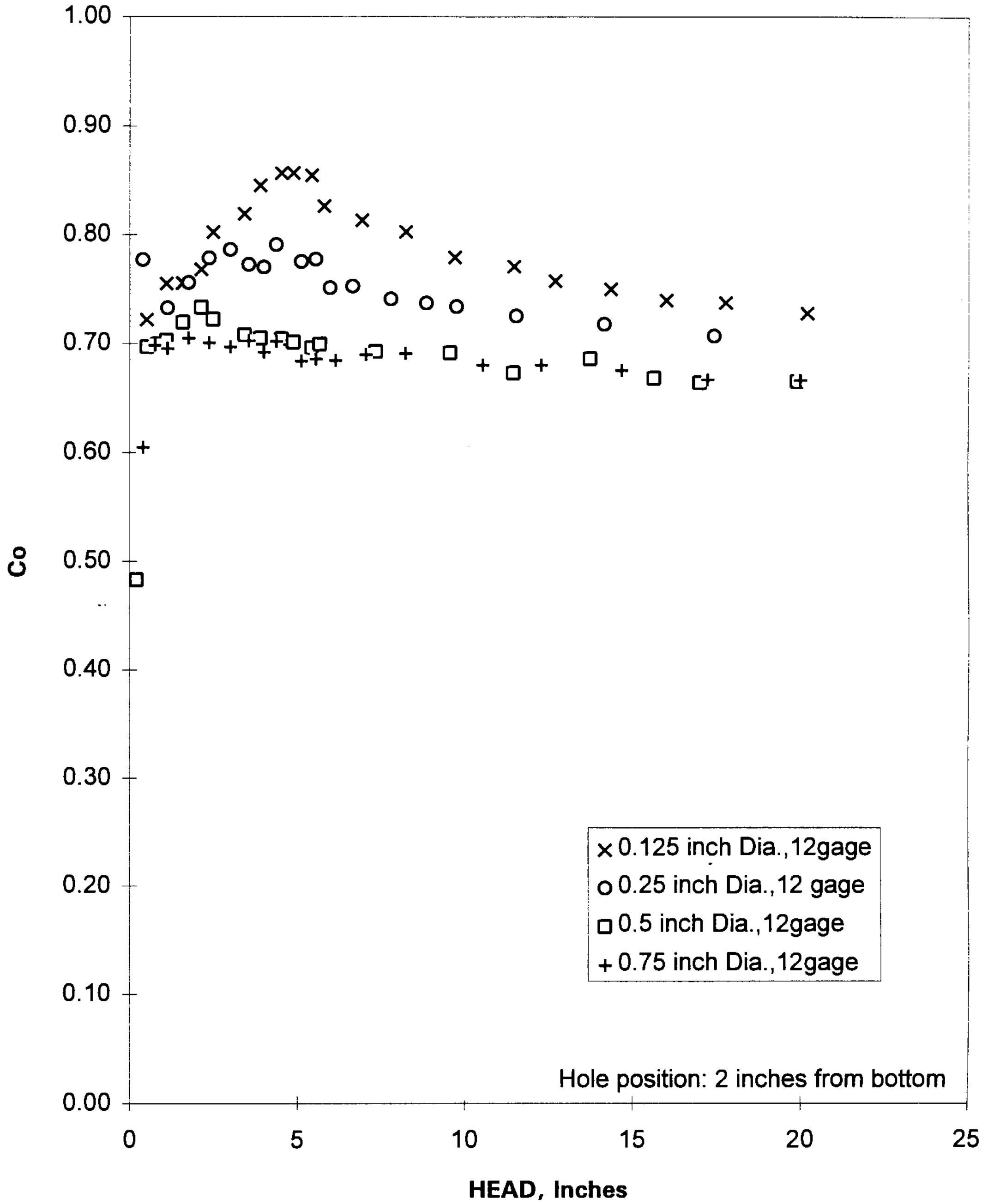


Figure 5-21 Effect of hole diameter.

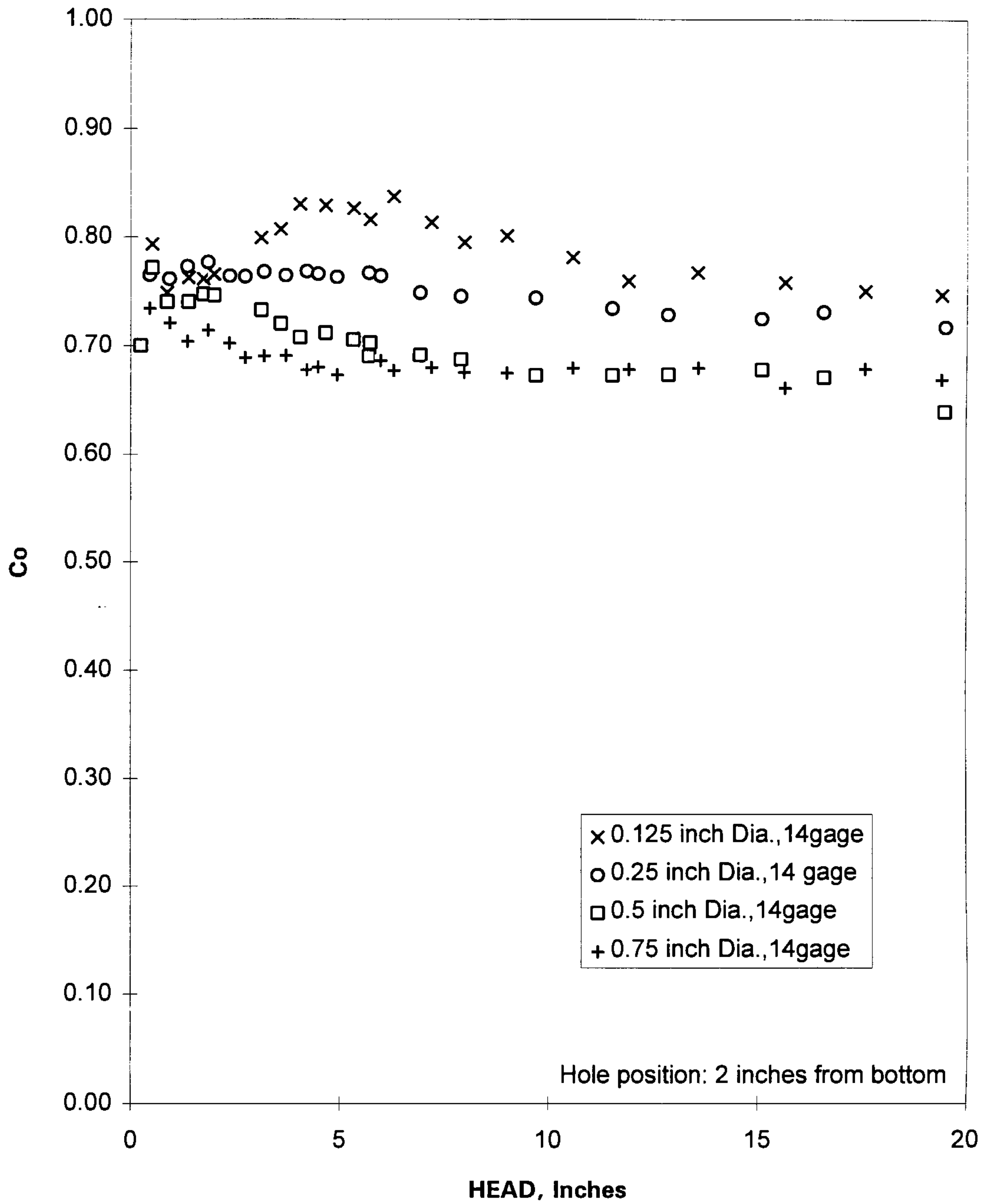


Figure 5-22 Effect of hole diameter.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The flow of a fluid through a side orifice plate was studied. Flow rate and head data were collected. These data were then reduced to orifice coefficients and Reynolds numbers. The following conclusions were drawn from the experiments :

1) There were no hysteresis effects and data for increasing heads were considered reliable. Only increasing head experiments were done after this conclusion.
2) The position of hole (2 inches from the bottom of the trough or 6 inches from the bottom of trough) did not really matter. Hence, only bottom holes were considered for further runs to reduce the number of experiments.
3) There was a reasonable effect due to the side wall on the 0.75 inch diameter hole which was closer to the side wall (plates 1 and 3 (figure 3-3)). So, for the 0.75 inch diameter hole, data obtained from plates 2, 4 and 5 (figure 3-4) were considered reliable.
4) There was a negligible effect on orifice coefficients if two holes were run simultaneously as compared to single hole runs.
5) In general, as plate thickness increases the orifice coefficient decreases although there is very little difference between 12 gage and 14 gage. Also, the effect of plate thickness decreases as the hole size increases from 0.125 inch to 0.75 inch.

6) The comparisons of side flow and down flow for 12 gage and 14 gage plates show a general trend of the two curves approaching each other. The curves merge after particular head. The down flow orifice coefficients are always higher.

7) The orifice coefficient decreases as the orifice diameter increases for a given plate thickness.

8) There is an unstable region below an head of 2 inches. Data below this head are not reliable and reproducible and should not be considered for correlation purposes.

Recommendations

Side orifices are used to minimize plugging and its effect on distribution. Hence, further study on side orifice can provide valuable information necessary for design. The following suggestions are made for further research:

1) To develop a correlation for the orifice coefficient with the data available. The variables to be considered for correlation are liquid head, diameter and plate thickness.

2) Conduct tests for horizontal velocities and see the effect of horizontal velocity on distribution.

3) Conduct simultaneous runs for side holes and bottom holes and study the interactions.

4) Conduct hot water tests to check viscosity effects on side flow.

5) Change the inlet pipe locations to various positions in the trough and study the effects of horizontal velocity on orifice coefficient for different hole diameters and plate thickness.

6) Conduct tests on a multi-hole distributor trough having side and bottom holes to check the effect of hole interactions.

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APPENDIX 1

PLATE DIAMETER AND THICKNESS MEASUREMENTS

Five plates were used for the experimental purposes. All the orifices were measured by vernier calipers. Two sets of five readings were taken; one set was in the direction of punch and the other set was in the opposite direction of punch. A set of five readings were taken for thickness measurements. The average value was calculated and used for all calculations.

APPENDIX 1

SIDE ORIFICE PLATE HOLE DIAMETERS (INCHES)

PLATE #: 1 (12 Gage)

Table A1-1

HOLE NUMBER	TYPE	STANDARD DIAMETER	MEASURED HOLE DIAMETER, INCHES 1	2	3	4	5	6	7	8	9	10	AVG. DIA
2A	Deburred	0.25	0.252	0.252	0.253	0.252	0.25	0.251	0.249	0.251	0.252	0.25	0.2512
3A	Non-deburred	0.5	0.504	0.502	0.502	0.504	0.504	0.504	0.504	0.505	0.5	0.504	0.5035
3B	Non-deburred	0.5	0.502	0.504	0.504	0.504	0.504	0.504	0.504	0.504	0.504	0.502	0.5034
4A	Non-deburred	0.75	0.748	0.748	0.752	0.745	0.752	0.75	0.75	0.75	0.75	0.75	0.7495
4B	Non-deburred	0.75	0.751	0.748	0.75	0.748	0.751	0.75	0.751	0.749	0.75	0.75	0.7498

APPENDIX 1(CONTD.)

SIDE ORIFICE PLATE HOLE DIAMETERS (INCHES)

PLATE# :2 (12 Gage)

TABLE A1-2

HOLE NUMBER	TYPE	STANDARD DIAMETER	MEASURED HOLE DIAMETER, INCHES										AVG. DIA
			1	2	3	4	5	6	7	8	9	10	
1A	Non-deburred	0.125	0.127	0.125	0.128	0.124	0.128	0.129	0.128	0.131	0.128	0.129	0.1297
2A	Deburred	0.25	0.253	0.253	0.252	0.25	0.252	0.253	0.251	0.252	0.252	0.253	0.2521
3A	Non-deburred	0.5	0.504	0.504	0.504	0.504	0.503	0.505	0.504	0.502	0.505	0.504	0.5035
4A	Non-deburred	0.75	0.751	0.753	0.75	0.75	0.75	0.748	0.75	0.745	0.751	0.749	0.7497
4B	Non-deburred	0.75	0.751	0.748	0.75	0.751	0.752	0.748	0.75	0.75	0.749	0.753	0.7504

APPENDIX 1(CONTD.)

SIDE ORIFICE PLATE HOLE DIAMETERS (INCHES)

PLATE #: 3 (14 Gage)

TABLE A1-3

HOLE NUMBER	TYPE	STANDARD DIAMETER	MEASURED HOLE DIAMETER, INCHES										AVG. DIA
			1	2	3	4	5	6	7	8	9	10	
2A	Deburred	0.25	0.252	0.251	0.253	0.253	0.252	0.25	0.248	0.25	0.248	0.252	0.2509
3A	Non-deburred	0.5	0.504	0.501	0.504	0.504	0.505	0.502	0.504	0.502	0.502	0.502	0.503

APPENDIX 1(CONTD.)

SIDE ORIFICE PLATE HOLE DIAMETERS (INCHES)

PLATE #: 4 (14 Gage)

TABLE A1-4

HOLE NUMBER	TYPE	STANDARD DIAMETER	MEASURED HOLE DIAMETER, INCHES 1	2	3	4	5	6	7	8	9	10	AVG. DIA
1A	Non-deburred	0.125	0.127	0.123	0.128	0.123	0.128	0.125	0.128	0.125	0.123	0.126	0.1256
2A	Deburred	0.25	0.247	0.249	0.251	0.25	0.249	0.253	0.247	0.25	0.247	0.247	0.249
3A	Non-deburred	0.5	0.504	0.5	0.505	0.504	0.505	0.504	0.502	0.502	0.504	0.504	0.5024
4A	Non-deburred	0.75	0.749	0.749	0.75	0.751	0.75	0.75	0.75	0.75	0.75	0.75	0.7498

APPENDIX 1(CONTD.)

SIDE ORIFICE PLATE HOLE DIAMETERS (INCHES)

PLATE #: 5 (10 Gage)

TABLE A1-5

HOLE NUMBER	TYPE	STANDARD DIAMETER	MEASURED HOLE DIAMETER, INCHES										AVG.
			1	2	3	4	5	6	7	8	9	10	DIA
1A	Non-deburred	0.125	0.129	0.135	0.139	0.135	0.137	0.126	0.127	0.125	0.126	0.127	0.1308
2A	Non-deburred	0.25	0.253	0.25	0.252	0.25	0.25	0.247	0.25	0.25	0.25	0.251	0.2503
3A	Non-deburred	0.5	0.502	0.5	0.502	0.502	0.501	0.5	0.5	0.501	0.501	0.502	0.5011
4A	Non-deburred	0.75	0.751	0.753	0.751	0.752	0.751	0.749	0.75	0.748	0.746	0.748	0.7499

APPENDIX 1(CONTD.)

SIDE ORIFICE PLATE THICKNESS (INCHES)

TABLE A1-6

PLATE #	STD. THICKNESS	1	2	3	4	5	AVG. THICKNESS
1	0.109	0.111	0.106	0.109	0.108	0.106	0.108
2	0.109	0.105	0.106	0.107	0.107	0.104	0.1058
3	0.083	0.08	0.077	0.077	0.07	0.076	0.076
4	0.083	0.086	0.085	0.082	0.08	0.082	0.083
5	0.141	0.141	0.145	0.144	0.15	0.15	0.146

APPENDIX 2

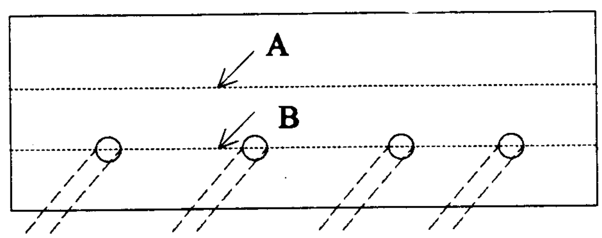
FLOW METER CALIBRATION
TABLE A2-1

FLOW RATE MEASURED GPM (A)	FLOWMETER READING GPM (B)	ABS. PERCENT ERROR 100*(A-B)/A
1.5694	1.375	12.39
1.623	1.451	10.60
1.8622	1.735	6.83
1.971	1.82	7.66
2.0631	1.96	5.00
2.174	2.11	2.94
2.207	2.085	5.53
2.2276	2.15	3.48
2.396	2.335	2.55
2.4038	2.348	2.32
2.7465	2.66	3.15
3.3485	3.745	11.84
	AVG. % ERROR	6.19

APPENDIX 3

Derivation of Orifice Coefficient Equation

The Bernoulli equation is applied to stations A and B as shown in Figure A3-1.



A-Water level in trough

B-Base level (Location of orifice)

Figure A3-1 Flow System Showing Stations.

(Front View of Trough)

The main assumptions are:

1) Incompressible fluid

2) Steady state

3) Uniform flow across A and B

4) Pressures at A and B remain constant and are equal to the atmospheric pressure.

5) Frictional effects are negligible, i.e., they are not considered in the derivation but are incorporated through the orifice coefficient.

Bernoulli's Equation, using the above assumptions, can be written as

$$\frac{p_A}{\rho} + g\frac{Z_A}{g_c} + \frac{\alpha_A V_A^2}{2g_c} = \frac{P_B}{\rho} + \frac{g Z_B}{g_c} + \frac{\alpha V_B^2}{2g_c} \qquad \text{(A3-1)}$$

This reduces to

$$\frac{\alpha_A V_A^2 - \alpha_B V_B^2}{2g_c} = \frac{P_B - P_A}{\rho} + (Z_B - Z_A)\frac{g}{g_c} \qquad \text{(A3-2)}$$

For an incompressible fluid , we can assume the density to be constant. The continuity equation then gives

$$-(Va/Vb) = \{(\pi D_B^2/4)(N)\}/A_T = \beta^2 \qquad \text{(A3-3)}$$

where

$$D_A = 2R_A = 2\frac{A_T}{W_P} \qquad \text{(A3-4)}$$

R_A = radius, m or ft

A_T = cross section area of the stream at the surface in the trough, m^2 or ft^2

W_P = wetted perimeter, m or ft

D_B = d = diameter of orifice

Substituting (A3-3) in (A3-2)

$$\frac{\alpha_A \beta^4 V_B^2 - \alpha_B V_B^2}{2g_c} = \frac{P_B - P_A}{\rho} + (Z_B - Z_A)\frac{g}{g_c} \qquad \text{(A3-5)}$$

$$V_B^2(\alpha_A \beta^4 - \alpha_B) = \frac{P_B - P_A}{\rho}(2g_c) + (Z_B - Z_A)2g \qquad \text{(A3-6)}$$

Since $P_A = P_B = P_{atmosphere}$ and $Z_A - Z_B = h$ = liquid level above the orifice, eqn(A3-6) becomes

$$V_B^2\left(\alpha_A \beta^4 - \alpha_B\right) = -2gh \quad \text{(A3-7)}$$

$$V_B^2 = \frac{-2gh}{\left(\alpha_A \beta^4 - \alpha_B\right)} \quad \text{(A3-8)}$$

The effects of jet contraction, kinetic energy correction and friction are incorporated in an orifice coefficient, C_o. Eqn(A3-8) becomes

$$V_B = \frac{C_o}{\sqrt{1-\beta^4}}\sqrt{2gh} \quad \text{(A3-9)}$$

This is the equation for determining the orifice coefficient.

For our case $\beta \ll 1$, so eqn (A3-9) becomes

$$V_B = C_o\sqrt{2gh} \quad \text{(A3-10)}$$

APPENDIX 4

EXPERIMENTAL DATA

All experimental data collected are documented here. The data collected were in terms of head in cm., volume of liquid collected in ml, the time of collection in seconds and the liquid temperature in degrees Fahrenheit. This data was then converted to orifice coefficients and Reynolds numbers.

TABLE A4-1

Plate #: 1
Hole Diameter: 0.7498 in.
Plate Thickness: 12 Gage
Liquid: Water
Increasing Head

Date: 07/07/94
Liquid Temp.: 77.5 F
Liquid Density: 996.967 Kg/Cu.m
Liquid Viscosity: 0.8776 cp
Hole Position: 5.08 cm from bottom

LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
5.2	0.02	438	17.11	0.405	1778	1.4331
5.4	0.22	508	13.88	0.580	2611	0.6179
5.6	0.42	1100	20.85	0.836	3817	0.6452
5.75	0.57	1240	20.61	0.954	4410	0.6316
5.95	0.77	1640	20.57	1.264	5844	0.7201
6.05	0.87	1790	20.51	1.383	6397	0.7416
7	1.82	1950	15.41	2.006	9396	0.7434
8.7	3.52	3355	20.57	2.586	12268	0.6891
10.55	5.37	4152	20.65	3.187	15314	0.6876
11.9	6.72	4635	20.75	3.541	17015	0.6830
14.85	9.67			4.235	20351	0.6810
16.7	11.52			4.541	21820	0.6689
20.55	15.37			5.246	25208	0.6691
23.3	18.12			5.636	27083	0.6620
26.55	21.37			6.124	29427	0.6624
30	24.82			6.584	31638	0.6608
33.5	28.32			6.895	33133	0.6479
39.25	34.07			7.481	35946	0.6408
42.2	37.02	7806	15.56	7.952	37728	0.6535
49.85	44.67	7422	13.52	8.702	41285	0.6510

TABLE A4-2

Plate #: 1
Hole Diameter: 0.7498 in.
Plate Thickness: 12 Gage
Liquid: Water
Decreasing Head

Date: 07/07/94
Liquid Temp.: 78.0 F
Liquid Density: 996.9 Kg/Cu.m
Liquid Viscosity: 0.8888 cp
Hole Position: 5.08 cm from bottom

LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
49.85	44.67	7422	13.52	8.702	41175	0.6510
45.3	40.12	7948	14.88	8.468	40063	0.6684
38.6	33.42	7763	15.89	7.745	36644	0.6699
30.6	25.42	7209	17.18	6.652	31071	0.6597
20.85	15.67	6157	18.13	5.383	25146	0.6799
18	12.82	6242	20.65	4.792	22672	0.6691
14	8.82	5133	20.87	3.899	18447	0.6564
10.5	5.32	4209	21.51	3.102	14675	0.6724
9.25	4.07	3469	21.25	2.588	12245	0.6414
7.9	2.72	2844	21.4	2.107	9967	0.6386
6.15	0.97	1650	20.18	1.296	6211	0.6580
5.85	0.67	1240	20.77	0.946	4535	0.5781
5.3	0.12	600	22.3	0.427	2044	0.6156

TABLE A4-3

Plate #: 1
Hole Diameter: 0.7495 in.
Plate Thickness: 12 Gage
Liquid: Water
Increasing Head

Date: 07/11/94
Liquid Temp.: 77.0 F
Liquid Density: 997.045 Kg/Cu.m
Liquid Viscosity:0.9003 cp
Hole Position:15.25 cm from bottom

LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
15.55	0.2	940	30.34	0.491	2178	0.5491
15.65	0.3	1340	30.58	0.695	3121	0.6341
15.8	0.45	1780	30.83	0.915	4166	0.6822
16.3	0.95	1980	20.62	1.522	7020	0.7809
16.95	1.6	1890	15.47	1.937	9048	0.7655
18.35	3	2030	12.71	2.532	11981	0.7309
19.9	4.55	2115	11.24	2.983	14115	0.6992
21.55	6.2			3.410	16136	0.6847
24	8.65			4.001	18934	0.6802
26	10.65			4.392	20784	0.6729
28.5	13.15			4.882	22806	0.6731
30.9	15.55	6850	20.5	5.297	24747	0.6716
36.7	21.35	7333	18.78	6.190	28919	0.6698
39.5	24.15	7888	18.79	6.443	30489	0.6555
42.9	27.55			6.884	32574	0.6557
47.35	32			7.346	34762	0.6493
49.75	34.4			7.655	36222	0.6525
59.5	44.15			8.474	40101	0.6377

TABLE A4-4

Plate #: 1
Hole Diameter: 0.7495 in.
Plate Thickness: 12 Gage
Liquid: Water
Decreasing Head

Date: 07/11/94
Liquid Temp.: 79.0 F
Liquid Density: 996.968 Kg/Cu.m
Liquid Viscosity: 0.8776 cp
Hole Position: 15.25 cm from bottom

LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
59.5	44.15			8.474	40098	0.6377
56.15	40.8			8.189	38255	0.6410
50.15	34.8			7.649	35732	0.6483
44	28.65			6.999	32694	0.6538
37.6	22.25			6.263	29637	0.6639
33.1	17.75			5.536	26197	0.6571
28.5	13.15			4.844	22921	0.6679
25.7	10.35			4.409	20862	0.6852
24.15	8.8			4.039	19109	0.6807
22.4	7.05			3.651	17277	0.6876
20.6	5.25			3.118	14942	0.6804
19	3.65			2.613	12520	0.6837
18.1	2.75			2.271	10884	0.6848
17.5	2.15			1.927	9351	0.6570
16.45	1.1			1.191	5778	0.5675
16.3	0.95			1.046	5074	0.5363
16.1	0.75	1700	30.07	0.896	4349	0.5174
15.85	0.5	1260	30.49	0.655	3179	0.4632
15.5	0.15	680	30.66	0.352	1706	0.4539

TABLE A4-5

Plate #: 1
Hole Diameter: 0.7498 in.
Plate Thickness: 12 Gage
Liquid: Water
Increasing Head

Date: 07/19/94
Liquid Temp.: 79.13 F
Liquid Density: 997.045 Kg/Cu.m
Liquid Viscosity: 0.8761 cp
Hole Position: 15.25 cm from bottom

LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
15.65	0.3	850	30.37	0.444	2073	0.4050
15.9	0.55	1260	31.47	0.635	2965	0.4279
16.05	0.7	1370	26.48	0.820	3881	0.4901
16.55	1.2	1990	20.1	1.569	7522	0.7163
17.75	2.4	1820	13.07	2.207	10579	0.7124
19.2	3.85	2145	12.38	2.747	13331	0.6999
21.1	5.75	2030	9.61	3.349	16253	0.6982
22.7	7.35	1900	8.07	3.732	18115	0.6883
26.4	11.05			4.510	21887	0.6783
28.95	13.6			4.990	24218	0.6765
33	17.65			5.616	27256	0.6683
37.1	21.75			6.174	29968	0.6620
43.7	28.35			6.927	33199	0.6505
50.25	34.9			7.573	36297	0.6410
56.5	41.15			8.141	39018	0.6346

TABLE A4-6

Plate #: 2
Hole Diameter: 0.7497 in.
Plate Thickness: 12 Gage
Liquid: Water
Increasing Head

Date: 07/12/94
Liquid Temp.: 80.23 F
Liquid Density: 996.568 Kg/Cu.m
Liquid Viscosity: 0.8641 cp
Hole Position: 5.08 cm from bottom

LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
5.2	0.02	495	20.45	0.384	1746	1.3570
5.45	0.27	945	22.43	0.668	3119	0.6428
5.7	0.52	1190	20.45	0.922	4475	0.6398
5.9	0.72	1640	21.59	1.204	5915	0.7097
6.3	1.12	1760	18.13	1.539	7560	0.7272
7.1	1.92	2000	15.54	2.040	10022	0.7364
8.05	2.87	2100	13.16	2.530	12427	0.7468
10.35	5.17	2230	10.95	3.228	16058	0.7101
12.05	6.87			3.722	18514	0.7102
13.2	8.02			3.864	19219	0.6824
15	9.82			4.315	21461	0.6886
15.6	10.42			4.439	22078	0.6877
19.6	14.42			5.310	26412	0.6993
20.8	15.62			5.412	26919	0.6848
23.1	17.92			5.843	27990	0.6903
26.1	20.92			6.323	30291	0.6914
32	26.82			7.045	33748	0.6804
36.4	31.22			7.600	36871	0.6803
42.5	37.32			8.254	40043	0.6757
49	43.82			8.824	42808	0.6667
56	50.82			9.498	46076	0.6663

TABLE A4-7

Plate #: 2
Hole Diameter: 0.7504 in.
Plate Thickness: 12 Gage
Liquid: Water
Increasing Head

Date: 07/12/94
Liquid Temp.: 81.5 F
Liquid Density: 996.374 Kg/Cu.m
Liquid Viscosity: 0.8505 cp
Hole Position: 15.25 cm from bottom

LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
15.65	0.3	1150	30.45	0.599	2975	0.5456
15.9	0.55	1560	30.48	0.811	4082	0.5461
16.2	0.85	1840	24.35	1.198	6101	0.6486
16.3	0.95	1840	20.65	1.412	7194	0.7234
17	1.65			1.827	9306	0.7101
17.7	2.35			2.239	11401	0.7290
20.1	4.75			3.046	15515	0.6978
21.4	6.05			3.552	18312	0.7209
24.2	8.85			4.275	22037	0.7173
26.55	11.2			4.791	24700	0.7146
29.15	13.8			5.277	27204	0.7091
33.35	18			5.976	30434	0.7031
36.1	20.75			6.328	31833	0.6934
40.5	25.15			6.917	34373	0.6886
46.15	30.8			7.579	37658	0.6817
51	35.65			8.161	40053	0.6823
60.25	44.9			8.999	44163	0.6704

TABLE A4-8

Plate #: 1
Hole Diameter: 0.5035 in.
Plate Thickness: 12 Gage
Liquid: Water
Increasing Head

Date: 07/19/94
Liquid Temp.: 80.5 F
Liquid Density: 996.54 Kg/Cu.m
Liquid Viscosity: 0.8611 cp
Hole Position: 5.08 cm from bottom

LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
5.3	0.12	290	30.97	0.148	1032	0.4753
5.55	0.37	525	30.54	0.273	1944	0.4969
5.85	0.67	940	25.98	0.574	4144	0.7773
7.05	1.87	1490	25.53	0.925	6685	0.7505
9.4	4.22	1860	21.27	1.386	10143	0.7485
11	5.82	1970	19.24	1.623	11876	0.7463
14.45	9.27	1950	15.68	1.971	14605	0.7182
17.5	12.32	1960	14.29	2.174	15909	0.6871
19.6	14.42	2030	13.43	2.396	17751	0.6999
23.85	18.67			2.700	20003	0.6931
29.5	24.32			3.075	23064	0.6917
34.3	29.12			3.275	24565	0.6732
40.1	34.92			3.655	27753	0.6861
44.95	39.77			3.800	28854	0.6684
48.4	43.22			3.935	29879	0.6640
55.75	50.57			4.265	32385	0.6653

TABLE A4-9

Plate #: 1
Hole Diameter: 0.5034 in.
Plate Thickness: 12 Gage
Liquid: Water
Increasing Head

Date: 07/20/94
Liquid Temp.: 80.5 F
Liquid Density: 996.54 Kg/Cu.m
Liquid Viscosity: 0.8611 cp
Hole Position:15.25 cm from bottom

LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
5.3	0.12	290	30.97	0.148	1032	0.4753
5.55	0.37	525	30.54	0.273	1944	0.4969
5.85	0.67	940	25.98	0.574	4144	0.7773
7.05	1.87	1490	25.53	0.925	6685	0.7505
9.4	4.22	1860	21.27	1.386	10143	0.7485
11	5.82	1970	19.24	1.623	11876	0.7463
14.45	9.27	1950	15.68	1.971	14605	0.7182
17.5	12.32	1960	14.29	2.174	15909	0.6871
19.6	14.42	2030	13.43	2.396	17751	0.6999
23.85	18.67			2.700	20003	0.6931
29.5	24.32			3.075	23064	0.6917
34.3	29.12			3.275	24565	0.6732
40.1	34.92			3.655	27753	0.6861
44.95	39.77			3.800	28854	0.6684
48.4	43.22			3.935	29879	0.6640
55.75	50.57			4.265	32385	0.6653

TABLE A4-10

Plate #: 1
Hole Diameter: 0.2512 in.
Plate Thickness: 12 Gage
Liquid: Water
Increasing Head

Date: 07/21/94
Liquid Temp.: 84.5 F
Liquid Density: 995.886 Kg/Cu.m
Liquid Viscosity: 0.8196 cp
Hole Position: 5.08 cm from bottom

LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
5.8	0.62	295	31.4	0.149	2237	0.8426
7.8	2.62	455	25.74	0.280	4261	0.7712
11.3	6.12	760	26.84	0.449	6909	0.8083
15.25	10.07	940	26.49	0.563	8764	0.7897
16.55	11.37	980	26.5	0.586	9134	0.7745
20.4	15.22	1120	26.99	0.658	10373	0.7511
22.1	16.92	1170	26.69	0.695	10958	0.7526
25	19.82	1240	26.54	0.741	11679	0.7411
27.7	22.52	1330	26.84	0.786	12387	0.7374
30	24.82	1400	27.05	0.820	12937	0.7336
34.5	29.32	1480	26.61	0.882	13903	0.7253
41.2	36.02	1620	26.55	0.967	15252	0.7179
49.5	44.32	1820	27.31	1.056	16459	0.7069

TABLE A4-11

Plate #: 1
Hole Diameter: 0.7495 in.
Plate Thickness: 12 Gage
Liquid: Water
Increasing Head

Date: 07/25/94
Liquid Temp.: 79.5 F
Liquid Density: 996.755 Kg/Cu.m
Liquid Viscosity: 0.8721 cp
Hole Position: 5.08 cm from bottom

LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
5.2	0.02	750	32.11	0.370	1797	1.3101
5.35	0.17	985	30.23	0.517	2539	0.6269
5.5	0.32	1200	27.73	0.686	3372	0.6068
5.7	0.52	1410	25.9	0.863	4295	0.5989
6	0.82	2190	25.76	1.348	6791	0.7447
6.5	1.32	2030	19.76	1.629	8307	0.7093
7.5	2.32	2270	16.73	2.151	10972	0.7066
9.2	4.02	4437	25.11	2.801	14463	0.6991
11.75	6.57	5816	26.16	3.524	18421	0.6881
13.55	8.37			4.010	20706	0.6936
17.2	12.02			4.761	24286	0.6872
19.7	14.52			5.232	26366	0.6871
22.5	17.32			5.693	28332	0.6845
26.05	20.87			6.183	30392	0.6773
29	23.82			6.596	32018	0.6763
33	27.82			6.999	33976	0.6640
38	32.82			7.562	36248	0.6605
43.1	37.92			8.088	38769	0.6573

TABLE A4-12

Plate #: 1
Hole Diameter: 0.5034 in.
Plate Thickness: 12 Gage
Liquid: Water
Increasing Head

Date: 07/25/94
Liquid Temp.: 79.5 F
Liquid Density: 996.755 Kg/Cu.m
Liquid Viscosity: 0.8721 cp
Hole Position: 5.08 cm from bottom

LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
5.2	0.02	150	31.24	0.076	550	0.5970
5.35	0.17	325	30.96	0.166	1218	0.4477
5.5	0.32	455	25.94	0.278	2035	0.5452
5.7	0.52	490	19.35	0.401	2975	0.6175
6	0.82	1000	25.04	0.633	4749	0.7755
6.5	1.32	1300	26.52	0.777	5902	0.7502
7.5	2.32	1640	26.05	0.998	7579	0.7268
9.2	4.02	2190	26.74	1.298	9981	0.7183
11.75	6.57	2602	25.39	1.625	12643	0.7032
13.55	8.37	3072	26.58	1.832	14084	0.7024
17.2	12.02	3697	27.09	2.164	16432	0.6922
19.7	14.52	4039	26.98	2.373	17802	0.6908
22.5	17.32	4280	26.09	2.601	19272	0.6932
26.05	20.87	4622	26.19	2.797	20473	0.6793
29	23.82	4906	25.95	2.997	21660	0.6812
33	27.82	5262	26.03	3.204	23158	0.6739
38	32.82	5646	26.06	3.434	24508	0.6650
43.1	37.92	6215	26.69	3.691	26341	0.6649

TABLE A4-13

Plate #: 1
Hole Diameter: 0.7498 in.
Plate Thickness: 12 Gage
Liquid: Water
Increasing Head

Date: 07/26/94
Liquid Temp.: 78.00 F
Liquid Density: 996.901 Kg/Cu.m
Liquid Viscosity: 0.8888 cp
Hole Position: 15.25 cm from bottom

LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
15.55	0.2	740	20.84	0.563	2629	0.6293
15.7	0.35	1160	25.57	0.719	3403	0.6078
15.95	0.6	1500	25.68	0.926	4381	0.5977
16.2	0.85	2303	26.44	1.381	6618	0.7490
17	1.65	3000	25.46	1.868	8951	0.7271
18.1	2.75	3868	25.58	2.397	11485	0.7226
19.5	4.15	4721	25.7	2.912	13953	0.7147
20.8	5.45	5346	26.01	3.258	15614	0.6979
24.6	9.25	6882	25.8	4.228	20262	0.6951
27.45	12.1	6199	21.05	4.669	22089	0.6711
30.95	15.6	6882	20.56	5.306	25105	0.6717
34.3	18.95	7436	20.15	5.850	28034	0.6720
37.8	22.45	8247	20.49	6.380	30574	0.6733
40.95	25.6	8645	20.02	6.845	32802	0.6765
45.5	30.15	9072	19.73	7.289	34927	0.6637
51.1	35.75	8645	17.12	8.005	38359	0.6694

TABLE A4-14

Plate #: 1
Hole Diameter: 0.5035 in.
Plate Thickness: 12 Gage
Liquid: Water
Increasing Head

Date: 07/26/94
Liquid Temp.: 78.0 F
Liquid Density: 996.901 Kg/Cu.m
Liquid Viscosity: 0.8888 cp
Hole Position: 15.25 cm from bottom

LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
15.55	0.2	365	30.82	0.188	1306	0.4655
15.7	0.35	660	30.38	0.344	2426	0.6455
15.95	0.6	780	25.92	0.477	3361	0.6829
16.2	0.85	1365	35.11	0.616	4398	0.7412
17	1.65	1621	30.02	0.856	6108	0.7389
18.1	2.75	1749	25.73	1.077	7689	0.7205
19.5	4.15	2204	26.39	1.324	9447	0.7206
20.8	5.45	2389	25.51	1.484	10593	0.7050
24.6	9.25	3128	25.85	1.918	13689	0.6994
27.45	12.1	3299	24.05	2.174	15320	0.6931
30.95	15.6	3597	23.38	2.439	17185	0.6847
34.3	18.95	3512	20.8	2.677	19101	0.6818
37.8	22.45	3853	21.01	2.907	20747	0.6804
40.95	25.6	3967	20.26	3.104	22150	0.6802
45.5	30.15	4934	23.37	3.347	23883	0.6758
51.1	35.75	4692	20.54	3.621	25842	0.6716

TABLE A4-15

Plate #: 1
Hole Diameter: 0.7495 in.
Plate Thickness: 12 Gage
Liquid: Water
Increasing Head

Date: 07/27/94
Liquid Temp.: 77.5 F
Liquid Density: 996.967Kg/Cu.m
Liquid Viscosity: 0.8945 cp
Hole Position: 5.08 cm from bottom

LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
5.2	0.02	320	30.2	0.168	785	0.5943
6	0.82	1580	20.5	1.222	5932	0.6751
8	2.82	3114	20.5	2.408	11838	0.7175
9.45	4.27	3739	20.42	2.903	14272	0.7029
12.6	7.42	4777	20.09	3.769	18764	0.6925
16	10.82	5644	20.11	4.449	22149	0.6769
19.1	13.92	6142	19.57	4.975	24767	0.6673
22.7	17.52	6924	19.59	5.603	27891	0.6698
26.7	21.52	6313	15.82	6.325	31489	0.6823
30.3	25.12	6227	14.75	6.693	32904	0.6682
35	29.82	6896	15.29	7.149	34710	0.6551
40.5	35.32	7720	15.62	7.835	38040	0.6597
46.5	41.32	7407	13.99	8.393	40240	0.6534
50.3	45.12	8673	15.68	8.768	41505	0.6532

TABLE A4-16

Plate #: 1
Hole Diameter: 0.5035 in.
Plate Thickness: 12 Gage
Liquid: Water
Increasing Head

Date: 07/27/94
Liquid Temp.: 80.00 F
Liquid Density: 996.605 Kg/Cu.m
Liquid Viscosity: 0.9235 cp
Hole Position: 15.25 cm from bottom

LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
16	0.65	620	22.10	0.445	3294	0.6116
19.1	3.75	1730	21.24	1.291	9564	0.7393
22.7	7.35	2318	20.91	1.758	13019	0.7188
26.7	11.35	2660	20.01	2.107	15608	0.6935
30.3	14.95	3058	20.52	2.362	17282	0.6775
35	19.65	3414	20.37	2.656	19192	0.6645
40.5	25.15	3755	19.84	3.000	21675	0.6633
46.5	31.15	4324	20.77	3.300	23542	0.6556
50.3	34.95	4381	19.60	3.543	24956	0.6645

TABLE A4-17

Plate #: 2
Hole Diameter: 0.1273 in.
Plate Thickness: 12 Gage
Liquid: Water
Increasing Head

Date: 08/08/94
Liquid Temp.: 75.00 F
Liquid Density: 997.234 Kg/Cu.m
Liquid Viscosity: 0.9239 cp
Hole Position: 5.08 cm from bottom

LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
6.15	0.97	80	32.71	0.039	1013	0.6828
7.15	1.97	110	30.74	0.057	1502	0.7010
9.3	4.12	170	31.28	0.086	2311	0.7362
11.75	6.57	227.5	30.95	0.117	3125	0.7885
12.8	7.62	247.5	30.53	0.129	3492	0.8075
15	9.82	305	31.78	0.152	4188	0.8421
17.65	12.47	330	30.7	0.170	4751	0.8370
19.95	14.77	355	30.73	0.183	5106	0.8265
22.8	17.62	390	31.41	0.197	5487	0.8134
26.15	20.97	400	29.93	0.212	5907	0.8025
29.85	24.67	430	30.56	0.223	6219	0.7790
34.35	29.17	450	29.74	0.240	6687	0.7704
37.45	32.27	460	29.41	0.248	6825	0.7571
41.7	36.52	420	25.49	0.261	7189	0.7497
45.9	40.72	440	25.64	0.272	7488	0.7395
50.4	45.22	457.5	25.38	0.286	7865	0.7371
56.55	51.37	480	25.31	0.301	8275	0.7276

TABLE A4-18

Plate #: 3
Hole Diameter: 0.7498 in.
Plate Thickness: 14 Gage
Liquid: Water
Increasing Head

Date: 08/09/94
Liquid Temp.: 77.00 F
Liquid Density: 997.045 Kg./Cu.m
Liquid Viscosity: 0.9003 cp
Hole Position: 5.08 cm from bottom

LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
6.85	1.67	95	30.54	0.049	1375	0.6799
8.35	3.17	125	30.32	0.065	1846	0.6541
9.9	4.72	172.5	30.57	0.089	2559	0.7336
11.85	6.67	212.5	30.22	0.111	3230	0.7691
14.25	9.07	260	30.34	0.136	3986	0.8037
16.5	11.32	305	30.7	0.157	4621	0.8341
21.2	16.02	360	30.34	0.188	5519	0.8374
23.5	18.32	372.5	30.22	0.195	5310	0.8135
25.5	20.32	382.5	30.16	0.201	5535	0.7947
28.1	22.92	407.5	30.02	0.215	5924	0.8009
32.1	26.92	440	30.67	0.227	6343	0.7810
35.5	30.32	452.5	30.56	0.235	6546	0.7596
39.7	34.52	470	29.46	0.253	7053	0.7670
45	39.82	500	29.53	0.268	7486	0.7579
49.85	44.67	477.5	26.92	0.281	7842	0.7496
54.5	49.32	500	26.96	0.294	8199	0.7459

TABLE A4-19

Plate #: 3
Hole Diameter: 0.1256 in.
Plate Thickness: 14 Gage
Liquid: Water
Increasing Head

Date: 08/09/94
Liquid Temp.: 77.80 F
Liquid Density: 996.91 Kg./Cu.m
Liquid Viscosity: 0.8911 cp
Hole Position: 5.08 cm from bottom

LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
5.9	0.72	1410	25.49	0.877	4096	0.5167
6.85	1.67	1970	17.64	1.770	8376	0.6850
8.35	3.17	3697	25.45	2.303	11034	0.6466
9.9	4.72	4791	25.46	2.983	14478	0.6866
11.85	6.67	5445	24.29	3.554	17464	0.6880
14.25	9.07	5218	20.35	4.065	19974	0.6748
16.5	11.32	5886	20.37	4.581	22510	0.6807
21.2	16.02	6753	19.74	5.423	24685	0.6775
23.5	18.32	7507	20.44	5.822	26847	0.6801
25.5	20.32	7592	19.76	6.091	28086	0.6756
28.1	22.92	7791	19.11	6.463	30190	0.6750
32.1	26.92	8673	19.49	7.054	32951	0.6798
35.5	30.32	9071	19.24	7.474	34911	0.6786
39.7	34.52	9853	19.56	7.985	37300	0.6795
45	39.82	8900	16.91	8.344	38974	0.6611
49.85	44.67	8900	15.55	9.073	42383	0.6788
54.5	49.32	9284	15.67	9.392	43873	0.6687

TABLE A4-20

Plate #: 4
Hole Diameter: 0.2509 in.
Plate Thickness: 14 Gage
Liquid: Water
Increasing Head

Date: 08/10/94
Liquid Temp.: 79.0 F
Liquid Density: 996.755 Kg/Cu.m
Liquid Viscosity: 0.8776 cp
Hole Position: 5.08 cm from bottom

LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
5.6	0.42	75	30.52	0.039	544	0.2684
6.5	1.32	337.5	30.44	0.176	2485	0.6831
7.5	2.32	500	30.27	0.262	3749	0.7676
10	4.82	710	30.44	0.370	5361	0.7520
12.9	7.72	910	30.58	0.472	6927	0.7581
15	9.82	1060	31.13	0.540	7926	0.7692
19.7	14.52	1260	30.52	0.654	9609	0.7669
22.8	17.62	1340	30.2	0.703	10328	0.7482
25.3	20.12	1420	30.08	0.748	10988	0.7450
29.85	24.67	1570	30.08	0.827	12149	0.7438
34.5	29.32	1700	30.27	0.890	13072	0.7342
37.9	32.72	1780	30.25	0.933	13696	0.7282
43.6	38.42	1930	30.41	1.006	14773	0.7248
47.35	42.17	1900	28.34	1.063	15605	0.7308
54.7	49.52	1820	25.54	1.130	16587	0.7168

TABLE A4-21

Plate #: 4
Hole Diameter: 0.503 in.
Plate Thickness: 14 Gage
Liquid: Water
Increasing Head

Date: 08/10/94
Liquid Temp.: 79.0 F
Liquid Density: 996.755 Kg/Cu.m
Liquid Viscosity: 0.8776 cp
Hole Position: 5.08 cm from bottom

LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
5.6	0.42	485	30.09	0.256	1779	0.4380
6.5	1.32	915	20.59	0.704	4968	0.6812
7.5	2.32	1300	20.38	1.011	7222	0.7376
10	4.82	1780	20.36	1.386	10024	0.7013
12.9	7.72	2050	18.1	1.795	13150	0.7179
15	9.82	2503	20.4	1.945	14245	0.6895
19.7	14.52	3015	20.17	2.369	17354	0.6908
22.8	17.62	3356	20.36	2.613	19139	0.6916
25.3	20.12	3555	20.3	2.776	20334	0.6876
29.85	24.67	3882	20.45	3.009	22042	0.6732
34.5	29.32	4081	19.72	3.281	24030	0.6732
37.9	32.72	4380	20.01	3.470	25414	0.6740
43.6	38.42	4920	20.61	3.785	27719	0.6784
47.35	42.17	4992	20.17	3.923	28733	0.6712
54.7	49.52	5205	20.37	4.050	29666	0.6395

TABLE A4-22

Plate #: 4
Hole Diameter: 0.7498 in.
Plate Thickness: 14 Gage
Liquid: Water
Increasing Head

Date: 08/15/94
Liquid Temp.: 76.83 F
Liquid Density: 997.045 Kg/Cu.m
Liquid Viscosity: 0.9023 cp
Hole Position: 5.08 cm from bottom

LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
6.35	1.17	2020	20.16	1.588	7137	0.7342
7.55	2.37	2843	20.3	2.220	10108	0.7211
8.65	3.47	3355	20.27	2.624	11945	0.7043
9.9	4.72	3981	20.33	3.104	14315	0.7143
11.2	6.02	4450	20.46	3.448	15900	0.7026
12.15	6.97	4720	20.56	3.639	17002	0.6892
13.3	8.12	5075	20.43	3.938	18398	0.6910
14.6	9.42	5331	19.91	4.245	20086	0.6915
15.9	10.72	5530	19.74	4.441	21016	0.6782
16.6	11.42	5715	19.69	4.601	21773	0.6808
17.75	12.57	6085	20.2	4.775	22885	0.6734
20.4	15.22	7435	22.01	5.355	25665	0.6863

TABLE A4-23

Plate #: 4
Hole Diameter: 0.249 in.
Plate Thickness: 14 Gage
Liquid: Water
Increasing Head

Date: 08/15/94
Liquid Temp.: 76.83 F
Liquid Density: 997.045 Kg/Cu.m
Liquid Viscosity: 0.9023 cp
Hole Position: 5.08 cm from bottom

LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
6.35	1.17	295	25.63	0.182	2469	0.7648
7.55	2.37	415	25.45	0.258	3543	0.7613
8.65	3.47	505	25.21	0.318	4353	0.7729
9.9	4.72	595	25.34	0.372	5169	0.7768
11.2	6.02	660	25.31	0.413	5741	0.7638
12.15	6.97	715	25.49	0.445	6255	0.7636
13.3	8.12	775	25.45	0.483	6791	0.7680
14.6	9.42	830	25.41	0.518	7378	0.7649
15.9	10.72	895	25.57	0.555	7906	0.7683
16.6	11.42	735	20.41	0.571	8134	0.7659
17.75	12.57	765	20.32	0.597	8613	0.7632
20.4	15.22	840	20.25	0.658	9490	0.7642

TABLE A4-24

Plate #: 4
Hole Diameter: 0.5024 in.
Plate Thickness: 12 Gage
Liquid: Water
Increasing Head

Date: 08/16/94
Liquid Temp.: 80.0 F
Liquid Density: 996.605 Kg/Cu.m
Liquid Viscosity: 0.8666 cp
Hole Position: 5.08 cm from bottom

LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
5.8	0.62	940	30.09	0.495	3541	0.7004
6.5	1.32	1530	30.46	0.796	5765	0.7718
7.4	2.22	1280	20.49	0.990	7170	0.7402
8.7	3.52	1620	20.59	1.247	9031	0.7403
9.6	4.42	1800	20.22	1.411	10346	0.7475
10.25	5.07	1880	19.75	1.509	11063	0.7463
13.1	7.92	2432	20.82	1.852	13577	0.7328
14.3	9.12	2461	19.97	1.953	14500	0.7203
15.5	10.32	2617	20.31	2.043	14976	0.7081
17.05	11.87	3158	22.72	2.203	16152	0.7121
18.75	13.57	2958	20.09	2.334	17115	0.7057
19.75	14.57	3072	20.22	2.409	17659	0.7027

TABLE A4-25

Plate #: 4
Hole Diameter: 0.1256 in.
Plate Thickness: 14 Gage
Liquid: Water
Increasing Head

Date: 08/16/94
Liquid Temp.: 80.0 F
Liquid Density: 996.605 Kg/Cu.m
Liquid Viscosity: 0.8666 cp
Hole Position: 5.08 cm from bottom

LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
6.5	1.32	97.5	30.22	0.051	1481	0.7932
7.4	2.22	120	30.39	0.063	1813	0.7486
8.7	3.52	155	30.61	0.080	2325	0.7624
9.6	4.42	172.5	30.44	0.090	2635	0.7614
10.25	5.07	190	31.14	0.097	2837	0.7654
13.1	7.92	242.5	30.45	0.126	3702	0.7993
14.3	9.12	262.5	30.41	0.137	4063	0.8074
15.5	10.32	292.5	30.97	0.150	4391	0.8304
17.05	11.87	307.5	30.41	0.160	4701	0.8290
18.75	13.57	327.5	30.38	0.171	5012	0.8266
19.75	14.57	332.5	30.14	0.175	5129	0.8164

TABLE A4-26

Plate #: 2
Hole Diameter: 0.7497 in.
Plate Thickness: 12 Gage
Liquid: Water
Increasing Head

Date: 08/17/94
Liquid Temp.: 81.0 F
Liquid Density: 996.452 Kg/Cu.m
Liquid Viscosity: 0.8558 cp
Hole Position: 5.08 cm from bottom

LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
6.2	1.02	1550	20.1	1.222	6005	0.6053
7.1	1.92	2020	16.54	1.936	9511	0.6988
8.05	2.87	3030	20.38	2.357	11578	0.6958
9.65	4.47	3755	19.96	2.983	14652	0.7055
11.2	6.02	4381	20.2	3.438	16891	0.7009
12.8	7.62	4950	20.39	3.849	18907	0.6973
14.2	9.02	5462	20.52	4.220	20730	0.7027
15.35	10.17	5562	19.97	4.415	21690	0.6924
16.3	11.12	5861	19.84	4.683	23004	0.7023
18.2	13.02	6288	20.19	4.937	24252	0.6842
19.3	14.12	6458	19.86	5.155	25324	0.6861

TABLE A4-27

Plate #: 2
Hole Diameter: 0.2521 in.
Plate Thickness: 12 Gage
Liquid: Water
Increasing Head

Date: 08/17/94
Liquid Temp.: 81.0 F
Liquid Density: 996.452 Kg/Cu.m
Liquid Viscosity: 0.8558 cp
Hole Position: 5.08 cm from bottom

LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
6.2	1.02	340	30.38	0.177	2592	0.7769
7.1	1.92	420	30.36	0.219	3204	0.7000
8.05	2.87	540	30.51	0.281	4099	0.7325
9.65	4.47	690	30.27	0.361	5279	0.7559
11.2	6.02	825	30.28	0.432	6310	0.7786
12.8	7.62	940	30.37	0.491	7168	0.7861
14.2	9.02	855	25.84	0.525	7663	0.7724
15.35	10.17	900	25.69	0.555	8113	0.7702
16.3	11.12	960	25.52	0.596	8712	0.7909
18.2	13.02	1020	25.56	0.633	9242	0.7754
19.3	14.12	1060	25.44	0.661	9649	0.7774

TABLE A4-28

Plate #: 2
Hole Diameter: 0.5039 in.
Plate Thickness: 12 Gage
Liquid: Water
Increasing Head

Date: 08/18/94
Liquid Temp.: 81.50 F
Liquid Density: 996.374 Kg/Cu.m
Liquid Viscosity: 0.8505 cp
Hole Position: 5.08 cm from bottom

LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
5.7	0.52	610	30.72	0.315	2300	0.4832
6.5	1.32	1390	30.44	0.724	5290	0.6975
7.95	2.77	2030	30.43	1.057	7729	0.7034
9.2	4.02	1679	20.41	1.304	9648	0.7199
10.6	5.42	1992	20.47	1.542	11413	0.7334
11.5	6.32	2105	20.34	1.641	12143	0.7226
13.9	8.72	2433	20.41	1.889	13982	0.7083
15.1	9.92	2547	20.12	2.006	14847	0.7052
16.7	11.52	2803	20.56	2.161	15990	0.7048
17.6	12.42	2888	20.49	2.234	16533	0.7018
19	13.82	3044	20.63	2.339	17311	0.6966

TABLE A4-29

Plate #: 2
Hole Diameter: 0.1277 in.
Plate Thickness: 12 Gage
Liquid: Water
Increasing Head

Date: 08/18/94
Liquid Temp.: 81.50 F
Liquid Density: 996.374 Kg/Cu.m
Liquid Viscosity: 0.8505 cp
Hole Position: 5.08 cm from bottom

LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
6.5	1.32	92.5	30.47	0.048	1388	0.7220
7.95	2.77	140	30.44	0.073	2103	0.7551
9.2	4.02	167.5	30.22	0.088	2566	0.7554
10.6	5.42	195	29.8	0.104	3029	0.7680
11.5	6.32	225	30.48	0.117	3417	0.8024
13.9	8.72	270	30.49	0.140	4099	0.8194
15.1	9.92	295	30.28	0.154	4510	0.8452
16.7	11.52	325	30.54	0.169	4926	0.8567
17.6	12.42	335	30.31	0.175	5116	0.8570
19	13.82	360	30.95	0.184	5384	0.8550

TABLE A4-30

Plate #: 5
Hole Diameter: 0.7499 in.
Plate Thickness: 10 Gage
Liquid: Water
Increasing Head

Date: 08/31/94
Liquid Temp.: 76.05 F
Liquid Density: 997.184 Kg/Cu.m
Liquid Viscosity: 0.9114 cp
Hole Position: 5.08 cm from bottom

LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
6.3	1.12	2274	21.31	1.692	7502	0.7991
7.9	2.72	2900	20.44	2.249	10105	0.6816
9.15	3.97	3468	20.37	2.699	12127	0.6771
10.85	5.67	4236	20.46	3.282	14941	0.6890
12.8	7.62	4861	20.47	3.765	17138	0.6817
14.55	9.37	5359	20.61	4.122	19010	0.6731
15.95	10.77	5558	20.05	4.394	20266	0.6693
17.75	12.57	6127	20.49	4.740	21860	0.6683
19.8	14.62	6567	20.35	5.116	23593	0.6688
20.8	15.62	6809	20.45	5.278	24658	0.6675
22.9	17.72	7065	20.1	5.572	26030	0.6616
25.05	19.87	7491	20.37	5.830	27235	0.6537
28.35	23.17	7918	19.9	6.307	29466	0.6550
30	24.82	8245	20.16	6.483	30287	0.6505
34.3	29.12	9083	20.37	7.069	33024	0.6548
37.3	32.12	9680	20.7	7.413	34633	0.6538
41.3	36.12	9837	19.88	7.844	36644	0.6524
45	39.82	10718	20.67	8.220	38401	0.6511
51.5	46.32	11685	20.99	8.824	41226	0.6481

TABLE A4-31

Plate #: 5
Hole Diameter: 0.1308 in.
Plate Thickness: 10 Gage
Liquid: Water
Increasing Head

Date: 08/31/94
Liquid Temp.: 76.05 F
Liquid Density: 996.967 Kg/Cu.m
Liquid Viscosity: 0.9114 cp
Hole Position: 5.08 cm from bottom

LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
6.3	1.12	90	29.49	0.048	1230	0.7511
7.9	2.72	130	30.43	0.068	1744	0.6747
9.15	3.97	165	30.11	0.087	2238	0.7163
10.85	5.67	212.5	30.48	0.111	2884	0.7626
12.8	7.62	255	30.42	0.133	3468	0.7909
14.55	9.37	282.5	30.42	0.147	3892	0.7902
15.95	10.77	305	30.49	0.159	4193	0.7939
17.75	12.57	312.5	30.4	0.163	4309	0.7552
19.8	14.62	330	30.43	0.172	4545	0.7387
20.8	15.62	337.5	30.49	0.175	4700	0.7295
22.9	17.72	365	31.29	0.185	4953	0.7217
25.05	19.87	372.5	30.39	0.194	5204	0.7162
28.35	23.17	407.5	30.51	0.212	5671	0.7227
30	24.82	417.5	30.49	0.217	5814	0.7159
34.3	29.12	447.5	30.34	0.234	6263	0.7119
37.3	32.12	462.5	30.42	0.241	6455	0.6987
41.3	36.12	487.5	30.42	0.254	6804	0.6945
45	39.82	432.5	25.88	0.265	7096	0.6898
51.5	46.32	450	25.4	0.281	7522	0.6780

TABLE A4-32

Plate #: 5
Hole Diameter: 0.5011 in.
Plate Thickness: 10 Gage
Liquid: Water
Increasing Head

Date: 08/31/94
Liquid Temp.: 77.0 F
Liquid Density: 997.045 Kg/Cu.m
Liquid Viscosity:0.9003 cp
Hole Position: 5.08 cm from bottom

LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
6.1	0.92	1060	25.48	0.659	4492	0.7697
7.05	1.87	1340	25.48	0.834	5753	0.6825
8.05	2.87	1820	25.63	1.126	7970	0.7438
11.5	6.32	2090	21.2	1.563	11206	0.6959
12.5	7.32	2317	21.35	1.721	12496	0.7119
14.7	9.52	2445	20.14	1.925	13978	0.6983
17.45	12.27	2772	20.38	2.156	15660	0.6891
18.9	13.72	2914	20.23	2.284	16586	0.6902
20.7	15.52	3057	20.11	2.409	17498	0.6847
23.1	17.92	3227	20.02	2.555	18558	0.6758
27.15	21.97	3512	20.15	2.763	20063	0.6598
28.9	23.72	3924	21.37	2.911	21139	0.6690
33.1	27.92	3924	19.97	3.115	22621	0.6599
38.8	33.62	4606	21.22	3.441	24990	0.6644
42.25	37.07	4606	20.23	3.609	25884	0.6636
47.1	41.92	4805	20.39	3.736	26791	0.6459
50.75	45.57	5161	20.95	3.905	28003	0.6476
60.8	55.62	5431	20.04	4.296	30807	0.6448

TABLE A4-33

Plate #: 5
Hole Diameter: 0.2503 in.
Plate Thickness: 10 Gage
Liquid: Water
Increasing Head

Date: 08/31/94
Liquid Temp.: 77.0 F
Liquid Density: 997.045 Kg/Cu.m
Liquid Viscosity:0.9003 cp
Hole Position: 5.08 cm from bottom

LIQUID ELEVATION CM	NET HEAD CM	VOLUME COLLECTED ML.	TIME SEC	FLOW RATE GPM	REYNOLDS NUMBER	ORIFICE COEFF.
6.1	0.92	300	25.35	0.188	2558	0.8776
7.05	1.87	330	25.59	0.204	2824	0.6707
8.05	2.87	460	25.52	0.286	4050	0.7568
11.5	6.32	630	25.66	0.389	5588	0.6946
12.5	7.32	725	25.3	0.454	6605	0.7533
14.7	9.52	820	25.41	0.512	7438	0.7439
17.45	12.27	910	25.7	0.561	8161	0.7190
18.9	13.72	940	25.44	0.586	8516	0.7095
20.7	15.52	1020	25.26	0.640	9307	0.7290
23.1	17.92	1100	25.58	0.682	9911	0.7225
27.15	21.97	1210	25.99	0.738	10730	0.7065
28.9	23.72	1240	25.52	0.770	11199	0.7096
33.1	27.92	1320	25.38	0.824	11987	0.7001
38.8	33.62	1440	25.46	0.897	13036	0.6938
42.25	37.07	1540	26.13	0.934	13413	0.6885
47.1	41.92	1580	25.39	0.986	14163	0.6836
50.75	45.57	1660	25.34	1.038	14909	0.6902
60.8	55.62	1800	25.36	1.125	16154	0.6769

APPENDIX 5

SAMPLE CALCULATIONS

The equations used for finding the Reynolds number and orifice coefficient are given in Chapter 4. They are:

$$Re = dv\rho/\mu$$

and

$$C_o = v_o/(2gh)^{1/2}$$

where

$$v_o = (\text{Volumetric flow rate})/(\text{orifice cross sectional area})$$

The procedure for calculating Reynolds number and orifice coefficient is as follows:

Thickness: 10 gage(0.146 in.)

Hole diameter: 0.2503 = 0.6358 cm.

Liquid elevation: 50.75 cm.

Manometer base line reading: 2.8 cm.

Actual base line reading: 2.7 cm.

Center line: 5.08 cm

Volume in cc.: 1660

Collection time: 25.34 sec.

Water temperature: 77°F

The liquid head is calculated as shown.

Net Head = (Liquid elevation above inside base of trough- Center line above inside base of trough) + (Actual base line reading - Manometer base line reading)

where,

Actual base line reading = The reading taken by using a ruler after filling the trough with water to a depth of around 1 inch.

Manometer base line reading = The manometer reading taken after filling the trough with water to a depth of around 1 inch.

The net head is ((50.75-5.08)+(2.7-2.8)) = 45.57 cm. The flow rate is $\frac{1660}{25.34} = 65.51$ cc/s which is equal to 1.038 gpm.

The velocity is calculated by dividing volumetric flow rate by cross-sectional area.

$$v = \frac{65.51 cc/s}{\frac{\pi}{4} d^2 cm^2} = 206.34 \text{ cm/s}$$

The viscosity is calculated using the correlation given in Appendix 7. The density is obtained from the table in Appendix 8. In this case, the density and viscosity are 997.045 kg/m^3 and 0.9003 cp respectively.

Substituting all the values, we get, Re = 14909 and C_o=0.6902.

APPENDIX 6

ERROR ANALYSIS

The method of Lyon (1970) will be used to determine the error in the derived quantities. This method was also used by Derasari (1992) and Mendes (1994) to quantify the errors in their experiments. According to this method,

$$\text{If } U = CX^{l}Y^{m}Z^{n}..... \tag{A6-1}$$

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 relative error in U, $\frac{E_u}{U}$, can be evaluated as

$$\frac{E_u}{|U|} = \left|l\frac{E_x}{X}\right| + \left|m\frac{E_y}{Y}\right| + \left|n\frac{E_z}{Z}\right| + ... \tag{A6-2}$$

The measured quantities are -

Volume of water collected, V (ml)

Time of collection, t (sec)

Liquid elevation or head, h (cm)

Liquid temperature, T (^{o}F)

Diameter of orifice, d (inches)

If E_M is the maximum estimated error for each measured quantity and if M is the maximum value of that quantity, then the relative error for that quantity is E_M/M. Table A6-1 shows the relative errors in the measured quantities

TABLE A6-1

Relative Errors in Measured Quantities

	V, ml	t, sec	h, cm	d, in
E_M	15	0.2	0.2	0.001
M	2000	30	60	0.7504
$\%E_M/M$	0.75	0.67	0.33	0.133

Since $Re = \dfrac{dv_o\rho}{\mu}$

$$C_o = \frac{v_o}{\sqrt{2gh}}$$

The relative errors in Re and C_O can be obtained from Eqn. A6-2 as

$$\frac{E_{Re}}{Re} = \frac{E_{v_o}}{v_o} + \frac{E_d}{d} + \frac{E_\rho}{\rho} + \frac{E_\mu}{\mu} \qquad \text{(A6-3)}$$

$$\frac{E_{C_o}}{C_o} = \frac{E_{v_o}}{v_o} + \frac{1}{2}\frac{E_h}{h} \qquad \text{(A6-4)}$$

Also, $v_o = \dfrac{Q}{A_o}$ and $Q = \dfrac{V}{t}$ and since the orifice cross-sectional area depends on the square of the orifice diameter, hence we have

$$\frac{E_{v_o}}{v_o} = \frac{E_Q}{Q} + 2\frac{E_d}{d} \qquad \text{(A6-5)}$$

and

$$\frac{E_Q}{Q} = \frac{E_V}{V} + \frac{E_t}{t} \qquad \text{(A6-6)}$$

Eqns. A6-4, A6-5 and A6-6 can be used to find the relative errors for C_O. The error for C_o is 2.43%.

APPENDIX 7

CORRELATION FOR CALCULATING VISCOSITY OF WATER

The viscosity of the water was calculated at the average temperature, using the following correlation (Reid, Sherwood and Prausnitz, 1977).

$\log_{10}\eta = A' + B'(T-T')$

η = Viscosity of the liquid, cp

T = Temperature, ^{o}K

For water, A' = -1.5668; B'=230.298; T' = 146.797

Temperature Range: -10 to 160 ^{o}C

Percentage Error: 0.51%

APPENDIX 8

DATA FOR DENSITY

The density data used for these experiments were obtained from Perry (1988).

TEMP. F	TEMP. C	DENSITY KG/M^3
70	21.11	997.971
71	21.67	997.845
72	22.22	997.723
73	22.78	997.59
74	23.33	997.455
75	23.89	997.324
76	24.44	997.184
77	25.00	997.045
78	25.56	996.901
79	26.11	996.755
80	26.67	996.605
81	27.22	996.452
82	27.78	996.295
83	28.33	996.138
84	28.89	996.006
85	29.44	995.814
86	30.00	995.647
87	30.56	995.482
88	31.11	995.307
89	31.67	995.132
90	32.22	994.956

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