AN EXPERIMENTAL STUDY OF HEAD LOSS AND PRESSURE RECOVERY IN PERFORATED PIPES

by

WEN-HSIUNG CHIU

B. S., Taiwan Provincial Cheng-Kung University, 1962

A MASTERS THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Civil Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1967

Approved by:

Richard M. Haynie

Major Professor

TABLE OF CONTENTS

TABLE OF CONTENTS (Contd.)

INTRODUCTION

Need For This Study

The problem of uniform distribution of a fluid flowing through a manifold with spaced outlets arises in many practical systems. Familiar examples are rapid sand filter underdrains, sewage disposal systems, sprinkler systems for irrigation, liquid-distribution systems, and pipe burners for gaseous fuels.

Because the manifold represents a regular piping pattern and is frequently recurring in many practical fields, it has received much theoretical and experimental study. It is well known that, in general, as the fluid flows along the manifold its longitudinal velocity decreases due to part of the fluid volume being discharged laterally through the openings. Therefore, the fluid in the manifold is being decelerated and, in accordance with Bernoulli's theorem, this tends to increase the fluid pressure. Friction loss as well as other losses, on the other hand, results in loss of pressure along the length. The relative magnitudes of the pressure recovery due to deceleration and pressure loss due to head loss determine whether the pressure rises or falls from the inlet end to the closed or dead end of the manifold. Although the flow characteristics, as mentioned above, are simple, there are some uncertainties existing in this type of flow pattern. These uncertainties, if incorrectly estimated, will lead to a considerable deviation from the assumed conditions. These uncertainties include the following:

1. Variable coefficient of discharge
2. Velocity head factor
3. Efficiency of conversion of kinetic energy to pressure energy
4. Friction factor

In order to handle these uncertainties, an assumption has been made that the manifold acts as a continuous, uniform, and homogeneous unit, and can be treated as a simple pipe pattern. Therefore, the manifold problem can be handled in a simple way by considering its overall effect.

Purpose of the Study

Although literature on the problem of manifold flow has been in existence since about 1900, little knowledge has been gathered of the overall effect of such uncertainties as listed above on the flow characteristics of manifold pipes. In this study experiments were conducted to determine the effect of the Reynolds number at the inlet end and area ratio of openings to the pipe cross section on the overall head loss and pressure recovery in a perforated pipe. In general, it is impossible to obtain an exactly uniform distribution of discharge through a manifold pipe of constant cross section with evenly spaced orifices of the same diameter. Therefore, the optimized flow conditions, which will ensure approximately uniform distribution of discharge and which will occur when the overall head loss is equal to the pressure recovery, have been observed.

Scope of the Study

The experiments were conducted in a 3" PVC pipe. For the first four series of runs, the orifices were drilled in one straight line level with the center line of the pipe. The diameter of orifice was changed in the order of 3/16", 1/4", 5/16", and 3/8"; and for each diameter of orifice the spacing between adjacent orifices was changed from 1.5" to 3", 6", 9", 12", 18", and 24" successively. In the fifth series of runs, the orifices were arranged in two rows, one on each side of the pipe; the diameter of orifice was fixed at a value of 3/8", and the spacing between adjacent orifices also was changed from

1.5" to 24" successively.

Flow varied from 0.012 to 0.143 c.f.s. during the runs. The static pressure head along a 12 ft. section of pipe was measured by five peizometer tubes. The head loss along the perforated pipe was computed. The effect of the Reynolds number and the area ratio on the overall head loss and pressure recovery was determined.

Theory

Assume the discharge, Q[1], of liquid moving under the head H is distributed uniformly and continuously over the whole pipe section. Let the discharge per unit pipe length be Q/L, cfs/ft. The residual discharge Q_o at point C, located a distance x from point A is equal to the discharge at point A minus the amount of discharge Qx/L over the length x of the pipe line, as shown in Figure 1.

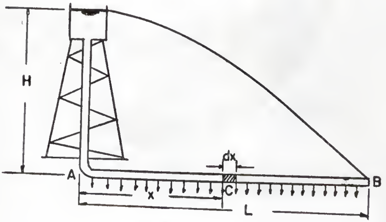


Figure 1.

$$Q_o = Q - Qx/L = Q(L - x)/L$$

---

[1]The symbols in this paper are introduced in text as they occur and are summarized for reference in Appendix 1.

By Chezy formula

$$Q = C\ A \sqrt{RS} \tag{1}$$

in which C is the Chezy coefficient, A denotes the cross sectional area of the pipe, R is the hydraulic radius, and S is the hydraulic gradient. Since A, C, and R are constant for a given pipe, we may define

$$K = C\ A \sqrt{R}$$

K has dimensions of volume flow rate (c.f.s.) and is called flow rate modulus. Therefore,

$$Q = K \sqrt{S} \tag{2}$$

The hydraulic gradient at point C is given by equation 2 as

$$S_o = \frac{{Q_c}^2}{K^2} = \frac{Q^2}{L^2K^2} (L - x)^2$$

On the other hand, if the head loss over an infinitesimal section dx is dH then

$$S_o = \frac{dH}{dx} = \frac{Q^2}{L^2K^2} (L - x)^2$$

or

$$dH = \frac{Q^2}{L^2K^2} (L - x)^2 dx$$

The integration of this equation from $x = 0$ to $x = L$ gives

$$H_{AB} = \frac{1}{3} \frac{Q^2L}{K^2} \tag{3}$$

A comparison of this formula with that describing the flow rate through section AB when the discharge is not distributed over the section

$$H = \frac{Q^2L}{K^2} \tag{4}$$

shows that $H = 3\ H_{AB}$. Thus, for a uniform distribution of discharge along the pipe the head required is only one third of that required for the same rate of flow through the unperforated pipe.

For the variation of pressure along a manifold pipe we consider the pipe with a long, narrow slot and neglect pipe friction. Consider a straight pipe with a uniform cross sectional area of A square feet having a slot e feet wide and L feet long parallel to the axis of the pipe as illustrated in Fig. 2. Assume the pressure on the slot to vary from h feet of water at one end to H feet of water at the other end and the pressure at any point x feet from the beginning of the slot to be y feet of water. The mass of water passing any section of the pipe x feet from the beginning of the slot in dt seconds will be

$$\frac{\gamma v A}{g} dt$$

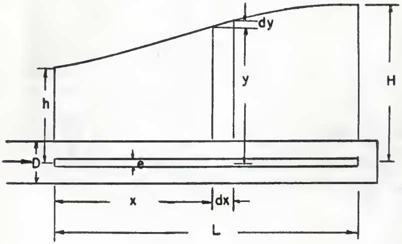


Figure 2.

where γ is the specific weight of water (62.4 pounds per cubic feet), v is the mean velocity in the pipe at that section, in feet per second, and g is acceleration of gravity (32.2 feet per second per second). At a section dx feet further along the pipe the velocity in the pipe is v - dv feet per second and the pressure has increased to y + dy feet of water. From the principle of momentum which states that the rate of change of momentum is equal to the sum of the external forces acting on the control surface of the fluid, it follows

$$[\gamma A(y + dy) - \gamma Ay] = \frac{\frac{\gamma vA}{g}dt[(v - dv) - v]}{dt}$$

hence

$$dy = - \frac{v}{g} dv \qquad (5)$$

$$\int dy = - \frac{1}{g}\int vdv$$

$$y = - \frac{v^2}{2g} + C$$

From the boundary conditions, $v = 0$ at $y = H$, we can solve for the constant of integration.

$$C = H$$

then

$$y = H - v^2/2g \qquad (6)$$

or

$$v = \sqrt{2g(H - y)} \qquad (7)$$

Equation 6 is important because it shows that the pressure at any point of the slot, when pipe friction is neglected, is equal to the head at the end of the slot minus the velocity head at the given point (1). Next consider the discharge from the slot in the distance dx

$$dq = C_q\ e\ dx \sqrt{2gy}$$

in which C_q is the coefficient of discharge of the slot. The discharge, dq, is also equal to the difference of the flow through the two sections dx apart, hence,

$$- Adv = C_q\ e\ dx \sqrt{2gy} \qquad (8)$$

$$dv = - \frac{C_q\ e \sqrt{2gy}}{A} dx$$

Substituting the value of v from eqn. 7 and the value of dv from eqn. 8 into eqn. 5.

$$dy = \frac{2C_q e}{A} \sqrt{(H - y)y}\, dx \tag{9}$$

Integrating eqn. 9 between the limit x, L and y, h, and solving for y.

$$y = \frac{H}{2}\left\{1 - \cos\left[\pi - \frac{2C_q e}{A}(L - x)\right]\right\} \tag{10}$$

Eqn. 10 gives the pressure head, y, at any point x from the beginning of the slot in terms of the dimensions of the pipe and the slot, the coefficient of discharge, and the head, H, at the end of the slot. It will be noticed that the ratio of y to H does not depend upon the rate of discharge, that is, whatever the discharge, the pressure at any given point is always a constant proportion of the head at the end of the slot.

The formulas found for the case of a slot in a pipe may be modified to apply to a series of holes in a pipe. Each hole may be taken as representing a part of the length of the slot. The distance x along the slot and the total length of the slot, may be represented by the number of holes, Z and N, respectively. The areas, eL, ex, and A will be replaced by $\frac{N\pi d^2}{4}$, $\frac{Z\pi d^2}{4}$, $\frac{\pi D^2}{4}$ with d denoting the diameter of the hole and D the diameter of the pipe. With these changes eqn. 10 may be written as

$$y = \frac{H}{2}\left\{1 - \cos\left[\pi - \frac{2C_q d^2}{D^2}(N - Z)\right]\right\} \tag{11}$$

The head y is, of course, the pressure head in the space beyond hole number Z.

REVIEW OF PREVIOUS INVESTIGATIONS

Many investigators have analyzed the flow characteristics of manifold flow, with an attempt to develop the rules and formulas for uniformity of discharge, each with a slightly different approach and, generally, with different results. In 1921, H. N. Jenk (2) published the design rules for rapid sand filter underdrains to accomplish uniformity of discharge. In 1927, N. Malishewsky (3), (4) conducted a series of experiments relating to the distribution of pressure and velocity head through perforated pipe lines and published his results in the A.W.W.A. Journal of 1927 and 1935. In 1929, M. L. Enger and M. I. Levy (1) published the experimental studies which indicated that the principles of impulse and momentum were applicable to perforated pipes. These studies also presented an empirical formula for the discharge coefficient of an orifice which revealed the important effect of variation in fluid velocity upon the variation of the orifice coefficient for free discharge.

In 1931, Jacob Kunz (5) applied the principle of conservation of energy to the manifold problem and determined the flow of a sheet of water through a slot of infinitesimal width in the wall of a pipe by means of a variable and a constant discharge coefficient. He was able to solve the flow problem of separated holes by using the method of difference equations. In 1940, R. D. Gladding (6) assumed that outlets were evenly spaced along a pipe line and each outlet discharged the same quantity of fluid and found a simple relationship between the loss of head in the pipe, the number of outlets, and the total discharge. In 1949, J. D. Keller (7) made a mathematical analysis of the flow of a fluid through a manifold having a uniform cross section and uniformly spaced discharge ports along its length. He concluded that the ratio of port area to the cross sectional area of pipe should not exceed unity and that the ratio of length to diameter should not be greater than 70 for substantially uniform distribution of flow to be obtained.

In 1950, W. M. Dow (8) made a theoretical analysis of the flow through a perforated pipe with a closed end for the special case of a constant linear rate of discharge along the length of the pipe. With this analysis, he developed several theoretical design equations for uniform distribution of fluid flowing through the perforated pipe in the case of laminar flow and turbulent flow. The validity of the theoretical design equations was checked by experimentation with conventional and modified pipe burners. The agreement between the theory and experiment was reported to be excellent.

In 1953, W. E. Howland (9) developed a method for computing the correct variation in size or in spacing of holes to affect uniformity of distribution of discharged fluid from a perforated pipe. In 1955, John Allen and Brian Albinson (10) analyzed the manifold problem for canal locks from a different and less rigid mathematical approach, and derived a formula for the required area of each evenly spaced port of a manifold in order that the quantity of water issuing from each of the ports would be the same. In 1956, J. H. Horlock (11) derived a differential equation for the ratio of longitudinal velocity to normal discharge velocity for an incompressible flow through a manifold of constant cross sectional area and constant slot width, and gave an analytical expression for this ratio; three years later, E. Markland (12) solved the differential equation by the relaxation method.

In 1959, A. Acrivos, B. D. Babcock, and R. L. Pigford (13) published a calculation method, based on the one-dimensional flow equation, for the pressure-rise and head-loss in the manifold pipe. In 1964, Bessel D. van't Woudt (14) showed experimentally that the existing knowledge can be applied to obtain uniform discharge from any length of pipe by discharging from subpipes of a given length and diameter provided the total discharge from twenty or more orifices on the subpipe is fixed and the diameter of an orifice is very small compared to the diameter of the pipe.

EXPERIMENTAL PROCEDURE

Experimental Apparatus

A photograph of the experimental apparatus is shown in Fig. 3, and a schematic diagram is presented in Fig. 4. Water was pumped from a reservior and flowed into a stilling tank, then passed through the pipe. The quantity of water used in the experiments varied from 0.012 to 0.143 c.f.s. An orifice was used for measuring the discharge flowing through the pipe. A sloping differential manometer was used to measure the pressure drop across the orifice. A 10 ft. length of straight pipe was used as the upstream approach to the test section to avoid interference from upstream fittings. Five evenly spaced piezometer tubes were used to measure the static pressure head along a 12-foot section of the perforated pipe. The scales on the piezometer tubes were graduated in increments of 0.001 ft.

Preliminary Experiments

The preliminary experimental work included orifice calibration and unperforated pipe tests. The orifice was calibrated over the range of flows. Rate of quantity flow was determined by timing a certain amount of water into the measuring tank. The calibration curve is shown in Fig. 5.(Δh represents the differential manometer reading, in inches of mercury)

Tests were made on unperforated pipe in order to obtain a basis for comparison with the later experiments on perforated pipe, and to enable the operator to become familiar with the characteristics of the PVC pipe. During every run the static pressure heads on the five piezometer tubes were measured; and the pressure drop between two sections 12 ft. apart was calculated. Figure 6 shows the relation of Darcy-Weisbach friction factor, f, to the Reynolds

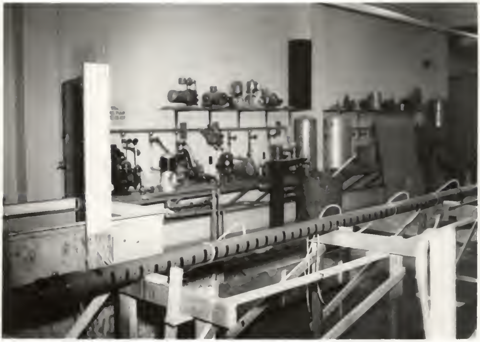


Figure 3. Experimental Apparatus

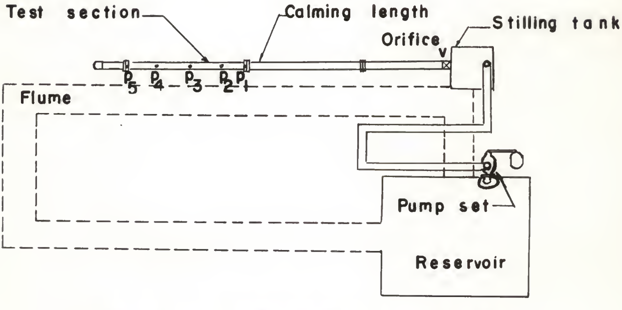


Figure 4. Experimental Apparatus

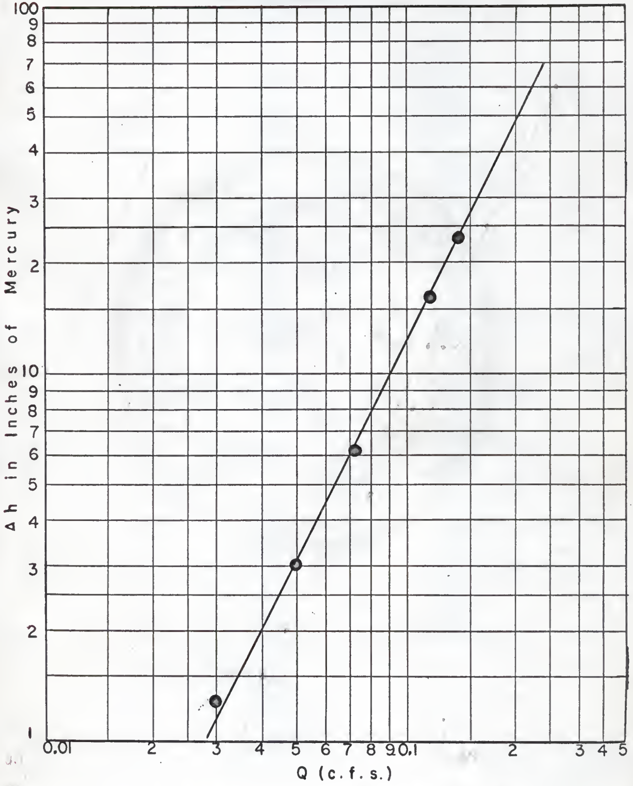


Figure 5, Orifice Calibration

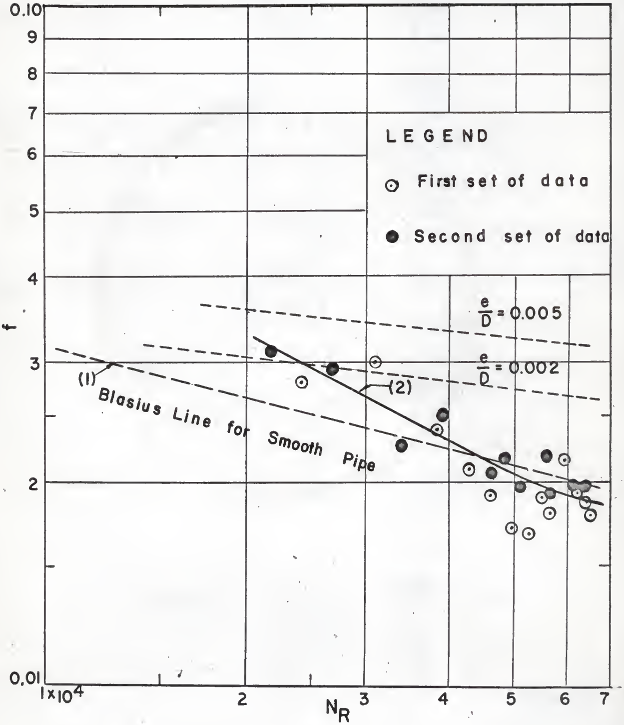


Fig. 6. Friction Factor in an Unperforated Pipe

number, N_R, for the 3" unperforated PVC pipe.

Experiments For Obtaining Data

As mentioned above, the experiments were composed of five series of runs, based on the diameter of the holes. At first, eight holes with a diameter of 3/16" were drilled evenly spaced along one side of the pipe. Whereas the first hole was located $17\frac{1}{2}$" downstream of the first piezometer tube, the last hole was located $\frac{1}{2}$" upstream of the last piezometer tube. Letting S define the spacing between adjacent holes and D denote the inside diameter of the pipe, this gave a ratio of S/D equal to 5.573. Attention was given to removing the burr in the hole after the hole was drilled. The water level in the stilling tank was kept approximately constant, at a value of about 57.3" above the center line of the pipe, by adjusting the openings of the control valve on the pump, and by keeping water overflowing from the stilling tank. After finishing the first set of runs, the numbers of holes was increased to 12; this gave a ratio of S/D equal to 3.715. In the same manner, the number of holes was increased to 16, 24, 48, and 96 for the 3rd, 4th, 5th, and 6th set of runs respectively. The holes that were not to be used for a particular run were covered with a waterproof covering. After the first series of runs, the diameter of the holes was increased successively to 1/4", 5/16", and 3/8". At certain series of runs the ratio, S/D, was changed from 5.573 to 0.465 or from 0.465 to 5.573. In the fifth series of runs the holes were arranged in two rows, one on each side of the pipe. The diameter of the holes was fixed at a value of 3/8", and the ratio, S/D, was changed from 5.573 to 0.465. The layout of the holes in each series of runs is shown in Fig. 7. Table 1 gives the relationship between hole diameter, ratio S/D, and area ratio.

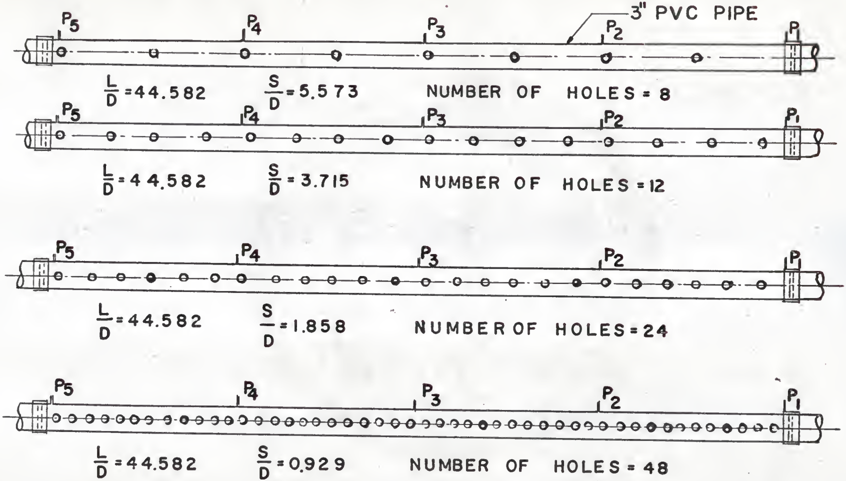


Fig. 7. Layout of Hole in One Side of Pipe

Table 1. Area ratio.

(a) One-Side	$\frac{L}{D} = 44.582$					
S/D	0.465	0.929	1.858	2.786	3.715	5.573
d (m) N	96	48	24	16	12	8
3/16	0.325	0.163	0.081	0.054	0.041	0.027
1/4	0.575	0.288	0.144	0.096	0.072	0.048
5/16	0.901	0.451	0.225	0.150	0.113	0.075
3/8	1.294	0.647	0.323	0.216	0.162	0.108

(b) Two-Side	$\frac{L}{D} = 44.582$					
S/D	0.929	1.858	2.786	3.715	5.573	
d (m) N	96	48	32	24	16	
3/8	1.294	0.647	0.431	0.323	0.216	

DATA ANALYSIS

Method of Analysis

Three methods of analysis were developed to determine the overall head loss and pressure recovery along the perforated pipe; they were referred to as the modified method of Enger and Levy, the momentum method, and the energy method.

<u>The Modified Method of Enger and Levy (1).</u> From eqn. 9

$$dy = \frac{2C_q e}{A} \sqrt{(H - y)y} \; dx$$

integrating over the entire length of the slot

$$\int_0^L dx = \frac{A}{2C_q e} \int_h^H \frac{dy}{\sqrt{(H - y)y}}$$

this gives

$$L = \frac{A}{2C_q e} \left[\pi - \cos^{-1}\left(1 - \frac{2h}{H}\right)\right]$$

therefore,

$$h = \frac{H}{2} \left[1 - \cos\left(\pi - \frac{2C_q eL}{A}\right)\right] \qquad (12)$$

Replacing eL, A by $\frac{\pi}{4} d^2 N$ and $\frac{\pi}{4} D^2$ respectively, then

$$h = \frac{H}{2} \left[1 - \cos\left(\pi - \frac{2C_q N \frac{\pi}{4} d^2}{\frac{\pi}{4} D^2}\right)\right]$$

or

$$h = \frac{H}{2} \left[1 - \cos\left(\pi - \frac{2C_q d^2}{D^2} N\right)\right] \qquad (13)$$

in which h is the static pressure head at the inlet end, H is the static pressure head at the closed end beyond the last hole, C_q denotes the discharge coefficient for the holes, and N is the total number of holes along the perforated pipe. Defining

$$h = P_1 \text{ and } H = P_5$$

then

$$P_1 = \frac{P_5}{2}\left[1 - \cos\left(\pi - \frac{2C_q d^2}{D^2} N\right)\right]$$

Let the theoretical pressure head recovery be ΔP_0, then

$$P_0 = P_5 - P_1 = P_5 - \frac{P_5}{2}\left[1 - \cos\left(\pi - \frac{2C_q d^2}{D^2} N\right)\right]$$

or

$$P_0 = P_5 \left\{1 - \frac{1}{2}\left[1 - \cos\left(\pi - \frac{2C_q d^2}{D^2} N\right)\right]\right\} \tag{14}$$

in which $\frac{d^2}{D^2}N$ is equal to the area ratio, P_1 and P_5 denote the static pressure heads, in feet of water, at the inlet end and the closed end of the perforated pipe respectively.

In order to evaluate the discharge coefficient, C_q, for the holes, one assumption was made. It was assumed that C_q represents the average discharge coefficient for all the holes. From this assumption we write

$$Q = \frac{\pi}{4} C_q N d^2 \sqrt{2g\bar{h}}$$

in which $\bar{h}$ denotes the average static pressure head along the perforated pipe. Since

$$\bar{h} = \frac{P_1 + P_5}{2}$$

then

$$Q = \frac{\pi}{4} C_q N d^2 \sqrt{g(P_1 + P_5)}$$

Therefore,

$$C_q = \frac{Q}{\frac{\pi}{4} N d^2} \frac{1}{\sqrt{g(P_1 + P_5)}} \tag{15}$$

From eqn. 15, the discharge coefficient of the holes, C_q, can be determined. By theorem of conservation of pressure recovery, the difference of theoretical pressure recovery and observed pressure recovery gives the overall head loss, H_L. Let the observed pressure recovery be ΔP then

$$H_L = \Delta P_0 - \Delta P \tag{16}$$

Consider the perforated pipe as a continuous, uniform, and homogeneous unit, we define

$$H_L = f \frac{L}{D} \frac{V_o^2}{2g} \tag{17}$$

in which f is defined as the overall friction factor of the perforated pipe, and V_o is the mean velocity at the inlet end. Since $V_o = Q/A$ then from eqn. 17, the overall friction factor, f, can be evaluated as soon as the overall head loss, H_L, is computed.

The Momentum Method. As shown in Fig. 8 ABB'A' is the control surface. Assuming the rate of change of momentum of the fluid discharged from the lateral opening in the x direction is dF_m

$$dF_m = u \frac{d}{dx} (\rho AV)dx$$

where u is the longitudinal component of discharged velocity at the distance x from the inlet end, and V is the longitudinal velocity in the pipe at that section.

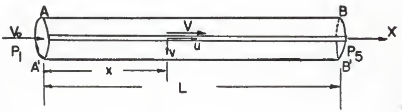


Figure 8.

Assuming $u = V$ then

$$dF_m = V \frac{d}{dx} (\rho AV) dx$$

By neglecting pipe friction, J. H. Horlock (11) gave the following expression to describe the variation of longitudinal velocity in the pipe.

$$\frac{V}{V_o} = \frac{\sin n(L - x)}{\sin nL} \qquad (18)$$

in which $n = \frac{C_d a}{A}$, and a denotes the area of opening per unit length of pipe.

In eqn. 18, taking the derivative of V with respect to x and assuming n is a constat, then

$$\frac{dV}{dx} = \frac{-n \cos n(L - x)}{\sin nL} V_o$$

therefore,

$$dF_m = - n \rho AV_o^2 \frac{\sin n(L - x)}{\sin nL} \frac{\cos n(L - x)}{\sin nL} dx$$

or

$$dF_m = - \frac{1}{2} n \rho AV_o^2 \frac{\sin 2n(L - x)}{\sin^2 nL} dx$$

Integrating along the entire length of pipe,

$$\int dF_m = \frac{- \frac{1}{2} \rho nAV_o^2}{\sin^2 nL} \int_0^L \sin 2n(L - x)\, dx$$

$$\Delta F_m = - \frac{1}{4} \rho V_o^2 \frac{A}{\sin^2 nL} \left[\cos 2n(L - x)\right]_0^L$$

hence

$$\Delta F_m = - \frac{1}{4} \rho V_o^2 \frac{A}{\sin^2 nL} \left[1 - \cos 2nL\right]$$

For separated holes

$$\Delta F_m = -\frac{1}{4}\rho V_o^2 \frac{A}{\sin^2(\frac{C_q d^2}{d^2}N)} \left[1 - \cos(\frac{2C_q d^2}{D^2}N)\right] \quad (19)$$

Applying the momentum principle for the control surface in the x direction,

$$-\rho Q V_o = \gamma(P_1 - P_5)A - F_L + \Delta F_m$$

or

$$-\Delta F_m - \rho Q V_o = \gamma(P_1 - P_5)A - F_L \quad (20)$$

in which F_L is the unbalanced force due to loss of head, P_1 and P_5 as defined before. Substituting the value of ΔF_m from eqn. 19 into eqn. 20, it follows

$$\frac{1}{4}\rho V_o^2 A \frac{1}{\sin^2(\frac{C_q d^2}{D^2}N)} \left[1 - \cos(\frac{2C_q d^2}{D^2}N)\right]$$

$$- \rho Q V_o = \gamma(P_1 - P_5)A - F_L$$

thus

$$\frac{1}{4}\rho Q V_o \frac{\left[1 - \cos(\frac{2C_q d^2}{D^2}N)\right]}{\sin^2(\frac{C_q d^2}{D^2}N)} - \rho Q V_o = \gamma(P_1 - P_5)A - F_L$$

Since

$$F_L = H_L \gamma A$$

then

$$H_L \gamma A = \gamma(P_1 - P_5)A + \rho Q V_o - \frac{1}{4}\rho Q V_o \frac{\left[1 - \cos(\frac{2C_q d^2}{D^2}N)\right]}{\sin^2(\frac{C_q d^2}{D^2}N)}$$

Dividing by $A\gamma$, we obtain

$$H_L = (P_1 - P_5) + \frac{\rho Q V_o}{A} - \frac{\rho Q V_o}{4A\gamma} \frac{\left[1 - \cos(\frac{2C_q d^2}{D^2}N)\right]}{\sin^2(\frac{C_q d^2}{D^2}N)}$$

or

$$H_L = -(P_5 - P_1) + \frac{V_o^2}{g} - \frac{V_o^2}{4g}\frac{[1 - \cos(\frac{2C_q d^2}{D^2}N)]}{\sin^2(\frac{C_q d^2}{D^2}N)}$$

therefore,

$$H_L = \frac{V_o^2}{2g}\left[2 - \frac{1 - \cos(\frac{2C_q d^2}{D^2}N)}{2\sin^2(\frac{C_q d^2}{D^2}N)}\right] - (P_5 - P_1) \tag{21}$$

in which C_q, the discharge coefficient of the holes, is defined as before. From eqn. 21 the overall head loss, H_L, can be calculated if the discharge, Q, the area ratio, $\frac{d^2N}{D^2}$, and the pressure recovery, $P_5 - P_1$, are measured.

The Energy Method. As shown in Fig. 9 the total energy at section AA' is $P_1 + \frac{V_o^2}{2g}$ and the total energy at section BB' is P_5.

Figure 9.

From the principle of conservation of energy, it gives

$$P_1 + \frac{V_o^2}{2g} = P_5 + H_L \tag{22}$$

therefore,

$$H_L = \frac{V_o^2}{2g} - (P_5 - P_1) \tag{23}$$

From eqn. 23 the overall head loss can be easily calculated whenever the velocity head at the inlet end and the pressure recovery from the inlet end to the closed end are known.

Computation

In computing the overall head loss, H_L, the flow of water was read in cubic feet per second from the orifice calibration curve. The cross sectional area of the pipe is 0.057 sq ft. The mean velocity of water at the inlet end was obtained by dividing the discharge by the cross sectional area. Using this velocity the Reynolds number at the inlet end, $\frac{V_o D}{\nu}$, was obtained. The observed pressure recovery from the inlet end to the closed end is equal to $P_5 - P_1$. All the experimental data were punched in IBM cards, and run through the 1620 digital computer. The computer programs used for these three methods of analysis are shown in Appendix 2. The input data to the computer programs are listed in Appendix 3, the output results by using the momentum method are given in Appendix 4.

DISCUSSION OF RESULTS

Relation of Friction Factor to Reynolds Number in the Unperforated Pipe. The curve obtained from plotting friction factor, f, against Reynolds number, N_R, for all the runs on the unperforated pipe is shown as curve 2 in Fig. 6; curve 1 is a graph of Blasius' smooth pipe equation, $f = \frac{0.3164}{N_R^{0.25}}$.

It is evident that for larger Reynolds number the value of f of the PVC pipe is less than that of the smooth pipe, but on the contrary, for smaller Reynolds number the relation is reversed. It is seen that the PVC pipe is not smooth, the value of the relative roughness, e/D, of the PVC pipe, as shown in Fig. 6, is as large as 0.005. In the perforated pipe tests, covering some holes by waterproof covering a type of wavy roughness results (15), but here we assume that the latter is negligible in comparison with the roughness of the pipe.

Loss of Head in the Unperforated Pipe. Figure 10 shows the plot of head loss, H_L, against the discharge of water, Q, in the unperforated pipe. The slope of this curve is 1.50, which indicates that the flow in the pipe is not completely turbulent.

Observed Pressure Recovery. Figures 11 through 14 show the relation between observed pressure recovery and flow rate of water for hole diameters of 3/16", 1/4", 5/16", and 3/8" respectively. Observing these figures, an exponential relationship is seen to exist between observed pressure recovery and discharge of water, with area ratio as a third parameter. In Fig. 15 this relation is even more clearly seen where the holes were arranged on each side of the pipe. Figure 16 illustrates that the observed pressure recovery becomes independent of area ratio when the discharge is greater than 0.120 c.f.s. for two rows of

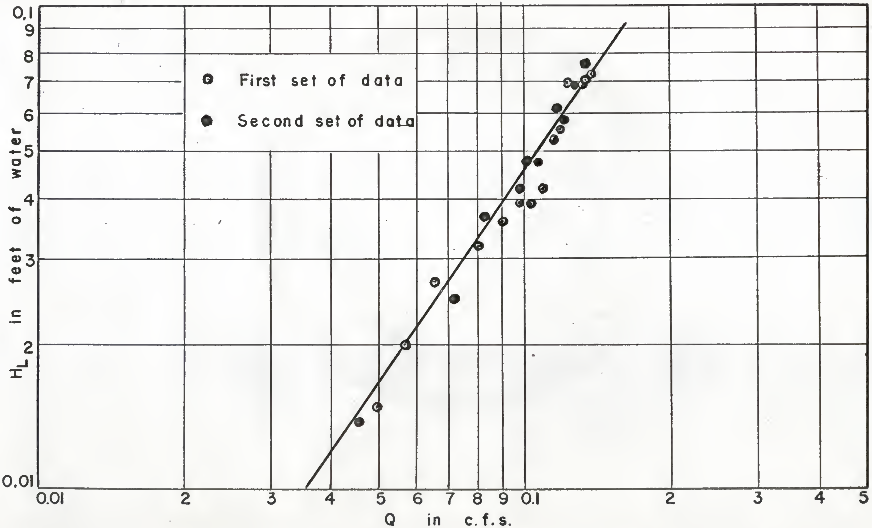


Fig. 10. Loss of Head in an Unperforated Pipe

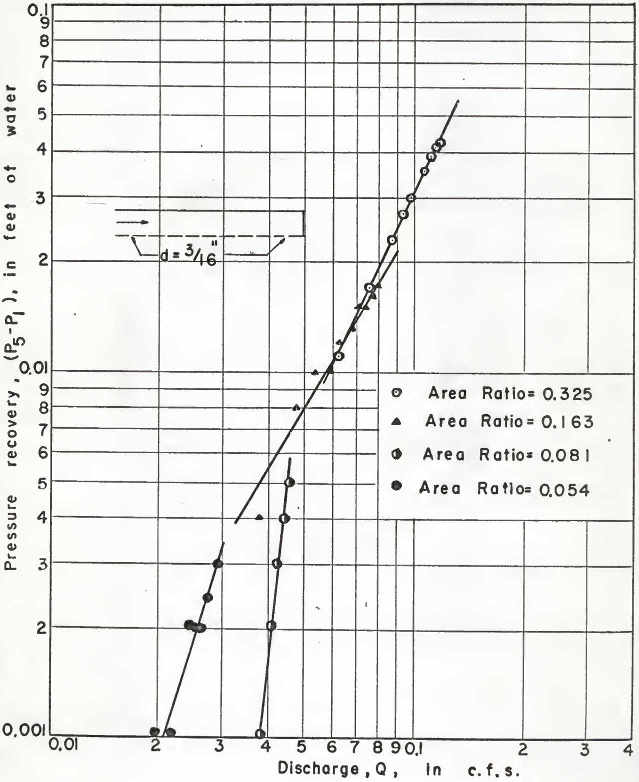


Fig. 11. Pressure Recovery in a Perforated Pipe

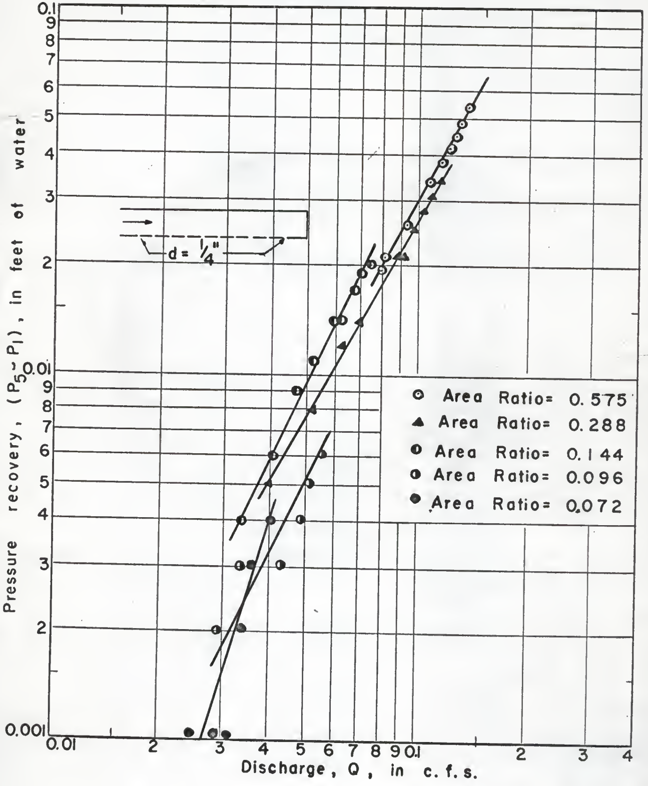


Fig. 12. Pressure Recovery in a Perforated Pipe

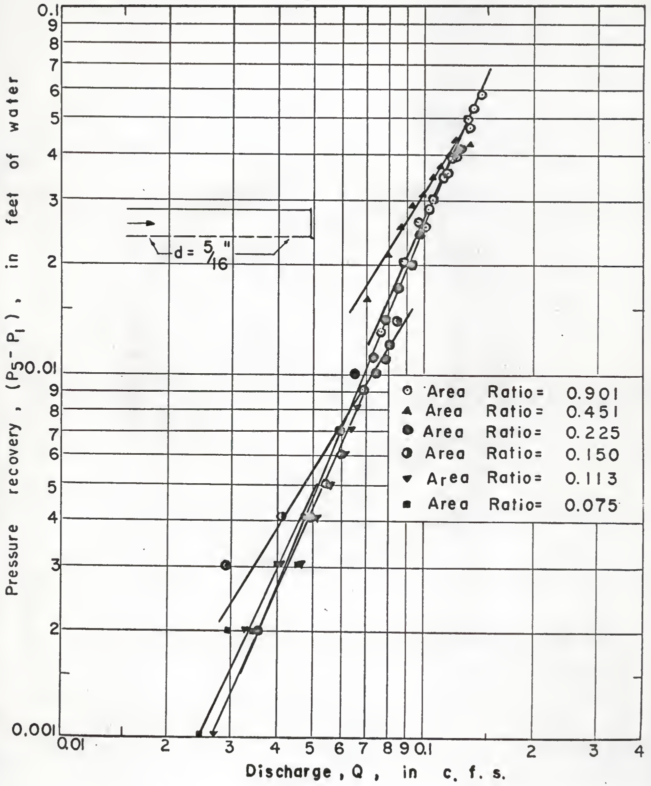


Fig. 13. Pressure Recovery in a Perforated Pipe

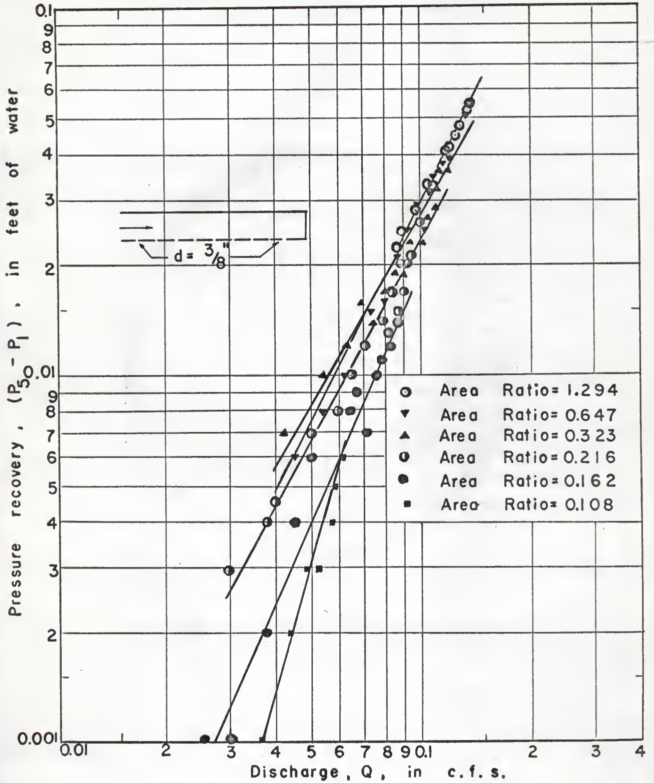


Fig. 14. Pressure Recovery in a Perforated Pipe

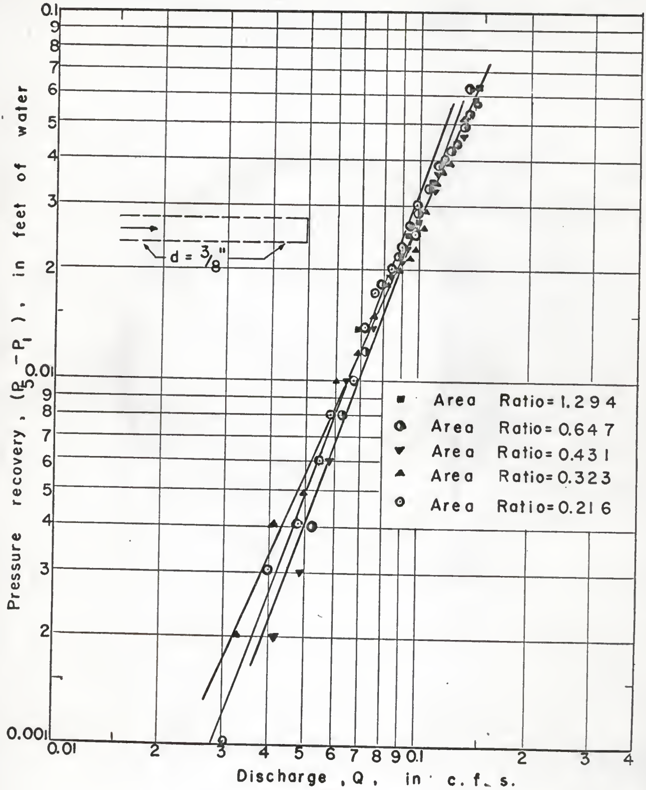


Fig. 15. Pressure Recovery in a Perforated Pipe

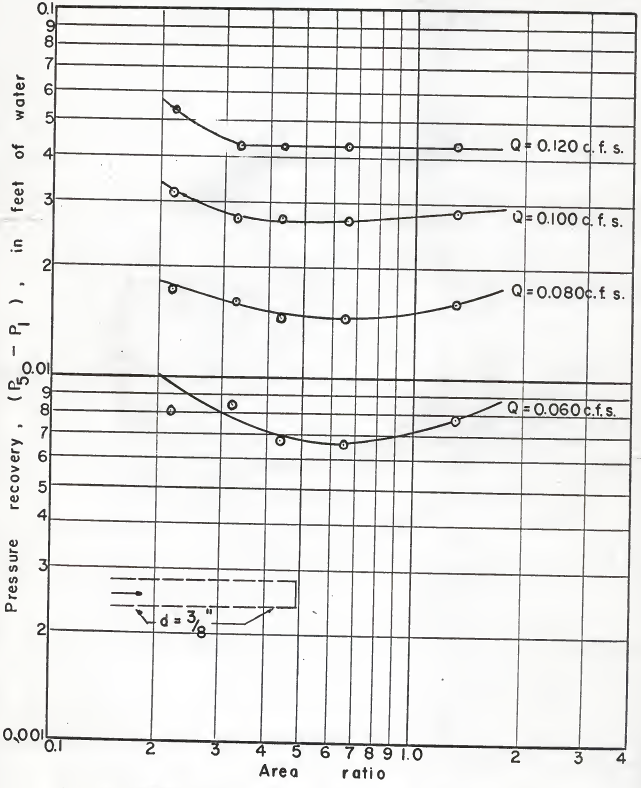


Fig. 16. Relationship between Pressure Recovery and Area Ratio in a Perforated Pipe with Holes on Each Side

holes. Figure 17 shows that the observed pressure recovery is nearly independent of the diameter of the hole when the total number of holes is equal to 96.

Uniformity of Discharge from the Orifices. There is no doubt that the distribution of static pressure along the perforated pipe plays an important role in the uniformity of discharge from the orifices. The uniform distribution of fluid discharged from the evenly spaced outlets in a pipe of uniform diameter can be secured only when the static pressure head is everywhere constant along the pipe. Figures 18 through 22 show the relation between the ratio of P_1 to P_5 and the discharge, Q, along the main pipe. It is seen that the smaller the area ratio is, the smaller will be the range of the discharge beyond which the ratio of P_1 to P_5 is independent of the discharge, Q. Thus for a given value of area ratio there is a limiting value of discharge beyond which P_1/P_5 is independent of discharge. Figure 23 illustrates the value of P_1/P_5 at every value of area ratio when the flow rate of water in the pipe is greater than that limiting value. From Fig. 23 one can determine the value of area ratio for any uniformity of distribution. Table 2 lists the magnitude of area ratio for certain ratios of P_1 to P_5. For example, if we define P_1/P_5 equal to 0.90 to be the condition of approximately uniform distribution of flow, this can be carried out when the area ratio is less than 0.67 for one row of orifices and 0.62 for two rows of orifices. From such values of area ratio, the perforated pipe can be easily designed by adjusting the size of the hole and the spacing of holes so as to satisfy this value of area ratio.

Overall Head Loss in the Perforated Pipe. Figures 24 through 27 show the relation between overall head loss, H_L, and discharge, Q, for hole diameters of 3/16", 1/4", 5/16", and 3/8" respectively. From these figures it is seen

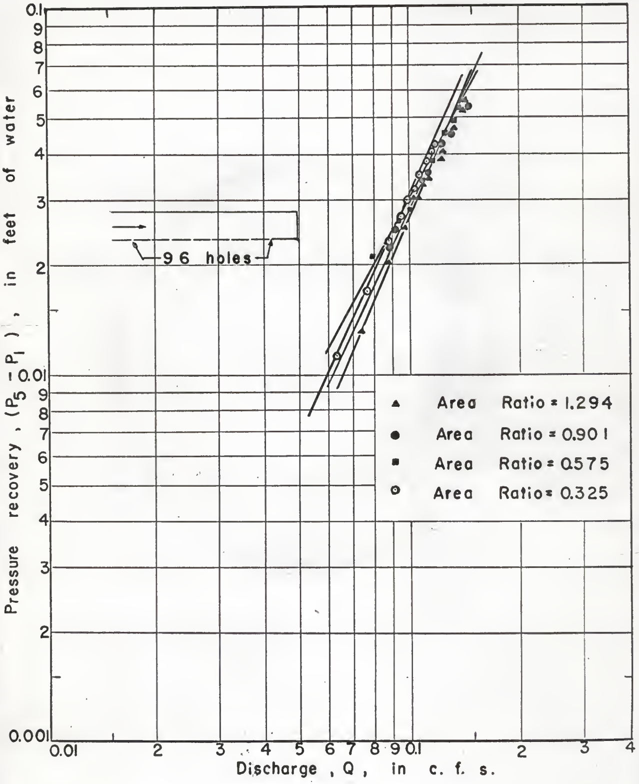


Fig. 17. Pressure Recovery in a Perforated Pipe

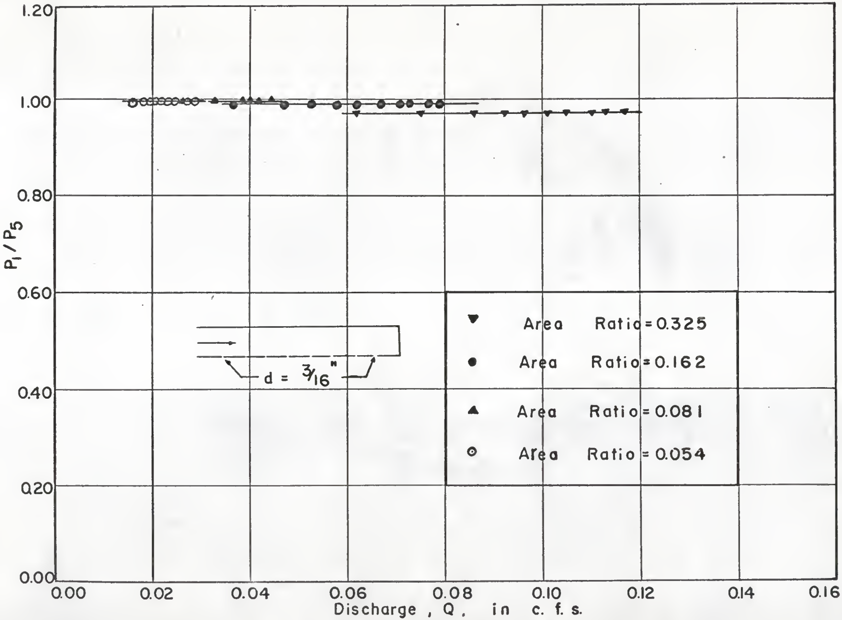


Fig. 18. Ratio of P_1 to P_5

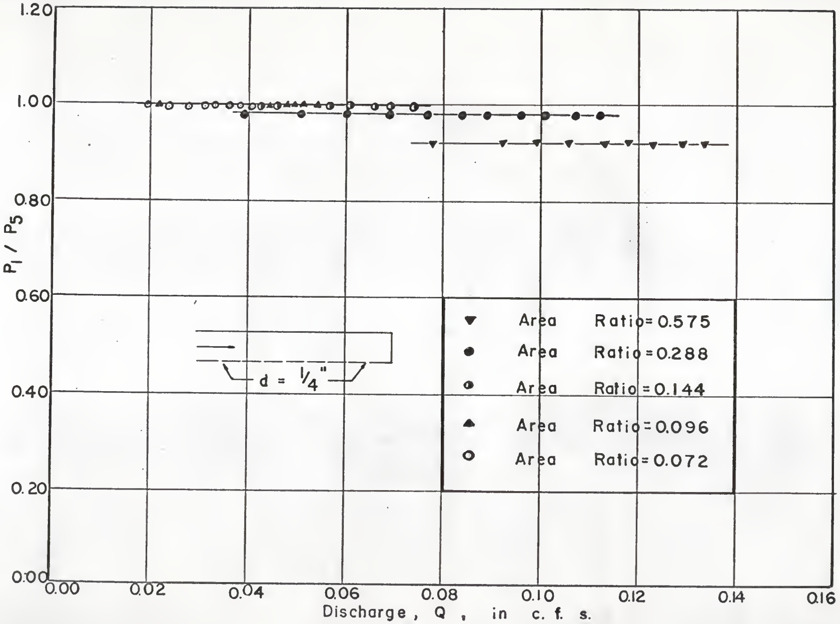


Fig. 19. Ratio of P_1 to P_5

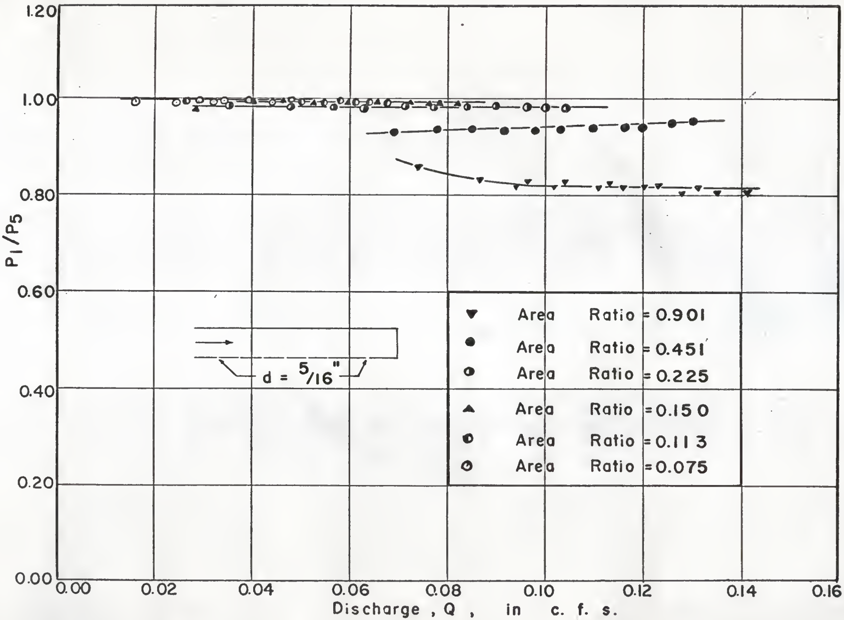


Fig. 20. Ratio of P_1 to P_5

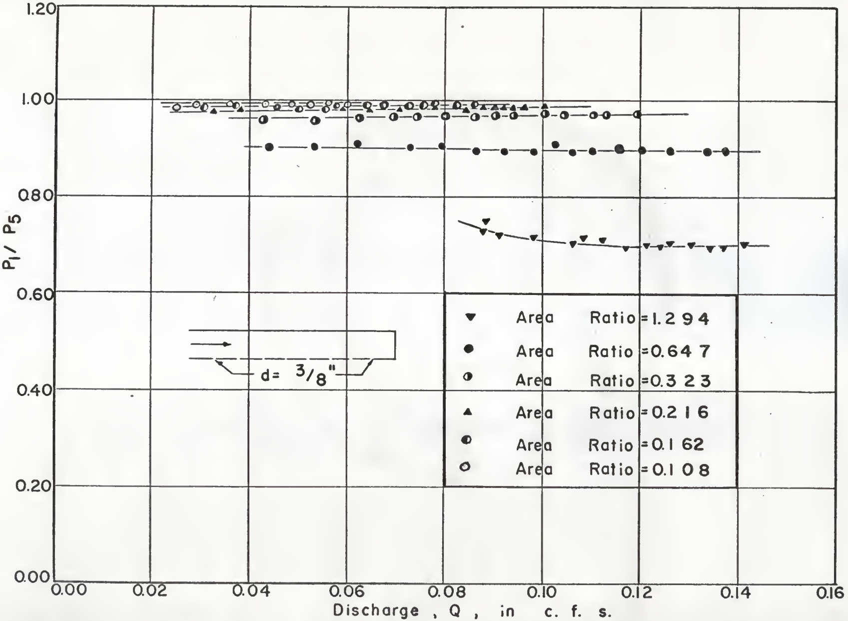


Fig. 21. Ratio of P_1 to P_5

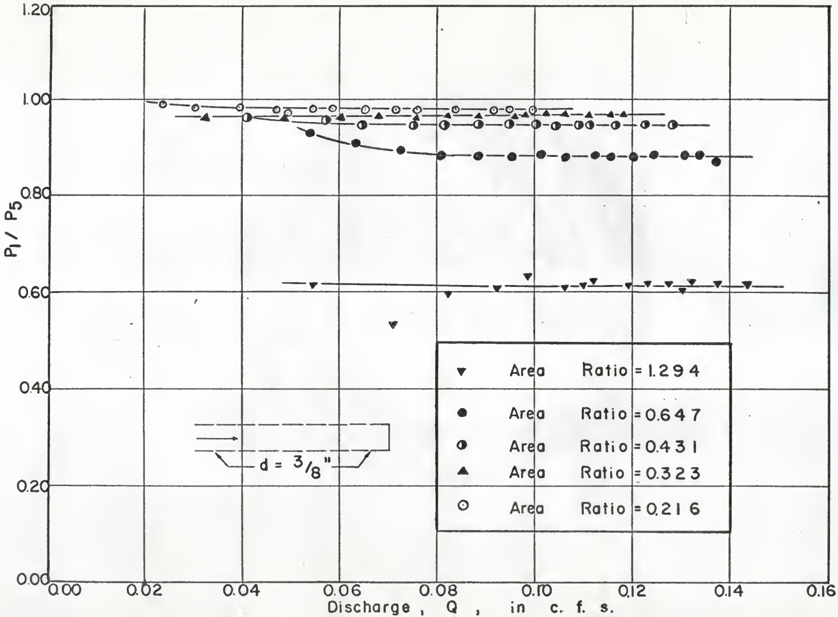


Fig. 22. Ratio of P_1 to P_5

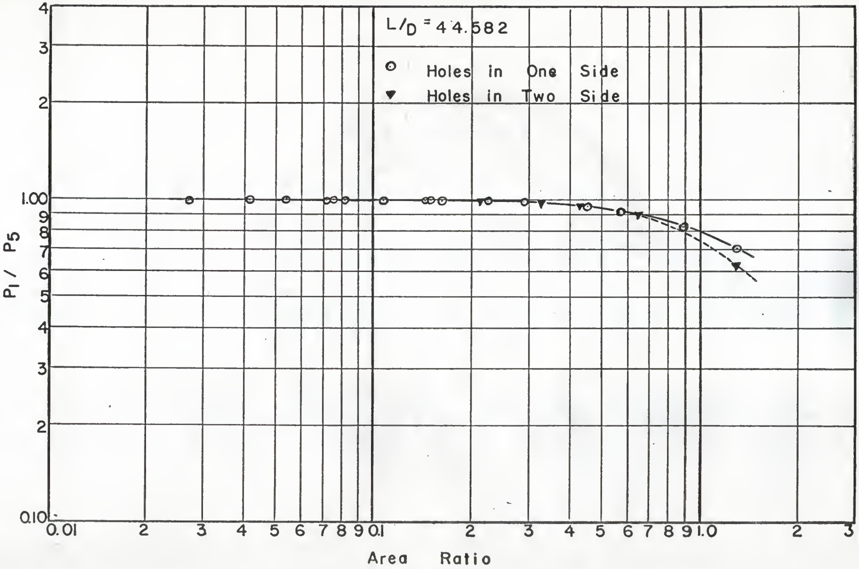


Fig. 23. Relationship between P1/ P5 and Area Ratio

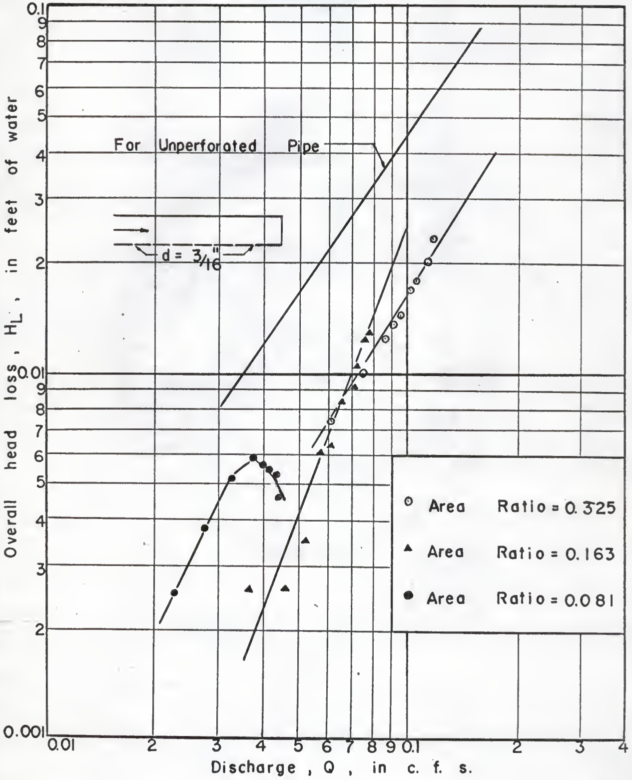


Fig. 24. Overall Head Loss in a Perforated Pipe

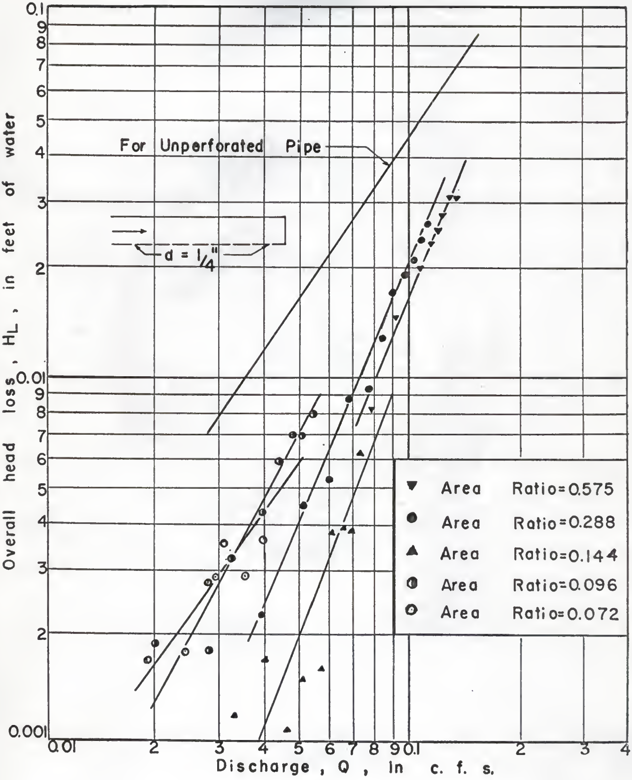


Fig. 25. Overall Head Loss in a Perforated Pipe

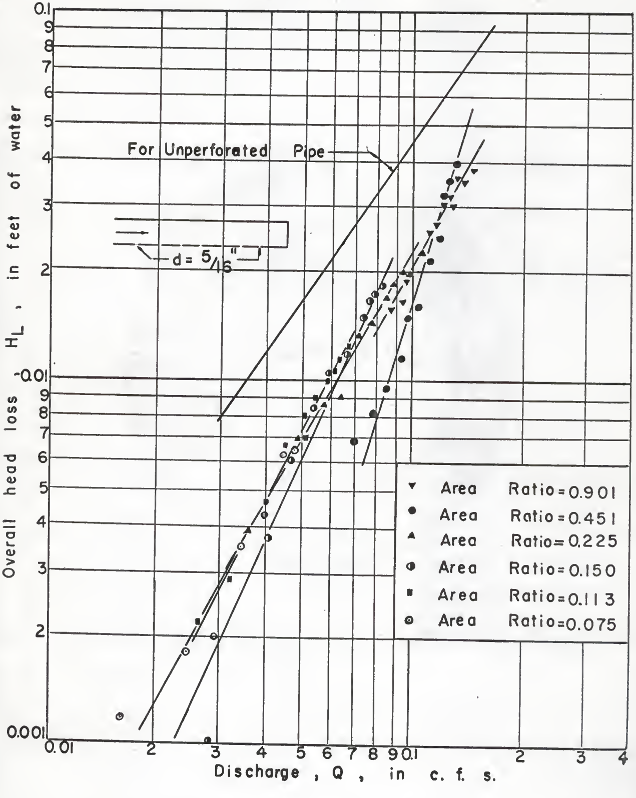


Fig. 26. Overall Head Loss in a Perforated Pipe

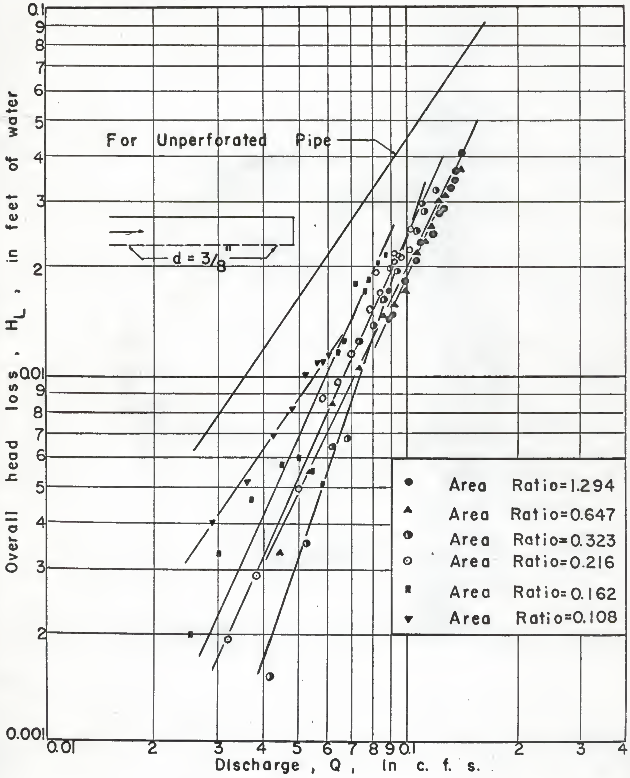


Fig. 27. Overall Head Loss in a Perforated Pipe

Table 2. Uniformity of distribution.

One-Side						
P_1/P_5	1.00	0.99	0.95	0.90	0.80	0.70
Area Ratio	0.075	0.200	0.480	0.670	1.000	1.320
Two-Side						
P_1/P_5	1.00	0.99	0.95	0.90	0.80	0.70
Area Ratio	0.075	0.200	0.480	0.620	0.880	1.115

that overall head loss is proportional to the velocity of the flow to the mth power, that is

$$H_L = C\ V^m$$

where C and m are functions of the area ratio and Reynolds number at the inlet end. Figures 28 and 29 are the plots of overall head loss, H_L, against discharge, Q, for a condition of 96 and 48 holes respectively. It is seen from Fig. 30 that, for the pipe with holes in both sides, the plots are distributed almost in a straight line which is parallel to the curve for unperforated pipe, and that at every flow rate the overall head loss in the unperforated pipe is 2.30 times that in the perforated pipe. R. D. Gladding (6) gave an equation to calculate the head loss in a closed pipe line with evenly spaced outlets, each discharging the same amount of fluid, q. The total discharge Q is then equal to Nq, where N is the total number of outlets.

$$\text{Total Loss of Head} = \left(\frac{\sum_{1}^{N} N^m}{N^{m+1}}\right) KLQ^m$$ in which K is constant and L is the length of the pipe. When m = 2

$$\text{Total Loss of Head} = \left(\frac{\sum_{1}^{N} N^2}{N^3}\right) KLQ^2$$

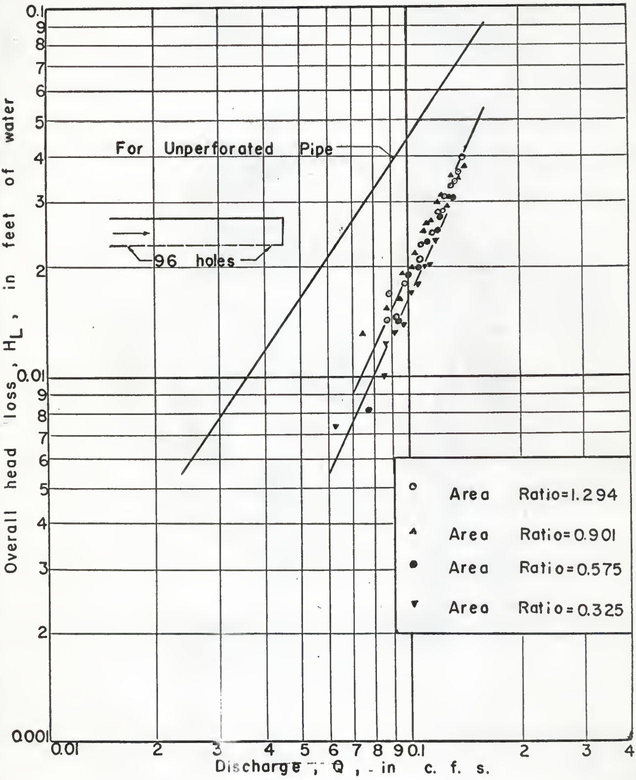


Fig. 28. Overall Head Loss in a Perforated Pipe

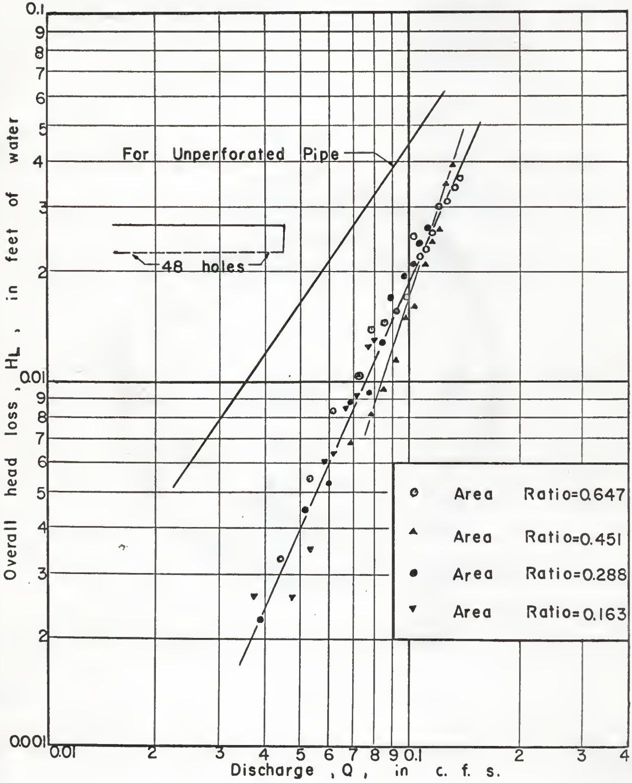


Fig. 29. Overall Head Loss in a Perforated Pipe

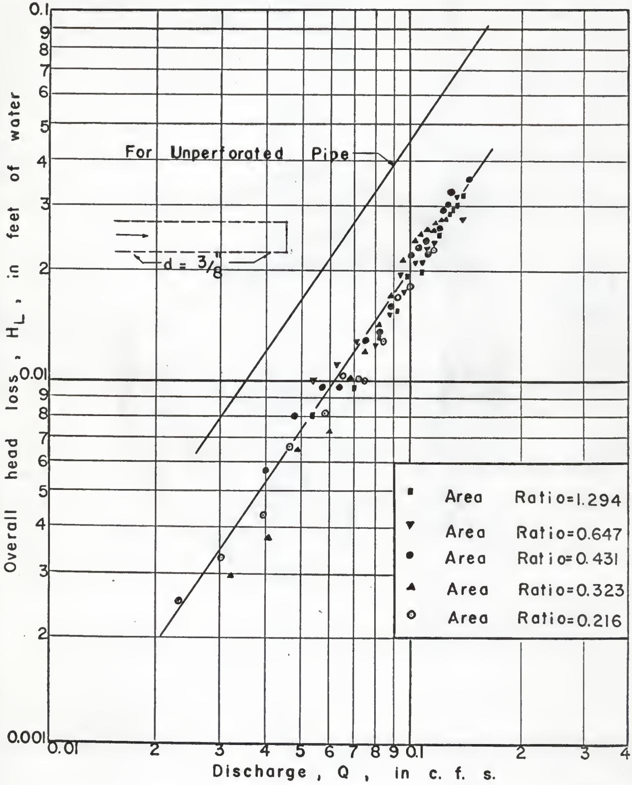


Fig. 30. Overall Head Loss in a Perforated Pipe

or

$$\text{Total Loss of Head} = \left(\frac{2N^3 + 3N^2 + N}{6N^3}\right)KLQ^2$$

And $\frac{2N^3 + 3N^2 + N}{6N^3}$ becomes 1/3 when N approaches to infinitive. That is to say when the number of outlets is very large the head loss in the perforated pipe is only 1/3 of that in the unperforated pipe on the conditions that the outlets are evenly spaced and each outlet is discharging the same quantity of fluid.

Relation of Overall Friction Factor to Reynolds Number in the Perforated Pipe. As defined before

$$H_L = f \frac{L}{D} \frac{V_o^2}{2g}$$

where f is the overall friction factor. An attempt was made to find the effect of the Reynolds number and area ratio upon the overall friction factor by plotting overall friction factor against Reynolds number with area ratio as a third parameter. Figure 31 shows this type of plot for a hole diameter of 3/8". Figure 32 illustrates the plot of the overall friction factor vs Reynolds number for the pipe with holes in both sides.

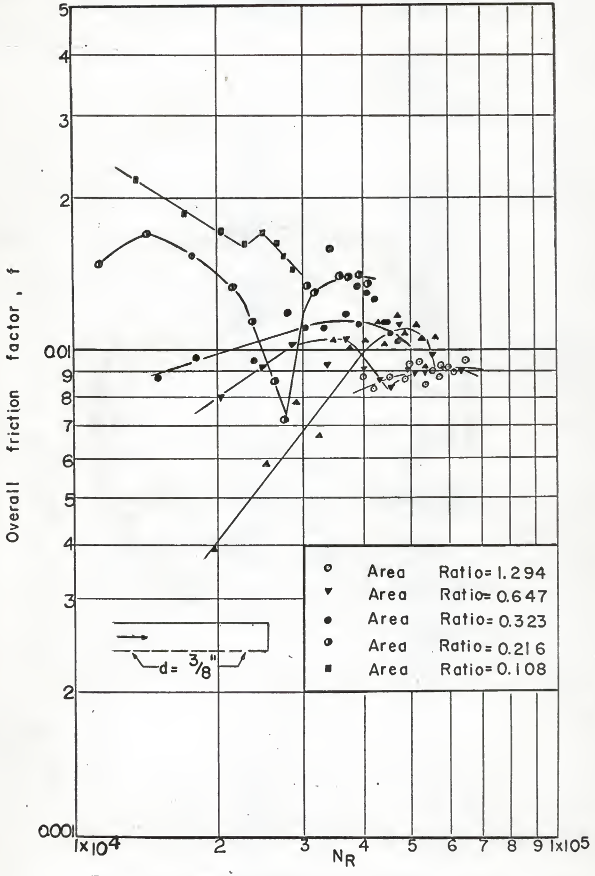


Fig. 31. Overall Friction Factor in a Perforated Pipe

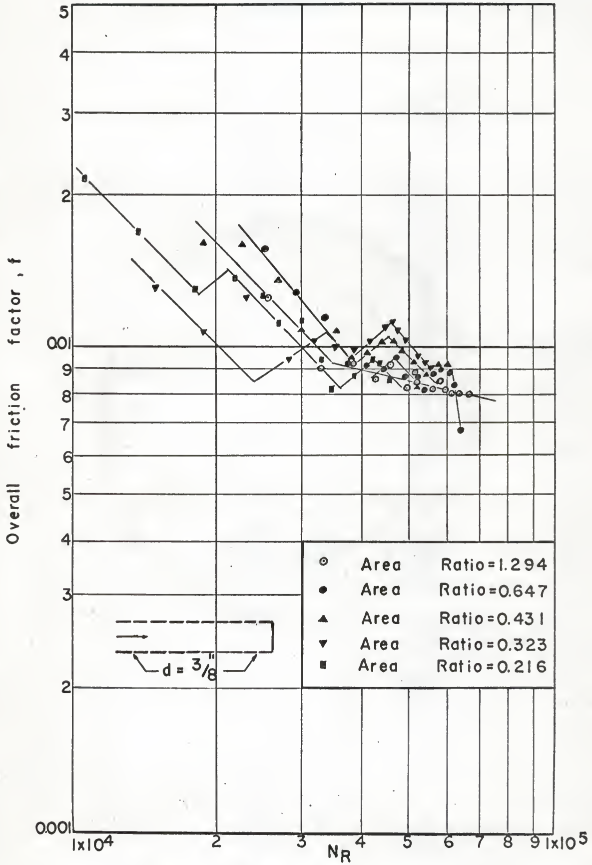


Fig. 32. Overall Friction Factor in a Perforated Pipe

CONCLUSIONS

Three methods of computing overall head loss along the perforated pipe, namely the modified method of Enger and Levy, the momentum method, and the energy method, were used in this study; the results agree with each other very well. These methods are helpful in the practical design of the perforated pipe with evenly spaced outlets on one side or on each side.

An exponential relationship was found to exist between observed pressure recovery and the flow rate of water, with area ratio as a parameter. The observed pressure recovery becomes independent of area ratio when the discharge is greater than 0.120 c.f.s. for two rows of holes with a diameter of 3/8". The observed pressure recovery is nearly independent of area ratio when the total number of holes is equal to or greater than 96 for both one row of holes and two rows of holes.

The uniform distribution of discharged water along the perforated pipe, as observed from experiments, can be secured when the area ratio is less than 0.075 for both one row of holes and two rows of holes. It is seen that the uniformity of 99 per cent can be obtained when the area ratio is less than 0.200 for both cases. The two curves separate at the point where area ratio is equal to 0.500, as illustrated in Fig. 23 and Table 2.

J. D. Keller concluded that the area ratio should not exceed unity and that the ratio of length to diameter should not be greater than 70 for substantially uniform distribution to be obtained. In this investigation when the area ratio is equal to unity, the uniformity is 80 per cent for one row of holes and 75 per cent for two rows of holes.

It is obvious, for the pipe with orifices on one side or on each side, that the overall head loss is less than that in the unperforated pipe. For the case of two rows of holes with a diameter of 3/8", the overall head loss is about 1/2.30 of that in the unperforated pipe. An attempt was made to find the relationship between overall friction factor and Reynolds number at the inlet end, but their relation is not obvious.

It was found, for the case of two rows of holes, that as the area ratio is equal to 2.588, there is open channel flow at some point along the perforated pipe. Decreasing the flow rate causes the point at which open channel flow occurs to move upstream.

It was found that there exists a maximum value of overall friction factor, 0.02243, in the perforated pipe. This was obtained when P_1 equals P_5 no matter what the Reynolds number and area ratio are.

RECOMMENDATIONS FOR FURTHER STUDY

Further research is needed to determine reliable relationships between area ratio, ratio of length to diameter of pipe, and Reynold number upon overall head loss and pressure recovery.

Further examination of the feasibility of defining the expression,

$$H_L = f \frac{L}{D} \frac{V_o^2}{2g}$$

, in order to compute the overall head loss along the perforated pipe would be of value. Further study is also needed to determine the actual relationship between overall friction factor and Reynolds number at the inlet end, so that the perforated pipe can be treated as a simple pipe.

Further investigation of the feasibility of applying the perforated pipe as a rotational sprinkler is also desirable.

ACKNOWLEDGMENT

I wish to express my sincere appreciation and deepest gratitude for the direction, guidance, and encouragement given by Dr. Richard M. Haynie, Assistant Professor of Civil Engineering at Kansas State University. Without his efforts and counsel this research would not have been as rapid or complete.

For his valuable suggestions in the organization and review of this thesis, I would like to extend my sincere thanks to Dr. Jack B. Blackburn, Head of the Civil Engineering Department at Kansas State University.

Appreciation is also expressed to Professor John E. Kipp and Professor Chen-Jung Hsu for being on the advisory committee and reviewing the manuscript.

BIBLIOGRAPHY

1. Enger, M. L. and M. I. Levy. "Pressure in Manifold Pipes." A.W.W.A., Vol. 21, May, 1929, p. 659.

2. Jenks, H. N. "An Investigation of Perforated-Pipe Filter Underdrain." Engg. News Record, Vol. 86, No. 4, 1921, p. 162.

3. Malishewsky, N. "Experiment in the Hydraulics of Filter Underdrain." A.W.W.A., Vol. 17, 1927, p. 667.

4. ________. "Pressure Head in Perforated Pipe." A.W.W.A., Vol. 27, 1935, p. 413.

5. Kunz, Jacob. "Jets from Manifold Tubes." Tr. A.S.M.E., Vol. 53, 1931, APM, p. 181.

6. Gladding, R. D. "Loss of Head Determination in Uniformly Tapped Pipes." Engg. News Record, Vol. 125, 1940, p. 697.

7. Keller, J. D. "The Manifold Problem." Journal of Applied Mechanics, Vol. 16, 1949, p. 77.

8. Dow, W. M. "The Uniform Distribution of a Fluid Flowing through a Perforated Pipe." Tr. A.S.M.E., Vol. 72, 1950, p. 432.

9. Howland, W. E. "Design of Perforated Pipe for Uniformity of Discharge." The Third Midwestern Conference on Fluid Mechanics, 1953, p. 687.

10. Allen, John and Brian Albinson. "An Investigation of the Manifold Problem for Incompressible Fluids with Special Reference to the Use of Manifolds for Canal Locks." Ins. of Civil Engineers, Vol. 4, 1955, p. 114.

11. Horlock, J. H. "An Investigation of the Flow in Manifolds with Open and Closed Ends." J. Roy. Aero. Soc., Vol. 60, 1956, p. 749.

12. Markland, "The Analysis of Flow from Pipe Manifolds." Engineering, Vol. 187, No. 4847, 1959, p. 150.

13. Acrivos, A., B. D. Babcock, and R. L. Pigford. "Flow Distributions in Manifolds." Chemical Engg. Science, Vol. 10, 1959, p. 112.

14. van't Woudt, Bessel D. "Uniform Discharge from Multi-Orificed Pipes." Tr. A.S.A.E., Vol. 7, No. 3, 1964, p. 352.

15. O'Sullivan, J. K. "Flow in Pipes with Drilled Holes." Engineering, Vol. 163, No. 4780, 1957, p. 684.

APPENDICES

APPENDIX I

Notations

The following symbols, adopted for use in this paper, conform in all essential respects with "American Standard Letter Symbols for Hydraulics" (ASA Z10.2 - 1942) prepared by a committee of the American Standards Association with Society representation, and approval by the Association in 1942:

A = cross sectional area of manifold pipe at any point;

a = area of opening per unit length of pipe;

C = Cauchy number;

C = coefficient;

C_q = coefficient of discharge;

d = diameter of orifice;

D = inside diameter of pipe;

dF_m = rate of change of momentum of the fluid discharged from the lateral opening in the flow direction;

e = width of slot;

f = friction factor in unperforated pipe;
overall friction factor in perforated pipe;

F_L = unbalanced force in the direction of flow;

g = gravitational acceleration;

H = pressure head;
pressure head at the downstream end of the slot;

H_{AB} = pressure difference between section A and section B;

H_L = loss of head in unperforated pipe;
overall head loss in perforated pipe;

h = pressure head at upstream end of the slot;

$\bar{h}$ = average static pressure along the perforated pipe;

K = constant;

L = active length of the manifold pipe;

m = coefficient;

n = numerical constant, $n = \frac{C_q a}{A}$;

N = total number of holes;

N_R = Reynolds number;

P_1 = static pressure head at the inlet end of the perforated pipe;

P_5 = static pressure head at the closed end of the perforated pipe;

ΔP = observed pressure head recovery;

ΔP_o = theoretical pressure head recovery;

Q = total rate of flow;

Q_o = total rate of flow at point C;

q = rate of flow from the outlet;

R = hydraulic radius;

s = spacing of orifices;

S = hydraulic gradient;

S_o = hydraulic gradient at point C;

t = time;

u = longitudinal component of discharging velocity;

V = mean velocity at any point of the perforated pipe;

V_o = mean velocity at inlet end, $V_o = Q/A$;

v = perpendicular component of the discharging velocity;

x = distance along manifold pipe from the inlet end;

y = pressure head at a point distance x downstream from the inlet end;

Z = number of holes before certain point at the perforated pipe;

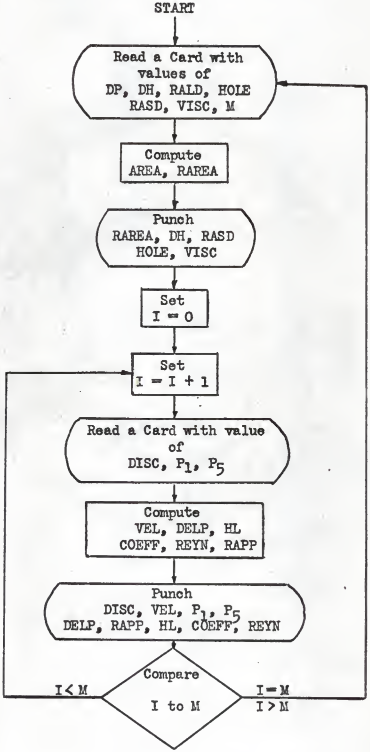
γ = specific weight;

ρ = density;

ν = kinetic viscosity.

APPENDIX II

Flow Diagram for Digital Computer Program



List of Symbols for Computer Program

DP = Diameter of pipe;

DH = Diameter of hole;

RALD = L/D, ratio of length of pipe to its diameter;

HOLE = Total number of holes;

RASD = S/D, ratio of spacing of holes to the pipe diameter;

VISC = Kinetic viscosity;

M = Number of runs;

AREA = Cross sectional area of pipe;

RAREA = Ratio of area of outlets to that of pipe cross section;

DISC = Total discharge of water in the perforated pipe;

P_1 = Static pressure head at the inlet end of the perforated pipe;

P_5 = Static pressure head at the closed end of the perforated pipe;

VEL = Mean velocity at the inlet end of the perforated pipe;

DELP = $P_5 - P_1$, observed pressure head recovery;

HL = Overall head loss along the perforated pipe;

COEFF = Overall friction factor;

REYN = Reynolds number at the inlet end;

RAPP = P_1/P_5, ratio of static pressure head at the inlet end to that at the closed end of the perforated pipe.

Computer Program Used for This Study

```
      PERFORATED PIPE STUDY  MODIFIED METHOD OF ENGER AND LEVY
  100 READ 1,DP,DH,RALD.HOLE,RASD,VISC,M
   10 AREA=.7854*DP**2./144.
   11 RAREA=HOLE*(DH/DP)**2.
  101 PUNCH 2,RAREA,DH,RASD
  102 PUNCH 3,HOLE,VISC
  103 PUNCH 4
      I=0
   31 I=I+1
  104 READ 5,DISC,P1,P5
   12 VEL=DISC/AREA
   13 DELP=P5-P1
      AH=AREA*RAREA
      VJ=SQRT(32.2*(P1+P5))
      CQ=DISC/(AH*VJ)
      X=2.*CQ*RAREA
      B=3.1416-X
      Y=1.-COS(B)
      DELPC=P5*(1.-.5*Y)
   14 HL=DELPC-DELP
   15 COEFF=HL/(RALD*VEL**2./64.4)
   16 REYN=VEL*DP/(12.*VISC)
   17 RAPP=P1/P5
  105 PUNCH 6,DISC,VEL,P1,P5,DELP,RAPP,HL,COEFF,REYN
   21 IF (I-M) 31,100,100
    1 FORMAT (F8.3,F8.3,F8.3,F8.3,F8.3,F10.8,2XI2)
    2 FORMAT (11HAREA RATIO=F7.3,5X14HHOLE DIAMETER=F5.3,5X4HS/D=F7.3)
    3 FORMAT (9HHOLE NO.=F8.3,5X12HKINE. VISC.=F10.8)
    4 FORMAT (4X52HQ     V       P1      P5    P5-P1  P1/P5    HL      F     R)
    5 FORMAT (F8.3,F8.3,F8.3)
    6 FORMAT (F5.3,5F7.3,F6.3,F7.4,F8.0)
      STOP
      END
```

```
    PERFORATED PIPE STUDY          MOMENTUM  METHOD
100 READ 1,DP,DH,RALD,HOLE,RASD,VISC,M
 10 AREA=.7854*DP**2./144.
 11 RAREA=HOLE*(DH/DP)**2.
101 PUNCH 2,RAREA,DH,RASD
102 PUNCH 3,HOLE,VISC
103 PUNCH 4
    I=0
 31 I=I+1
104 READ 5,DISC,P1,P5
 12 VEL=DISC/AREA
 13 DELP=P5-P1
    AH=AREA*RAREA
    VJ=SQRT(32.2*(P1+P5))
    CQ=DISC/(AH*VJ)
    X=CQ*RAREA
    Y=1.-COS(2.*X)
    Z=(SIN(X))**2.
    CON=2.-.5*Y/Z
 14 HL=CON*(VEL**2./64.4)-DELP
 15 COEFF=HL/(RALD*VEL**2./64.4)
 16 REYN=VEL*DP/(12.*VISC)
 17 RAPP=P1/P5
105 PUNCH 6,DISC,VEL,P1,P5,DELP,RAPP,HL,COEFF,REYN
 21 IF (I-M) 31,100,100
  1 FORMAT (F8.3,F8.3,F8.3,F8.3,F8.3,F10.8,2XI2)
  2 FORMAT (11HAREA RATIO=F7.3,5X14HHOLE DIAMETER=F5.3,5X4HS/D=F7.3)
  3 FORMAT (9HHOLE NO.=F8.3,5X12HKINE. VISC.=F10.8)
  4 FORMAT (4X52HQ     V       P1      P5    P5-P1  P1/P5   HL      F     R)
  5 FORMAT (F8.3,F8.3,F8.3)
  6 FORMAT (F5.3,5F7.3,F6.3,F7.4,F8.0)
    STOP
    END
```

```
    PERFORATED PIPE STUDY    ENERGY METHOD
100 READ 1,DP,DH,RALD,HOLE,RASD,VISC,M
 10 AREA=.785+*DP**2./144.
 11 RAREA=HOLE*(DH/DP)**2.
101 PUNCH 2,RAREA,DH,RASD
102 PUNCH 3,HOLE,VISC
103 PUNCH 4
    I=0
 31 I=I+1
104 READ 5,DISC,P1,P5
 12 VEL=DISC/AREA
 13 DELP=P5-P1
 14 HL=(VEL**2./64.4)-DELP
 15 COEFF=HL/(RALD*VEL**2./64.4)
 16 REYN=VEL*DP/(12.*VISC)
 17 RAPP=P1/P5
105 PUNCH 6,DISC,VEL,P1,P5,DELP,RAPP,HL,COEFF,REYN
 21 IF (I-M) 31,100,100
  1 FORMAT (F8.3,F8.3,F8.3,F8.3,F8.3,F10.8,2XI2)
  2 FORMAT (11HAREA RATIO=F7.3,5X14HHOLE DIAMETER=F5.3,5X4HS/D=F7.3)
  3 FORMAT (9HHOLE NO.=F8.3,5X12HKINE. VISC.=F10.8)
  4 FORMAT (4X52HQ     V      P1     P5   P5-P1  P1/P5   HL      F   . R)
  5 FORMAT (F8.3,F8.3,F8.3)
  6 FORMAT (F5.3,5F7.3,F6.3,F7.4,F8.0)
    STOP
    END
```

APPENDIX III

Input Data to Digital Computer Program

INSIDE DIAMETER OF PIPE=3.230 IN.   L/D=44.582

HOLE DIAMETER=.188   HOLE NO.=96   S/D= .465
KINE. VISC.=.00000980   10 RUNS   ONE-SIDE

Q	P1	P5	Q	P1	P5
.117	1.572	1.614	.113	1.460	1.501
.110	1.381	1.419	.105	1.255	1.290
.10[illegible]	1.155	1.187	.096	1.057	1.087
.092	.955	.982	.086	.848	.871
.075	.644	.661	.062	.436	.447

HOLE DIAMETER=.188   HOLE NO.=48   S/D= .929
KINE. VISC.=.00000980   10 RUNS   ONE-SIDE

Q	P1	P5	Q	P1	P5
.079	3.223	3.240	.077	2.990	3.006
.073	2.707	2.722	.071	2.446	2.461
.067	2.142	2.155	.062	1.869	1.881
.058	1.597	1.607	.053	1.293	1.303
.047	1.009	1.017	.037	.529	.533

HOLE DIAMETER=.188   HOLE NO.=24   S/D=1.858
KINE. VISC.=.00000984   8 RUNS   ONE-SIDE

Q	P1	P5	Q	P1	P5
.045	4.269	4.274	.044	3.792	3.796
.042	3.386	3.389	.040	2.930	2.932
.038	2.421	2.422	.033	1.907	1.907
.028	1.129	1.129	.023	.507	.507

HOLE DIAMETER=.188   HOLE NO.=16   S/D=2.786
KINE. VISC.=.00000984   8 RUNS   ONE-SIDE

Q	P1	P5	Q	P1	P5
.029	4.247	4.250	.026	3.572	3.574
.025	3.061	3.063	.022	2.481	2.482
.021	1.927	1.928	.019	1.382	1.383
.018	.897	.897	.016	.449	.449

HOLE DIAMETER=.188 HOLE NO.=12 S/D=3.715
KINE. VISC.=.00000973 7 RUNS ONE-SIDE

Q	P1	P5	Q	P1	P5
.024	4.319	4.321	.022	3.592	3.593
.021	2.939	2.940	.020	2.077	2.078
.019	1.400	1.401	.018	.848	.849
.016	.391	.391			

HOLE DIAMETER=.188 HOLE NO.= 8 S/D=5.573
KINE. VISC.=.00000973 5 RUNS ONE-SIDE

Q	P1	P5	Q	P1	P5
.016	4.202	4.202	.015	2.225	2.225
.014	1.885	1.885	.013	1.186	1.186
.012	.561	.561			

HOLE DIAMETER=.250 HOLE NO.=96 S/D= .465
KINE. VISC.=.00000984 9 RUNS ONE-SIDE

Q	P1	P5	Q	P1	P5
.133	.601	.655	.129	.562	.611
.123	.517	.562	.118	.471	.513
.113	.435	.473	.106	.386	.420
.099	.341	.369	.092	.292	.318
.078	.206	.227			

HOLE DIAMETER=.250 HOLE NO.=48 S/D= .929
KINE. VISC.=.00000991 11 RUNS ONE-SIDE

Q	P1	P5	Q	P1	P5
.112	1.836	1.870	.107	1.669	1.700
.101	1.498	1.526	.096	1.329	1.354
.089	1.168	1.189	.084	1.035	1.056
.077	.859	.878	.069	.675	.689
.060	.502	.514	.051	.346	.354
.039	.179	.184			

HOLE DIAMETER=.250 HOLE NO.=24 S/D=1.858
KINE. VISC.=.00000991 10 RUNS ONE-SIDE

Q	P1	P5	Q	P1	P5
.074	3.434	3.454	.069	3.039	3.058
.066	2.739	2.756	.061	2.320	2.334
.057	1.985	1.999	.051	1.586	1.597
.046	1.281	1.290	.040	.992	.998
.033	.648	.652	.022	.243	.243

HOLE DIAMETER=.250 HOLE NO.=16 S/D=2.786
KINE. VISC.=.00000986 9 RUNS ONE-SIDE

Q	P1	P5	Q	P1	P5
.054	4.053	4.059	.050	3.581	3.586
.048	3.173	3.177	.043	2.587	2.590
.039	2.127	2.130	.033	1.395	1.398
.028	.875	.877	.024	.462	.463
.020	.153	.153			

HOLE DIAMETER=.250 HOLE NO.=12 S/D=3.715
KINE. VISC.=.00001056 7 RUNS ONE-SIDE

Q	P1	P5	Q	P1	P5
.040	3.994	3.998	.035	3.314	3.317
.033	2.764	2.766	.031	2.200	2.201
.028	1.556	1.557	.024	1.002	1.003
.019	.325	.325			

HOLE DIAMETER=.313 HOLE NO.=96 S/D= .465
KINE. VISC.=.00001029 15 RUNS ONE-SIDE

Q	P1	P5	Q	P1	P5
.141	.245	.303	.135	.225	.278
.131	.215	.262	.128	.207	.256
.123	.190	.231	.120	.183	.222
.116	.172	.210	.113	.165	.200
.111	.154	.188	.104	.145	.175
.102	.135	.165	.096	.125	.150
.094	.119	.145	.086	.100	.120
.074	.080	.093			

HOLE DIAMETER=.313 HOLE NO.=48 S/D= .929
KINE. VISC.=.00001026 11 RUNS ONE-SIDE

Q	P1	P5	Q	P1	P5
.130	.885	.927	.126	.813	.854
.120	.749	.792	.116	.683	.723
.110	.619	.656	.103	.552	.587
.098	.479	.510	.092	.429	.458
.085	.371	.396	.078	.310	.331
.069	.227	.243			

HOLE DIAMETER=.313 HOLE NO.=24 S/D=1.858
KINE. VISC.=.00001026 11 RUNS ONE-SIDE

Q	P1	P5	Q	P1	P5
.104	2.209	2.239	.100	2.010	2.038
.096	1.834	1.858	.090	1.615	1.635
.084	1.402	1.419	.077	1.205	1.219
.071	1.028	1.039	.063	.804	.814
.057	.612	.619	.048	.412	.416
.035	.191	.193			

HOLE DIAMETER=.313 HOLE NO.=16 S/D=2.786
KINE. VISC.=.00001035 10 RUNS ONE-SIDE

Q	P1	P5	Q	P1	P5
.082	3.185	3.199	.078	2.869	2.881
.076	2.626	2.637	.072	2.345	2.355
.066	2.010	2.019	.059	1.583	1.589
.053	1.272	1.277	.046	.997	1.001
.040	.640	.644	.028	.266	.269

HOLE DIAMETER=.313 HOLE NO.=12 S/D=3.715
KINE. VISC.=.00001045 10 RUNS ONE-SIDE

Q	P1	P5	Q	P1	P5
.067	3.677	3.686	.064	3.374	3.382
.061	2.923	2.930	.058	2.670	2.676
.054	2.219	2.224	.050	1.888	1.892
.045	1.526	1.529	.040	1.194	1.197
.032	.656	.658	.026	.324	.325

HOLE DIAMETER=.313 HOLE NO.= 8 S/D=5.573
KINE. VISC.=.00001050 8 RUNS ONE-SIDE

Q	P1	P5	Q	P1	P5
.050	3.989	3.994	.047	3.469	3.473
.044	2.957	2.960	.039	2.374	2.377
.034	1.882	1.884	.029	1.294	1.296
.024	.729	.730	.016	.298	.298

HOLE DIAMETER=.375 HOLE NO.=96 S/D= .465
KINE. VISC.=.00001035 15 RUNS ONE-SIDE

Q	P1	P5	Q	P1	P5
.141	.133	.188	.137	.125	.179
.134	.119	.171	.130	.115	.163
.126	.110	.155	.124	.105	.150
.121	.100	.142	.117	.096	.137
.112	.090	.125	.108	.085	.118
.106	.081	.114	.098	.073	.101
.091	.066	.091	.088	.062	.082
.087	.060	.082			

HOLE DIAMETER=.375 HOLE NO.=48 S/D= .929
KINE. VISC.=.00001026 16 RUNS ONE-SIDE

Q	P1	P5	Q	P1	P5
.137	.480	.534	.133	.445	.496
.126	.405	.450	.120	.363	.402
.115	.337	.375	.110	.304	.339
.106	.288	.320	.102	.263	.288
.098	.245	.274	.092	.219	.244
.086	.191	.212	.079	.160	.176
.073	.143	.158	.062	.110	.120
.053	.081	.089	.044	.060	.066

HOLE DIAMETER=.375 HOLE NO.=24 S/D=1.858
KINE. VISC.=.00001016 15 RUNS ONE-SIDE

Q	P1	P5	Q	P1	P5
.119	1.504	1.540	.113	1.385	1.421
.112	1.338	1.370	.110	1.254	1.283
.104	1.156	1.183	.100	1.058	1.081
.094	.950	.973	.090	.869	.888
.086	.771	.790	.080	.685	.702
.074	.584	.598	.069	.476	.492
.062	.394	.406	.053	.281	.291
.042	.179	.186			

HOLE DIAMETER=.375 HOLE NO.=16 S/D=2.786
KINE. VISC.=.00001008 16 RUNS ONE-SIDE

Q	P1	P5	Q	P1	P5
.100	2.495	2.521	.096	2.323	2.346
.096	2.377	2.400	.094	2.227	2.248
.092	2.110	2.130	.090	2.035	2.052
.087	1.910	1.925	.084	1.798	1.815
.082	1.635	1.698	.078	1.521	1.535
.070	1.244	1.256	.064	1.023	1.033
.059	.877	.885	.050	.627	.634
.038	.352	.356	.032	.232	.235

HOLE DIAMETER=.375 HOLE NO.=12 S/D=2.786
KINE. VISC.=.00001000 14 RUNS ONE-SIDE

Q	P1	P5	Q	P1	P5
.086	3.106	3.120	.082	2.809	2.821
.078	2.581	2.592	.075	2.390	2.400
.072	2.184	2.191	.067	1.885	1.894
.064	1.682	1.690	.058	1.420	1.431
.055	1.260	1.269	.050	1.027	1.033
.045	.791	.795	.037	.565	.567
.030	.309	.310	.025	.218	.219

HOLE DIAMETER=.375 HOLE NO.= 8 S/D=5.573
KINE. VISC.=.00001006 8 RUNS ONE-SIDE

Q	P1	P5	Q	P1	P5
.060	3.560	3.566	.058	3.210	3.215
.056	2.908	2.912	.052	2.546	2.549
.048	2.105	2.108	.043	1.702	1.704
.036	1.206	1.207	.029	.760	.760

HOLE DIAMETER=.375 HOLE NO.=96 S/D= .929
KINE. VISC.=.00001014 15 RUNS TWO-SIDE

Q	P1	P5	Q	P1	P5
.143	.104	.167	.137	.095	.153
.132	.089	.142	.130	.082	.134
.127	.081	.130	.123	.075	.120
.119	.070	.113	.112	.063	.100
.110	.058	.093	.106	.055	.089
.098	.048	.075	.092	.040	.065
.082	.029	.048	.070	.016	.030
.054	.010	.016			

HOLE DIAMETER=.375 HOLE NO.=48 S/D=1.858
KINE. VISC.=.00001014 15 RUNS TWO-SIDE

Q	P1	P5	Q	P1	P5
.137	.452	.515	.133	.421	.474
.130	.409	.458	.124	.375	.419
.120	.341	.383	.115	.315	.355
.112	.298	.335	.106	.267	.300
.101	.242	.270	.095	.212	.238
.088	.180	.202	.080	.146	.164
.072	.114	.126	.063	.091	.099
.054	.065	.069			

HOLE DIAMETER=.375 HOLE NO.=32 S/D=2.786
KINE. VISC.=.00001014 15 RUNS TWO-SIDE

Q	P1	P5	Q	P1	P5
.128	.998	1.044	.122	.889	.931
.116	.808	.847	.111	.742	.779
.109	.706	.739	.104	.648	.677
.100	.605	.631	.094	.523	.546
.088	.456	.477	.081	.381	.399
.075	.311	.325	.064	.227	.237
.057	.177	.183	.048	.117	.120
.040	.077	.079			

HOLE DIAMETER=.375 HOLE NO.=24 S/D=3.715
KINE. VISC.=.00001010 15 RUNS TWO-SIDE

Q	P1	P5	Q	P1	P5
.118	1.525	1.565	.115	1.425	1.462
.111	1.335	1.369	.106	1.196	1.227
.102	1.115	1.141	.098	1.015	1.038
.095	.948	.970	.088	.813	.833
.082	.700	.718	.075	.585	.600
.068	.473	.485	.060	.365	.375
.049	.230	.235	.040	.142	.146
.032	.094	.096			

HOLE DIAMETER=.375 HOLE NO.=16 S/D=5.573
KINE. VISC.=.00001024 13 RUNS TWO-SIDE

Q	P1	P5	Q	P1	P5
.099	2.471	2.500	.094	2.235	2.260
.091	2.042	2.065	.083	1.727	1.747
.075	1.395	1.412	.071	1.217	1.231
.065	1.040	1.050	.058	.823	.831
.054	.688	.694	.047	.515	.519
.039	.356	.359	.030	.171	.172
.023	.092	.092			

APPENDIX IV

Output Data from Momentum Method

AREA RATIO= .325 HOLE DIAMETER= .188 S/D= .465
HOLE NO.= 96.000 KINE. VISC.= .00000980

Q	V	P1	P5	P5-P1	P1/P5	HL	F	R
.117	2.056	1.572	1.614	.042	.974	.024	.0081	56474.
.113	1.986	1.460	1.501	.041	.973	.020	.0074	54543.
.110	1.933	1.381	1.419	.038	.973	.020	.0077	53095.
.105	1.845	1.255	1.290	.035	.973	.018	.0076	50682.
.101	1.775	1.155	1.187	.032	.973	.017	.0078	48751.
.096	1.687	1.057	1.087	.030	.972	.014	.0072	46338.
.092	1.617	.955	.982	.027	.973	.014	.0075	44407.
.086	1.511	.848	.871	.023	.974	.012	.0079	41511.
.075	1.318	.644	.661	.017	.974	.010	.0083	36201.
.062	1.090	.436	.447	.011	.975	.007	.0090	29926.

AREA RATIO= .163 HOLE DIAMETER= .188 S/D= .929
HOLE NO.= 48.000 KINE. VISC.= .00000980

Q	V	P1	P5	P5-P1	P1/P5	HL	F	R
.079	1.388	3.223	3.240	.017	.995	.013	.0097	38132.
.077	1.353	2.990	3.006	.016	.995	.012	.0098	37167.
.073	1.283	2.707	2.722	.015	.994	.011	.0093	35236.
.071	1.248	2.446	2.461	.015	.994	.009	.0085	34270.
.067	1.177	2.142	2.155	.013	.994	.009	.0089	32340.
.062	1.090	1.869	1.881	.012	.994	.006	.0078	29926.
.058	1.019	1.597	1.607	.010	.994	.006	.0085	27996.
.053	.931	1.293	1.303	.010	.992	.003	.0058	25582.
.047	.826	1.009	1.017	.008	.992	.003	.0055	22686.
.037	.650	.529	.533	.004	.992	.003	.0088	17859.

AREA RATIO= .081 HOLE DIAMETER= .188 S/D= 1.858
HOLE NO.= 24.000 KINE. VISC.= .00000984

Q	V	P1	P5	P5-P1	P1/P5	HL	F	R
.045	.791	4.269	4.274	.005	.999	.005	.0109	21632.
.044	.773	3.792	3.796	.004	.999	.005	.0128	21152.
.042	.738	3.386	3.389	.003	.999	.005	.0145	20190.
.040	.703	2.930	2.932	.002	.999	.006	.0166	19229.
.038	.668	2.421	2.422	.001	1.000	.006	.0192	18267.
.033	.580	1.907	1.907	0.000	1.000	.005	.0224	15864.
.028	.492	1.129	1.129	0.000	1.000	.004	.0224	13460.
.023	.404	.507	.507	0.000	1.000	.003	.0224	11057.

AREA RATIO= .054 HOLE DIAMETER= .188 S/D= 2.786
HOLE NO.= 16.000 KINE. VISC.= .00000984

Q	V	P1	P5	P5-P1	P1/P5	HL	F	R
.029	.510	4.247	4.250	.003	.999	.001	.0057	13941.
.026	.457	3.572	3.574	.002	.999	.001	.0086	12499.
.025	.439	3.061	3.063	.002	.999	.000	.0075	12018.
.022	.387	2.481	2.482	.001	1.000	.001	.0128	10576.
.021	.369	1.927	1.928	.001	.999	.001	.0118	10095.
.019	.334	1.382	1.383	.001	.999	.000	.0095	9134.
.018	.316	.897	.897	0.000	1.000	.002	.0224	8653.
.016	.281	.449	.449	0.000	1.000	.001	.0224	7692.

AREA RATIO= .041 HOLE DIAMETER= .188 S/D= 3.715
HOLE NO.= 12.000 KINE. VISC.= .00000973

Q	V	P1	P5	P5-P1	P1/P5	HL	F	R
.024	.422	4.319	4.321	.002	1.000	.000	.0062	11668.
.022	.387	3.592	3.593	.001	1.000	.001	.0128	10695.
.021	.369	2.939	2.940	.001	1.000	.001	.0118	10209.
.020	.351	2.077	2.078	.001	1.000	.000	.0107	9723.
.019	.334	1.400	1.401	.001	.999	.000	.0095	9237.
.018	.316	.848	.849	.001	.999	.000	.0080	8751.
.016	.281	.391	.391	0.000	1.000	.001	.0224	7778.

AREA RATIO= .027 HOLE DIAMETER= .188 S/D= 5.573
HOLE NO.= 8.000 KINE. VISC.= .00000973

Q	V	P1	P5	P5-P1	P1/P5	HL	F	R
.016	.281	4.202	4.202	0.000	1.000	.001	.0224	7778.
.015	.264	2.225	2.225	0.000	1.000	.001	.0224	7292.
.014	.246	1.885	1.885	0.000	1.000	.000	.0224	6806.
.013	.228	1.186	1.186	0.000	1.000	.000	.0224	6320.
.012	.211	.561	.561	0.000	1.000	.000	.0224	5834.

AREA RATIO= .575 HOLE DIAMETER= .250 S/D= .465
HOLE NO.= 96.000 KINE. VISC.= .00000984

Q	V	P1	P5	P5-P1	P1/P5	HL	F	R
.133	2.337	.601	.655	.054	.918	.031	.0082	63936.
.129	2.267	.562	.611	.049	.920	.031	.0087	62013.
.123	2.162	.517	.562	.045	.920	.028	.0085	59129.
.118	2.074	.471	.513	.042	.918	.025	.0083	56725.
.113	1.986	.435	.473	.038	.920	.023	.0085	54321.
.106	1.863	.386	.420	.034	.919	.020	.0083	50956.
.099	1.740	.341	.369	.028	.924	.019	.0091	47591.
.092	1.617	.292	.318	.026	.918	.015	.0081	44226.
.078	1.371	.206	.227	.021	.907	.008	.0063	37496.

AREA RATIO= .288 HOLE DIAMETER= .250 S/D= .929
HOLE NO.= 48.000 KINE. VISC.= .00000991

Q	V	P1	P5	P5-P1	P1/P5	HL	F	R
.112	1.968	1.836	1.870	.034	.982	.026	.0098	53460.
.107	1.880	1.669	1.700	.031	.982	.024	.0098	51074.
.101	1.775	1.498	1.526	.028	.982	.021	.0096	48210.
.096	1.687	1.329	1.354	.025	.982	.019	.0097	45823.
.089	1.564	1.168	1.189	.021	.982	.017	.0100	42482.
.084	1.476	1.035	1.056	.021	.980	.013	.0085	40095.
.077	1.353	.859	.878	.019	.978	.009	.0074	36754.
.069	1.213	.675	.689	.014	.980	.009	.0087	32935.
.060	1.054	.502	.514	.012	.977	.005	.0068	28640.
.051	.896	.346	.354	.008	.977	.004	.0080	24344.
.039	.685	.179	.184	.005	.973	.002	.0071	18616.

AREA RATIO= .144 HOLE DIAMETER= .250 S/D= 1.858
HOLE NO.= 24.000 KINE. VISC.= .00000991

Q	V	P1	P5	P5-P1	P1/P5	HL	F	R
.074	1.300	3.434	3.454	.020	.994	.006	.0053	35322.
.069	1.213	3.039	3.058	.019	.994	.004	.0038	32935.
.066	1.160	2.739	2.756	.017	.994	.004	.0042	31503.
.061	1.072	2.320	2.334	.014	.994	.004	.0048	29117.
.057	1.002	1.985	1.999	.014	.993	.002	.0023	27208.
.051	.896	1.586	1.597	.011	.993	.001	.0026	24344.
.046	.808	1.281	1.290	.009	.993	.001	.0025	21957.
.040	.703	.992	.998	.006	.994	.002	.0049	19093.
.033	.580	.648	.652	.004	.994	.001	.0053	15752.
.022	.387	.243	.243	0.000	1.000	.002	.0224	10501.

AREA RATIO= .096 HOLE DIAMETER= .250 S/D= 2.786
HOLE NO.= 16.000 KINE. VISC.= .00000986

Q	V	P1	P5	P5-P1	P1/P5	HL	F	R
.054	.949	4.053	4.059	.006	.999	.008	.0128	25906.
.050	.879	3.581	3.586	.005	.999	.007	.0131	23987.
.048	.844	3.173	3.177	.004	.999	.007	.0143	23028.
.043	.756	2.587	2.590	.003	.999	.006	.0148	20629.
.039	.685	2.127	2.130	.003	.999	.004	.0132	18710.
.033	.580	1.395	1.398	.003	.998	.002	.0095	15832.
.028	.492	.875	.877	.002	.998	.002	.0105	13433.
.024	.422	.462	.463	.001	.998	.002	.0143	11514.
.020	.351	.153	.153	0.000	1.000	.002	.0224	9595.

AREA RATIO= .072 HOLE DIAMETER= .250 S/D= 3.715
HOLE NO.= 12.000 KINE. VISC.= .00001056

Q	V	P1	P5	P5-P1	P1/P5	HL	F	R
.040	.703	3.994	3.998	.004	.999	.004	.0107	17918.
.035	.615	3.314	3.317	.003	.999	.003	.0110	15678.
.033	.580	2.764	2.766	.002	.999	.003	.0138	14782.
.031	.545	2.200	2.201	.001	1.000	.004	.0176	13886.
.028	.492	1.556	1.557	.001	.999	.003	.0165	12542.
.024	.422	1.002	1.003	.001	.999	.002	.0143	10751.
.019	.334	.325	.325	0.000	1.000	.002	.0224	8511.

AREA RATIO= .901 HOLE DIAMETER= .313 S/D= .465
HOLE NO.= 96.000 KINE. VISC.= .00001029

Q	V	P1	P5	P5-P1	P1/P5	HL	F	R
.141	2.478	.245	.303	.058	.809	.037	.0088	64817.
.135	2.372	.225	.278	.053	.809	.034	.0088	62059.
.131	2.302	.215	.262	.047	.821	.035	.0096	60220.
.128	2.249	.207	.256	.049	.809	.030	.0084	58841.
.123	2.162	.190	.231	.041	.823	.032	.0098	56543.
.120	2.109	.183	.222	.039	.824	.030	.0098	55164.
.116	2.039	.172	.210	.038	.819	.027	.0092	53325.
.113	1.986	.165	.200	.035	.825	.026	.0096	51946.
.111	1.951	.154	.188	.034	.819	.025	.0095	51026.
.104	1.828	.145	.175	.030	.829	.022	.0095	47809.
.102	1.793	.135	.165	.030	.818	.020	.0089	46889.
.096	1.687	.125	.150	.025	.833	.019	.0097	44131.
.094	1.652	.119	.145	.026	.821	.016	.0087	43212.
.086	1.511	.100	.120	.020	.833	.015	.0098	39534.
.074	1.300	.080	.093	.013	.860	.013	.0113	34018.

AREA RATIO= .451 HOLE DIAMETER= .313 S/D= .929
HOLE NO.= 48.000 KINE. VISC.= .00001026

Q	V	P1	P5	P5-P1	P1/P5	HL	F	R
.130	2.285	.885	.927	.042	.955	.039	.0108	59935.
.126	2.214	.813	.854	.041	.952	.035	.0104	58091.
.120	2.109	.749	.792	.043	.946	.026	.0085	55325.
.116	2.039	.683	.723	.040	.945	.025	.0085	53481.
.110	1.933	.619	.656	.037	.944	.021	.0081	50715.
.103	1.810	.552	.587	.035	.940	.016	.0070	47487.
.098	1.722	.479	.510	.031	.939	.015	.0073	45182.
.092	1.617	.429	.458	.029	.937	.012	.0064	42416.
.085	1.494	.371	.396	.025	.937	.010	.0062	39189.
.078	1.371	.310	.331	.021	.937	.008	.0063	35961.
.069	1.213	.227	.243	.016	.934	.007	.0067	31812.

AREA RATIO= .225 HOLE DIAMETER= .313 S/D= 1.858
HOLE NO.= 24.000 KINE. VISC.= .00001026

Q	V	P1	P5	P5-P1	P1/P5	HL	F	R
.104	1.828	2.209	2.239	.030	.987	.022	.0095	47948.
.100	1.757	2.010	2.038	.028	.986	.020	.0093	46104.
.096	1.687	1.834	1.858	.024	.987	.020	.0103	44260.
.090	1.582	1.615	1.635	.020	.988	.019	.0109	41494.
.084	1.476	1.402	1.419	.017	.988	.017	.0112	38728.
.077	1.353	1.205	1.219	.014	.989	.014	.0114	35500.
.071	1.248	1.028	1.039	.011	.989	.013	.0122	32734.
.063	1.107	.804	.814	.010	.988	.009	.0106	29046.
.057	1.002	.612	.619	.007	.989	.009	.0124	26279.
.048	.844	.412	.416	.004	.990	.007	.0143	22130.
.035	.615	.191	.193	.002	.990	.004	.0148	16136.

AREA RATIO= .150 HOLE DIAMETER= .313 S/D= 2.786
HOLE NO.= 16.000 KINE. VISC.= .00001035

Q	V	P1	P5	P5-P1	P1/P5	HL	F	R
.082	1.441	3.185	3.199	.014	.996	.018	.0127	37477.
.078	1.371	2.869	2.881	.012	.996	.017	.0132	35649.
.076	1.336	2.626	2.637	.011	.996	.017	.0135	34735.
.072	1.265	2.345	2.355	.010	.996	.015	.0134	32906.
.066	1.160	2.010	2.019	.009	.996	.012	.0128	30164.
.059	1.037	1.583	1.589	.006	.996	.011	.0144	26965.
.053	.931	1.272	1.277	.005	.996	.008	.0141	24223.
.046	.808	.997	1.001	.004	.996	.006	.0136	21024.
.040	.703	.640	.644	.004	.994	.004	.0107	18281.
.028	.492	.266	.269	.003	.989	.000	.0045	12797.

AREA RATIO= .113 HOLE DIAMETER= .313 S/D= 3.715
HOLE NO.= 12.000 KINE. VISC.= .00001045

Q	V	P1	P5	P5-P1	P1/P5	HL	F	R
.067	1.177	3.677	3.686	.009	.998	.013	.0131	30328.
.064	1.125	3.374	3.382	.008	.998	.012	.0133	28970.
.061	1.072	2.923	2.930	.007	.998	.011	.0136	27612.
.058	1.019	2.670	2.676	.006	.998	.010	.0141	26254.
.054	.949	2.219	2.224	.005	.998	.009	.0144	24444.
.050	.879	1.888	1.892	.004	.998	.008	.0149	22633.
.045	.791	1.526	1.529	.003	.998	.007	.0155	20370.
.040	.703	1.194	1.197	.003	.997	.005	.0137	18106.
.032	.562	.656	.658	.002	.997	.003	.0133	14485.
.026	.457	.324	.325	.001	.997	.002	.0155	11769.

AREA RATIO= .075 HOLE DIAMETER= .313 S/D= 5.573
HOLE NO.= 8.000 KINE. VISC.= .00001050

Q	V	P1	P5	P5-P1	P1/P5	HL	F	R
.050	.879	3.989	3.994	.005	.999	.007	.0131	22525.
.047	.826	3.469	3.473	.004	.999	.007	.0140	21174.
.044	.773	2.957	2.960	.003	.999	.006	.0152	19822.
.039	.685	2.374	2.377	.003	.999	.004	.0132	17570.
.034	.598	1.882	1.884	.002	.999	.004	.0143	15317.
.029	.510	1.294	1.296	.002	.998	.002	.0113	13065.
.024	.422	.729	.730	.001	.999	.002	.0143	10812.
.016	.281	.298	.298	0.000	1.000	.001	.0224	7208.

AREA RATIO= 1.294 HOLE DIAMETER= .375 S/D= .465
HOLE NO.= 96.000 KINE. VISC.= .00001035

Q	V	P1	P5	P5-P1	P1/P5	HL	F	R
.141	2.478	.133	.188	.055	.707	.040	.0095	64442.
.137	2.408	.125	.179	.054	.698	.036	.0090	62614.
.134	2.355	.119	.171	.052	.696	.034	.0089	61242.
.130	2.285	.115	.163	.048	.706	.033	.0091	59414.
.126	2.214	.110	.155	.045	.710	.031	.0092	57586.
.124	2.179	.105	.150	.045	.700	.029	.0087	56672.
.121	2.126	.100	.142	.042	.704	.028	.0090	55301.
.117	2.056	.096	.137	.041	.701	.025	.0084	53473.
.112	1.968	.090	.125	.035	.720	.025	.0094	51188.
.108	1.898	.085	.118	.033	.720	.023	.0092	49360.
.106	1.863	.081	.114	.033	.711	.021	.0087	48445.
.098	1.722	.073	.101	.028	.723	.018	.0088	44789.
.091	1.599	.066	.091	.025	.725	.015	.0083	41590.
.088	1.546	.062	.082	.020	.756	.017	.0104	40219.
.087	1.529	.060	.082	.022	.732	.014	.0088	39762.

AREA RATIO= .647 HOLE DIAMETER= .375 S/D= .929
HOLE NO.= 48.000 KINE. VISC.= .00001026

Q	V	P1	P5	P5-P1	P1/P5	HL	F	R
.137	2.408	.480	.534	.054	.899	.036	.0090	63163.
.133	2.337	.445	.496	.051	.897	.034	.0089	61319.
.126	2.214	.405	.450	.045	.900	.031	.0092	58091.
.120	2.109	.363	.402	.039	.903	.030	.0098	55325.
.115	2.021	.337	.375	.038	.899	.025	.0090	53020.
.110	1.933	.304	.339	.035	.897	.023	.0089	50715.
.106	1.863	.288	.320	.032	.900	.022	.0091	48870.
.102	1.793	.263	.288	.025	.913	.025	.0112	47026.
.098	1.722	.245	.274	.029	.894	.017	.0083	45182.

.092	1.617	.219	.244	.025	.898	.016	.0086	42416.
.086	1.511	.191	.212	.021	.901	.014	.0092	39650.
.079	1.388	.160	.176	.016	.909	.014	.0104	36422.
.073	1.283	.143	.158	.015	.905	.011	.0093	33656.
.062	1.090	.110	.120	.010	.917	.008	.0103	28585.
.053	.931	.081	.089	.008	.910	.005	.0091	24435.
.044	.773	.060	.066	.006	.909	.003	.0079	20286.

AREA RATIO= .323 HOLE DIAMETER= .375 S/D= 1.858
HOLE NO.= 24.000 KINE. VISC.= .00001016

Q	V	P1	P5	P5-P1	P1/P5	HL	F	R
.119	2.091	1.504	1.540	.036	.977	.032	.0105	55404.
.113	1.986	1.385	1.421	.036	.975	.025	.0092	52611.
.112	1.968	1.338	1.370	.032	.977	.028	.0105	52145.
.110	1.933	1.254	1.283	.029	.977	.029	.0112	51214.
.104	1.828	1.156	1.183	.027	.977	.025	.0108	48420.
.100	1.757	1.058	1.081	.023	.979	.025	.0117	46558.
.094	1.652	.950	.973	.023	.976	.019	.0103	43765.
.090	1.582	.869	.888	.019	.979	.020	.0115	41902.
.086	1.511	.771	.790	.019	.976	.016	.0104	40040.
.080	1.406	.685	.702	.017	.976	.014	.0100	37246.
.074	1.300	.584	.598	.014	.977	.012	.0105	34453.
.069	1.213	.476	.492	.016	.967	.007	.0067	32125.
.062	1.090	.394	.406	.012	.970	.006	.0078	28866.
.053	.931	.281	.291	.010	.966	.003	.0058	24676.
.042	.738	.179	.186	.007	.962	.001	.0039	19554.

AREA RATIO= .216 HOLE DIAMETER= .375 S/D= 2.786
HOLE NO.= 16.000 KINE. VISC.= .00001008

Q	V	P1	P5	P5-P1	P1/P5	HL	F	R
.100	1.757	2.495	2.521	.026	.990	.022	.0103	46927.
.096	1.687	2.323	2.346	.023	.990	.021	.0108	45050.
.096	1.687	2.377	2.400	.023	.990	.021	.0108	45050.
.094	1.652	2.227	2.248	.021	.991	.021	.0113	44112.
.092	1.617	2.110	2.130	.020	.991	.021	.0114	43173.
.090	1.582	2.035	2.052	.017	.992	.022	.0126	42235.
.087	1.529	1.910	1.925	.015	.992	.021	.0132	40827.
.084	1.476	1.798	1.815	.017	.991	.017	.0112	39419.
.082	1.441	1.685	1.698	.013	.992	.019	.0134	38481.
.078	1.371	1.521	1.535	.014	.991	.015	.0117	36603.
.070	1.230	1.244	1.256	.012	.990	.011	.0110	32849.
.064	1.125	1.023	1.033	.010	.990	.010	.0110	30034.
.059	1.037	.877	.885	.008	.991	.009	.0117	27687.
.050	.879	.627	.634	.007	.989	.005	.0093	23464.
.038	.668	.352	.356	.004	.989	.003	.0095	17832.
.032	.562	.232	.235	.003	.987	.002	.0087	15017.

AREA RATIO= .162 HOLE DIAMETER= .375 S/D= 3.715
HOLE NO.= 12.000 KINE. VISC.= .00001000

Q	V	P1	P5	P5-P1	P1/P5	HL	F	R
.086	1.511	3.106	3.120	.014	.996	.021	.0136	40681.
.082	1.441	2.809	2.821	.012	.996	.020	.0141	38788.
.078	1.371	2.581	2.592	.011	.996	.018	.0140	36896.
.075	1.318	2.390	2.400	.010	.996	.017	.0141	35477.
.072	1.265	2.184	2.191	.007	.997	.018	.0161	34058.
.067	1.177	1.885	1.894	.009	.995	.013	.0131	31693.
.064	1.125	1.682	1.690	.008	.995	.012	.0133	30274.
.058	1.019	1.420	1.431	.011	.992	.005	.0071	27436.
.055	.967	1.260	1.269	.009	.993	.006	.0085	26017.
.050	.879	1.027	1.033	.006	.994	.006	.0112	23651.
.045	.791	.791	.795	.004	.995	.006	.0132	21286.
.037	.650	.565	.567	.002	.996	.005	.0156	17502.
.030	.527	.309	.310	.001	.997	.003	.0172	14191.
.025	.439	.218	.219	.001	.995	.002	.0149	11826.

AREA RATIO= .108 HOLE DIAMETER= .375 S/D= 5.572
HOLE NO.= 8.000 KINE. VISC.= .00001006

Q	V	P1	P5	P5-P1	P1/P5	HL	F	R
.060	1.054	3.560	3.566	.006	.998	.011	.0146	28212.
.058	1.019	3.210	3.215	.005	.998	.011	.0155	27272.
.056	.984	2.908	2.912	.004	.999	.011	.0165	26332.
.052	.914	2.546	2.549	.003	.999	.010	.0172	24451.
.048	.844	2.105	2.108	.003	.999	.008	.0163	22570.
.043	.756	1.702	1.704	.002	.999	.007	.0174	20219.
.036	.633	1.206	1.207	.001	.999	.005	.0188	16927.
.029	.510	.760	.760	0.000	1.000	.004	.0224	13636.

AREA RATIO= 1.294 HOLE DIAMETER= .375 S/D= .929
HOLE NO.= 96.000 KINE. VISC.= .00001014

Q	V	P1	P5	P5-P1	P1/P5	HL	F	R
.143	2.513	.104	.167	.063	.623	.035	.0080	66709.
.137	2.408	.095	.153	.058	.621	.032	.0080	63910.
.132	2.320	.089	.142	.053	.627	.031	.0082	61578.
.130	2.285	.082	.134	.052	.612	.029	.0080	60645.
.127	2.232	.081	.130	.049	.623	.028	.0082	59245.
.123	2.162	.075	.120	.045	.625	.028	.0085	57379.
.119	2.091	.070	.113	.043	.619	.025	.0082	55513.

.112	1.968	.063	.100	.037	.630	.023	.0086	52248.
.110	1.933	.058	.093	.035	.624	.023	.0089	51315.
.106	1.863	.055	.089	.034	.618	.020	.0083	49449.
.098	1.722	.048	.075	.027	.640	.019	.0093	45717.
.092	1.617	.040	.065	.025	.615	.016	.0086	42918.
.082	1.441	.029	.048	.019	.604	.013	.0092	38253.
.070	1.230	.016	.030	.014	.533	.009	.0091	32655.
.054	.949	.010	.016	.006	.625	.008	.0128	25191.

AREA RATIO= .647 HOLE DIAMETER= .375 S/D= 1.858
HOLE NO.= 48.000 KINE. VISC.= .00001014

Q	V	P1	P5	P5-P1	P1/P5	HL	F	R
.137	2.408	.452	.515	.063	.878	.027	.0067	63910.
.133	2.337	.421	.474	.053	.888	.032	.0084	62044.
.130	2.285	.409	.458	.049	.893	.032	.0089	60645.
.124	2.179	.375	.419	.044	.895	.030	.0090	57846.
.120	2.109	.341	.383	.042	.890	.027	.0088	55980.
.115	2.021	.315	.355	.040	.887	.023	.0083	53647.
.112	1.968	.298	.335	.037	.890	.023	.0086	52248.
.106	1.863	.267	.300	.033	.890	.021	.0087	49449.
.101	1.775	.242	.270	.028	.896	.021	.0096	47116.
.095	1.670	.212	.238	.026	.891	.017	.0090	44317.
.088	1.546	.180	.202	.022	.891	.015	.0091	41052.
.080	1.406	.146	.164	.018	.890	.013	.0093	37320.
.072	1.265	.114	.126	.012	.905	.013	.0116	33588.
.063	1.107	.091	.099	.008	.919	.011	.0130	29389.
.054	.949	.065	.069	.004	.942	.010	.0160	25191.

AREA RATIO= .431 HOLE DIAMETER= .375 S/D= 2.786
HOLE NO.= 32.000 KINE. VISC.= .00001010

Q	V	P1	P5	P5-P1	P1/P5	HL	F	R
.128	2.249	.998	1.044	.046	.956	.033	.0093	59948.
.122	2.144	.889	.931	.042	.955	.029	.0092	57138.
.116	2.039	.808	.847	.039	.954	.026	.0089	54328.
.111	1.951	.742	.779	.037	.953	.022	.0084	51986.
.109	1.916	.706	.739	.033	.955	.024	.0094	51050.
.104	1.828	.648	.677	.029	.957	.023	.0099	48708.
.100	1.757	.605	.631	.026	.959	.022	.0103	46835.
.094	1.652	.523	.546	.023	.958	.019	.0103	44024.
.088	1.546	.456	.477	.021	.956	.016	.0097	41214.
.081	1.423	.381	.399	.018	.955	.013	.0096	37936.
.075	1.318	.311	.325	.014	.957	.013	.0108	35126.
.064	1.125	.227	.237	.010	.958	.010	.0110	29974.
.057	1.002	.177	.183	.006	.967	.010	.0138	26696.
.048	.844	.117	.120	.003	.975	.008	.0163	22481.
.040	.703	.077	.079	.002	.975	.006	.0166	18734.

AREA RATIO= .323 HOLE DIAMETER= .375 S/D= 3.715
HOLE NO.= 24.000 KINE. VISC.= .00001010

Q	V	P1	P5	P5-P1	P1/P5	HL	F	R
.118	2.074	1.525	1.565	.040	.974	.027	.0090	55265.
.115	2.021	1.425	1.462	.037	.975	.026	.0093	53860.
.111	1.951	1.335	1.369	.034	.975	.025	.0095	51986.
.106	1.863	1.198	1.227	.029	.976	.025	.0104	49645.
.102	1.793	1.115	1.141	.026	.977	.024	.0107	47771.
.098	1.722	1.015	1.038	.023	.978	.023	.0112	45898.
.095	1.670	.948	.970	.022	.977	.021	.0110	44493.
.088	1.546	.813	.833	.020	.976	.017	.0104	41214.
.082	1.441	.700	.718	.018	.975	.014	.0099	38404.
.075	1.318	.585	.600	.015	.975	.012	.0100	35126.
.068	1.195	.473	.485	.012	.975	.010	.0103	31848.
.060	1.054	.365	.375	.010	.973	.007	.0094	28101.
.049	.861	.230	.235	.005	.979	.007	.0127	22949.
.040	.703	.142	.146	.004	.973	.004	.0107	18734.
.032	.562	.094	.096	.002	.979	.003	.0133	14987.

AREA RATIO= .216 HOLE DIAMETER= .375 S/D= 5.573
HOLE NO.= 16.000 KINE. VISC.= .00001024

Q	V	P1	P5	P5-P1	P1/P5	HL	F	R
.099	1.740	2.471	2.500	.029	.988	.018	.0086	45732.
.094	1.652	2.235	2.260	.025	.989	.017	.0092	43423.
.091	1.599	2.042	2.065	.023	.989	.017	.0094	42037.
.083	1.459	1.727	1.747	.020	.989	.013	.0089	38341.
.075	1.318	1.395	1.412	.017	.988	.010	.0083	34646.
.071	1.248	1.217	1.231	.014	.989	.010	.0094	32798.
.065	1.142	1.040	1.050	.010	.990	.010	.0114	30026.
.058	1.019	.823	.831	.008	.990	.008	.0113	26793.
.054	.949	.688	.694	.006	.991	.008	.0128	24945.
.047	.826	.515	.519	.004	.992	.007	.0140	21711.
.039	.685	.356	.359	.003	.992	.004	.0132	18016.
.030	.527	.171	.172	.001	.994	.003	.0172	13858.
.023	.404	.092	.092	0.000	1.000	.003	.0224	10625.

APPENDIX V

COMPARISON OF OVERALL HEAD LOSS AS CALCULATED BY THE MODIFIED METHOD OF ENGER AND LEVY, THE MOMENTUM METHOD, AND THE ENERGY METHOD

AREA RATIO= .901 HOLE DIAMETER= .313 S/D= .465
HOLE NO.= 96.000 KINE. VISC.= .00001029

Q	MODIFIED METHOD	MOMENTUM METHOD	ENERGY METHOD
.141	.036	.037	.037
.135	.033	.034	.034
.131	.034	.035	.035
.128	.029	.030	.030
.123	.030	.032	.032
.120	.029	.030	.030
.116	.025	.027	.027
.113	.025	.026	.026
.111	.024	.025	.025
.104	.021	.022	.022
.102	.019	.020	.020
.096	.018	.019	.019
.094	.016	.016	.016
.086	.015	.015	.015

AREA RATIO= .451 HOLE DIAMETER= .313 S/D= .929
HOLE NO.= 48.000 KINE. VISC.= .00001026

Q	MODIFIED METHOD	MOMENTUM METHOD	ENERGY METHOD
.130	.039	.039	.039
.126	.035	.035	.035
.120	.026	.026	.026
.116	.024	.025	.025
.110	.021	.021	.021
.103	.016	.016	.016
.098	.015	.015	.015
.092	.012	.012	.012
.085	.010	.010	.010
.078	.008	.008	.008
.069	.007	.007	.007

AREA RATIO= .225 HOLE DIAMETER= .313 S/D= 1.858
HOLE NO.= 24.000 KINE. VISC.= .00001026

Q	MODIFIED METHOD	MOMENTUM METHOD	ENERGY METHOD
.104	.022	.022	.022
.100	.020	.020.	.020
.096	.020	.020.	.020
.090	.019	.019.	.019

.084	.017	.017	.017
.077	.014	.014	.014
.071	.013	.013	.013
.063	.009	.009	.009
.057	.009	.009	.009
.048	.007	.007	.007
.035	.004	.004	.004

AREA RATIO= .150 HOLE DIAMETER= .313 S/D= 2.786
HOLE NO.= 16.000 KINE. VISC.= .00001035

Q	MODIFIED METHOD	MOMENTUM METHOD	ENERGY METHOD
.082	.018	.018	.018
.078	.017	.017	.017
.076	.017	.017	.017
.072	.015	.015	.015
.066	.012	.012	.012
.059	.011	.011	.011
.053	.008	.008	.008
.046	.006	.006	.006
.040	.004	.004	.004
.028	.001	.000	.001

AREA RATIO= .113 HOLE DIAMETER= .313 S/D= 3.715
HOLE NO.= 12.000 KINE. VISC.= .00001045

Q	MODIFIED METHOD	MOMENTUM METHOD	ENERGY METHOD
.067	.013	.013	.013
.064	.012	.012	.012
.061	.011	.011	.011
.058	.010	.010	.010
.054	.009	.009	.009
.050	.008	.008	.008
.045	.007	.007	.007
.040	.005	.005	.005
.032	.003	.003	.003
.026	.002	.002	.002

AREA RATIO= .075 HOLE DIAMETER= .313 S/D= 5.573
HOLE NO.= 8.000 KINE. VISC.= .00001050

Q	MODIFIED METHOD	MOMENTUM METHOD	ENERGY METHOD
.050	.007	.007	.007
.047	.007	.007	.007
.044	.006	.006	.006
.039	.004	.004	.004
.034	.004	.004	.004
.029	.002	.002	.002
.024	.002	.002	.002
.016	.001	.001	.001

AN EXPERIMENTAL STUDY OF HEAD LOSS AND PRESSURE RECOVERY IN PERFORATED PIPES

by

WEN-HSIUNG CHIU

B. S., Taiwan Provincial Cheng-Kung University, 1962

AN ABSTRACT

OF A MASTERS THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Civil Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1967

ABSTRACT

For years, the study of the uniform distribution of discharged fluid and the head loss along the manifold pipe has attracted the interest of many investigators. As the flow characteristics of perforated pipe involve complexities by reason of several uncertain factors, such as variable coefficient of discharge, velocity head factor, efficiency of conversion of kinetic energy to pressure energy, and friction factor. The author has studied the problem by combining results of experiments and of simplified analysis. The perforated pipe was considered as a continuous, uniform, and homogeneous unit, and treated as a simple pipe. Experiments were conducted to determine the effect of the Reynolds number at the inlet end of the perforated pipe and ratio of area of the holes to the pipe cross sectional area on the overall head loss and pressure recovery. Three methods of analysis, namely the modified method of Enger and Levy, the momentum method, and the energy method, have been employed in this study. These methods are helpful in the practical design of a perforated pipe with evenly spaced outlets on one side or on each side.

Approximately uniform distribution of discharged fluid may be secured from a perforated pipe with holes of equal size and equal spacing if the total area of holes is small in relation to the cross sectional area of the pipe and if the pipe is of large diameter in relation to its length. It was found from this study, that the uniformity of 99 per cent can be secured when the area ratio is less than 0.200 for both one row of holes and two rows of holes; that the uniformity of 90 per cent can be obtained when the area ratio is less than 0.67 and 0.62 for one row of holes and two rows of holes respectively.