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Hydraulic Characteristics of a Modified Venturi Section

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HYDRAULIC CHARACTERISTICS OF A MODIFIED VENTURI SECTION

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Mohammad Aslam Rasheed

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ABSTRACT

Hydraulic Characteristics of a Modified Venturi Section

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The measurement of water in open channels on extremely flat grades is difficult because of the head loss that is necessary. A modified ventrui section, the contraction of which is provided by a top cover section mounted in a rectangular flume, is proposed to meet the requirements of a suitable measuring device for use in canals of flat gradients.

The method of finite differences has been used for the mathematical solution to the idealized inviscid flow problem. This was followed by a laboratory investigation to ascertain the hydraulic characteristics of the proposed design.

The experiments were conducted in a 3 feet by 3 feet by 200 feet concrete flume. The equation for discharge as obtained in this study is as follows:

$$Q = C_D A_t \sqrt{2g \Delta h}$$

Coefficient of discharge C_D has been calculated for throat openings of 5, 6, 7, 8 and 9 inches.

The results have been presented in the form of curves and these curves have been compared with the work done by previous investigators.

(78 pages)

INTRODUCTION

One of the important problems in irrigation is measuring irrigation water that flows in open channels. Several devices have been used for measuring irrigation water including weirs and Parshall flumes. Usually weirs and Parshall flumes may be used effectively. However, in areas of flat topography, low canal gradients and lack of freeboard may not provide sufficient head to allow for the use of such devices. One of the main disadvantages of weirs and Parshall flumes in canals of flat gradients is the reduction of the capacity of the canal owing to the further reduction of the gradient.

Characteristics of a suitable water measuring device

Following are the desirable characteristics of a suitable water measuring device for use on canals of low gradients.

1. A low resistance to flow i.e. low head loss;
2. Easily measurable head;
3. Small effect on silt and debris deposition;
4. Simple construction and low cost;
5. Freedom from clogging by floating debris.

Objectives

The objective of this study is to develop a modified venturi section to measure water in open channels on extremely flat grades. The contraction of the venturi section is provided by a movable top cover section installed in a rectangular flume.

The design will be done by

1. Determining the head loss caused by the section.
2. Determining the coefficient of discharge for the section.
3. Developing an equation for discharge for the section.

The development includes both a mathematical solution to the idealized inviscid flow problem by the method of finite differences and a laboratory investigation to ascertain the validity of the design and its hydraulic characteristics.

The work done in this thesis is a continuation of the work previously done by graduate students at the University of California and Utah State University.

REVIEW OF LITERATURE

Water measuring devices in use

There are many different types of water measuring devices in use in irrigation systems. The most commonly used devices are, the weir in its different forms, orifices, venturi flumes and Parshall flumes. Each device has its own advantages and disadvantages, depending on canal gradients and other specific requirements.

The weir is a simple device, easy to construct and simple to operate. It consists of a small overflow dam constructed across the channel to create a measurable head. The weir is a suitable metering device for open channels with steep grades. One of the main disadvantages of a weir is that the aerated nappe requires an unrecoverable height of fall which increases with the size of the structure. The upstream stilling pool, required for accurate results, causes a reduction in velocity which might cause deposition of sediments. For these reasons a weir is not considered a suitable measuring device for open channels with small slopes, especially in medium to large canals.

A submerged orifice has an advantage over the weir, because the required head loss is smaller than that for a weir, as some of the velocity head can be recovered. The disadvantages of a submerged orifice are that it requires an operating head which is attained by impounding the water. This makes the installation a little difficult. The range of flow that can be measured with an orifice of fixed dimensions is often too low to satisfy the requirements.

Orifices collect sediments and floating debris. These limitations reduce their utility for measuring water in open channels with low grades.

The venturi tube is one of the best measuring devices because it offers a low resistance to the flow and a high degree of accuracy. It creates an easily measurable differential head, but is expensive to construct when applied to open channels. It must run full to accurately measure the flow. Venturi tubes are not suitable for large channels.

The Parshall measuring flume is probably the best measuring device available for use in canals with low gradients. It violates the criterion of low resistance to the flow, because the head loss depends on the total head measurement, which itself is dependent on the size of the structure and flow.

Modified venturi section

Considering the limitations of the available metering devices the pioneers of a modified venturi section thought of a device that could be used effectively on canals with flat grades. The device was based on the principles of a venturi tube. The principle of a venturi tube as stated by Daugherty and Ingersell is,

> A converging tube is an efficient device for converting pressure head to velocity head, while the diverging tube converts velocity head to the pressure head. The definite relationship between the pressure differential and the rate of flow affords a basis for flow measurement. (Daugherty and Ingersell, 1954, p. 125)

The modified venturi section differs from a venturi tube as in the case of the modified venturi section the area and shape of the channel section remain constant. The required convergence is obtained by introducing a top cover-section in a rectangular flume. Thus the channel can be considered a closed conduit for the length of the device.

According to Garton (1950) a device utilizing the top cover section was first tested by the Bureau of Reclamation in 1915. The first field application of a similar device was made by I. H. Tielman, Chief Engineer of the Consolidated Irrigation District at Selma, California.

The first known experimental work to find the best possible shape for a modified venturi section was done by Yallalee (1938) at the University of California. As a result of these investigations Yallalee recommended the shape of the section shown in Figure 1. This shape was obtained by joining two arcs of different radii. The surface which comes in contact with water starts as a plane surface 60 degrees to the horizontal and tangent to the arc of radius R. Another arc of radius 3R is tangential to this and a plane surface at 20 degrees to the horizontal on the other end. The overall length for a radius of 2 feet was 8.84 feet. The experiments were performed in a flume 0.5 feet wide.

Ferguson (1949) revised the shape of the top cover section in order to facilitate construction. A straight line was used in place of the arc of radius 3R on the downstream portion. The top cover section was made from corrugated sheet metal. Ferguson's (1949) experiments were performed in a plywood flume 48 feet long and 0.5 feet wide. A 3 inch plate orifice made of brass was used to measure the quantity of water actually coming into the flume.

Garton (1950) conducted a field study for a modified venturi section by using a device similar to the one used by Ferguson but it had a width of 24 1/2

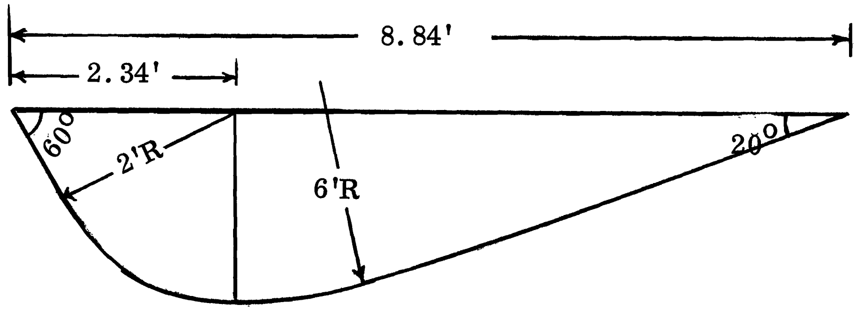

Figure 1. Shape of modified venturi section as proposed by Yallalee.

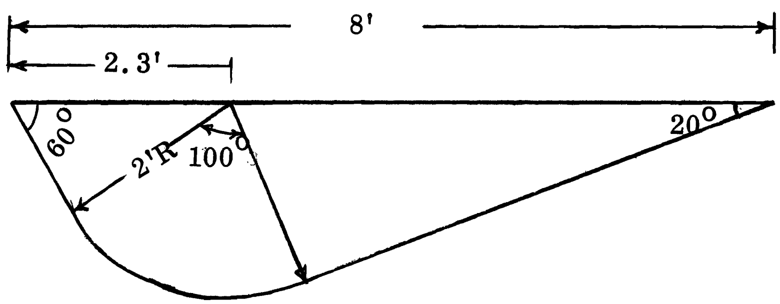

Figure 2. Shape of modified venturi section as proposed by Ferguson.

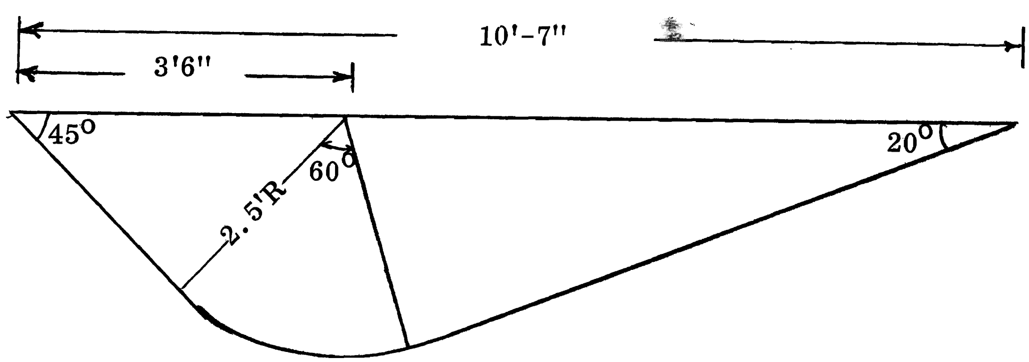

Figure 3. Shape of modified venturi section used in this thesis.

inches instead of 6 inches. Garton's study was conducted in a trapezoidal concrete canal. The trapezoidal section was built with a bottom width of 2 feet and 1 1/2:1 side slopes. The lined section was 55 feet long. The modified venturi section was installed in a rectangular concrete section 10 feet long, 2.5 feet deep and 24.5 inches wide. The top cover section was supported by a frame of steel angles. A 24 inch rectangular supressed weir was used to measure the flow. The precision of flow measurement is not known.

Skjerseth (1951) conducted a study to determine the hydraulic characteristics of a modified venturi section. This work was a further extension of the work done by Ferguson and Garton. He used two different sections. One of these was similar to Ferguson's but was constructed from 16 ounce copper instead of corrugated galvanized steel. The second model was the same as used by Garton. Skjerseth also applied the principles of dimensional analysis to develop a general equation applicable to geometrically similar devices.

Equation of discharge

The discharge through a section can be calculated by the application of Bernoulli's theorem and the equation of continuity. The application of Bernoulli theorem is dependent on the assumptions that the flow is incompressible, steady uniform across a cross section and there is no friction loss through the section. To simplify the application of Bernoulli theorem the flow is also assumed to be turbulent so that the value of energy coefficient can be taken as unity. Ferguson (1949) applied this equation between two points on the top cover section. Garton (1950) in addition also applied this equation between two points in the side of the test channel. Yallalee (1938) applied this equation between a section upstream of the device and the throat section. The expression for discharge used by Ferguson and Garton was one form of the venturi tube equation, i. e.,

$$Q = \frac{C_q \; A_t \sqrt{2\,g\,(h_x - h_t)}}{\sqrt{1 - (\frac{A_t}{A_x})^2}} \qquad (1)$$

Where

Q = discharge

C_q = coefficient of discharge

A_1 = cross sectional area at point x

A_t = cross sectional area at the throat

h_x, h_t = piezometric head at points x and t respectively

g = acceleration due to gravity

From equation (1) the expression for coefficient of discharge was written as follows:

$$C_q = \frac{Q\sqrt{1 - (\frac{A_t}{A_x})^2}}{A_t\sqrt{2g(h_x - h_t)}} \qquad (2)$$

THEORY

Numerical solution

The solution to the problem of fluid flow under the modified venturi section is based on potential theory, and is obtained by formulating a boundary value problem whose solution has been obtained using the method of finite differences. The velocity components u and v in the x and y coordinate directions for two dimensional inviscid flow can be obtained from either the stream function ψ or potential function ϕ as shown by the following equations

$$u = \frac{\partial \psi}{\partial y} = \frac{\partial \phi}{\partial x} \tag{3}$$

and

$$v = - \frac{\partial \psi}{\partial x} = \frac{\partial \phi}{\partial y} \tag{4}$$

Substituting these expressions in the continuity equation and irrotational equation respectively gives partial differential equations for ϕ and ψ. From the solution of either of these equations, the velocity, pressure etc. can be obtained anywhere throughout the flowfield. The major difficulty in obtaining the solution for either ϕ or ψ is that the position of the upper surface of the flow region in unknown, and consequently the region of the boundary value problem cannot be defined. An approach which has been used by Southwell (1946) and others is to assume a position, relax the field points, and then adjust the position in light of the inconsistencies which appear in the solution. No systematic means of adjusting the position of the unknown boundary is available and any change in the position has an influence throughout the entire flow field. In the problem at hand the added difficulty exists as it is desired to find a shape of the top cover section that would result in a velocity distribution with mild enough adverse pressure gradients to prevent separation.

In order to overcome these difficulties inherent in obtaining the solution in the physical plane, the problem has been transformed to a problem in the plane of the potential function ϕ and the stream function ψ. The coordinate directions x and y appear to be the most appropriate dependent variables in the formulation. The governing equation can be obtained by following the rules for transformation of variables as given by Taylor (1955), that is if $\phi = F(x, y)$ and $\psi = G(x, y)$ then x and y are also some functions of ϕ and ψ or $x = f(\phi, \psi)$ and $y = g(\phi, \psi)$ such that

$$\frac{\partial y}{\partial \psi} = \frac{1}{J} \frac{\partial \phi}{\partial x} \tag{5}$$

$$\frac{\partial x}{\partial \phi} = \frac{1}{J} \frac{\partial \psi}{\partial y} \tag{6}$$

$$\frac{\partial y}{\partial \phi} = -\frac{1}{J} \frac{\partial \psi}{\partial x} \tag{7}$$

$$\frac{\partial x}{\partial \psi} = -\frac{1}{J} \frac{\partial \phi}{\partial y} \tag{8}$$

Where J is the Jacobian given by

$$J = \begin{vmatrix} \frac{\partial \phi}{\partial x} & \frac{\partial \phi}{\partial y} \\ \frac{\partial \psi}{\partial x} & \frac{\partial \psi}{\partial y} \end{vmatrix} = v^2 \tag{9}$$

By substituting these last equations into (3) and (4) one arrives at the Cauchy-Rieman condition

$$\frac{\partial x}{\partial \phi} = \frac{\partial y}{\partial \psi} \tag{10}$$

$$\frac{\partial y}{\partial \phi} = -\frac{\partial x}{\partial \psi} \tag{11}$$

Upon integrating (10) and (11) one can obtain the solution of x from the solution of y or the solution of y from the solution of x as indicated below.

$$x = \int_{\psi} \left(\frac{\partial y}{\partial \psi}\right)_{\phi} d\phi \tag{12}$$

$$x = -\int_{\phi} \left(\frac{\partial y}{\partial \psi}\right)_{\psi} d\psi \tag{13}$$

$$y = -\int_{\psi} \left(\frac{\partial y}{\partial \psi}\right)_{\phi} d\phi \tag{14}$$

$$y = \int_{\phi} \left(\frac{\partial y}{\partial \phi}\right)_{\psi} d\psi \tag{15}$$

In these last equations the subscripts by the integral sign denote that the integration is to be carried out along either a ϕ = constant line or ψ = constant line. Jeppson (1966) in Appendix A describes methods for performing the indicated partial differentiation and integration by numerical methods which are well adapted to digital computers.

From the Cauchy-Rieman conditions either x or y may be eliminated by differentiation giving the following Laplace equations

$$\frac{\partial^2 x}{\partial \phi^2} + \frac{\partial^2 x}{\partial \psi^2} = 0 \qquad (16)$$

$$\frac{\partial^2 y}{\partial \phi^2} + \frac{\partial^2 y}{\partial \psi^2} = 0 \qquad (17)$$

In order to formulate the boundary value problems for either x or y in the $\phi\psi$ plane it is necessary to have a relation between x and y and such quantities as the velocity and the direction of flow in the $\phi\psi$ plane. Jeppson (1966) has developed several of these relations and shown how they can be used for boundary conditions. Two of these relations which have been used here are

$$V = \frac{1}{\sqrt{\left(\frac{\partial y}{\partial \phi}\right)^2 + \left(\frac{\partial y}{\partial \psi}\right)^2}} \qquad (18)$$

and

$$\theta = \cot^{-1}\left[\left(\frac{\partial y}{\partial \psi}\right) / \left(\frac{\partial x}{\partial \phi}\right) \right] \qquad (19)$$

The last two equations also permit a determination of the velocity and direction of flow at any point in the flow field.

The problem can most readily be solved for y first. The formulation of the boundary value problem for y is shown in Figure 4. In the formulation it is

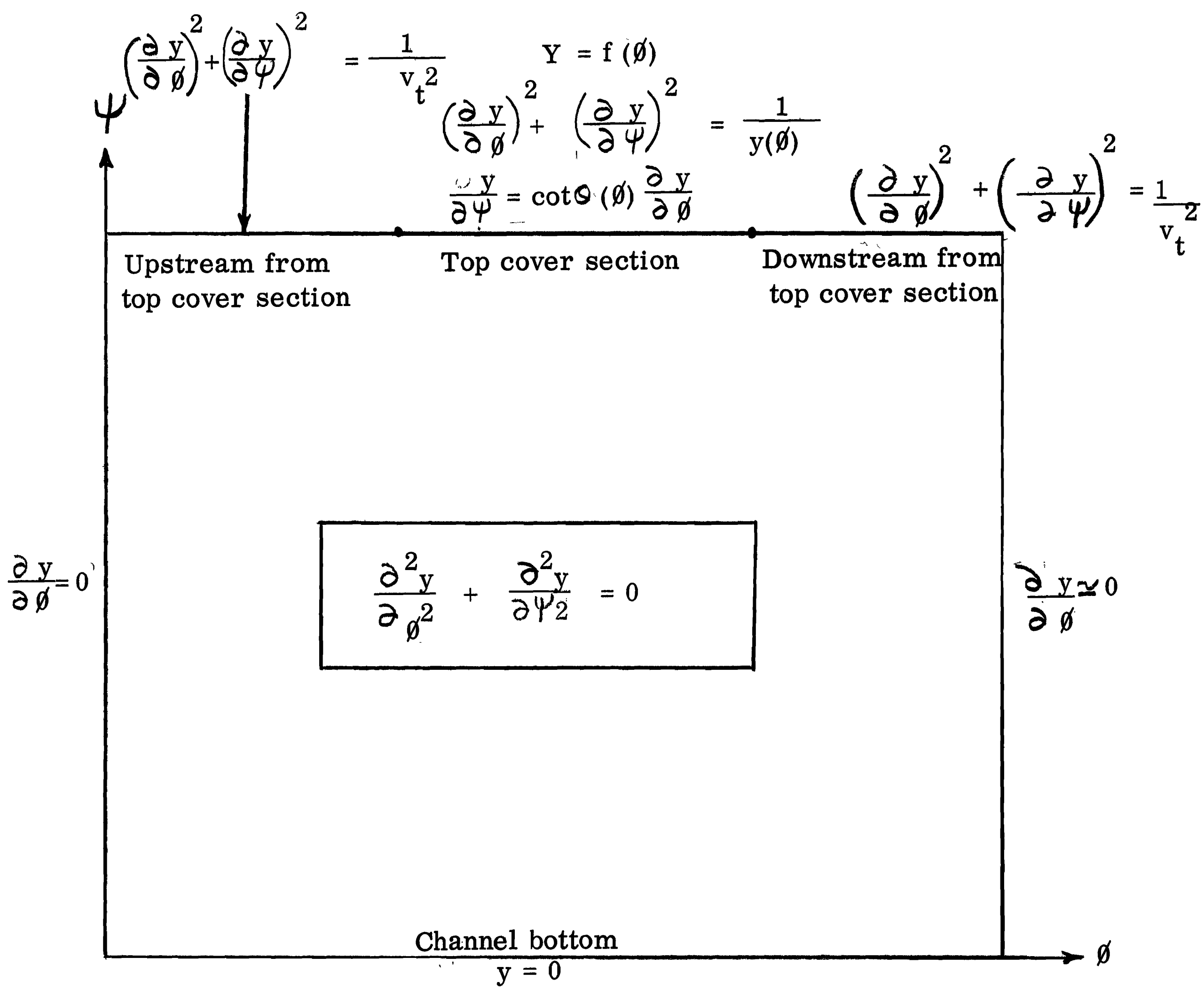

Figure 4. Formulation of flow under the top cover section in potential plane.

assumed that at some distance upstream and downstream from the device the flow is uniform. It would be just as easy to specify a typical open channel velocity distribution for the end sections as the normal derivative given in Figure 4. Any of the three conditions for the top cover section may be used. The first would be used if one wished to specify the height as a function of the potential. The second would be used if one wished to determine the shape which would give a given velocity or pressure distribution along the top cover section. The third specify the shape by giving local angle for the top cover section.

The solution to the boundary value problem formulated in Figure 4 has been obtained by finite differences using the following nine point operator on a square grid network line $\Delta\phi = \Delta\psi$,

$$\begin{aligned} y(I,J) = 0.05 \Big[4 \big\{ & y(I+1, J) + y(I-1, J) + y(I, J+1) \\ & + y(I, J-1) \big\} + y(I+1, J+1) + y(I-1, J+1) \\ & + y(I-1, J-1) + y(I+1, J-1) \Big] \end{aligned} \qquad (20)$$

in which I increases with ϕ as given $I = \frac{\phi}{\Delta\phi}$ and J with ψ as given by $J = \frac{\psi}{\Delta\psi}$.

The operators, used for the boundary conditions along the free surfaces and top cover section are the same as those used by Jeppson (1966) in the solution of plane jet and cavity problems. These operators can be had also by examining the Fortran IV Program which has been used to obtain the solutions and which is given in the Appendix.

Dimensional analysis of the problem

> Dimensional analysis is based solely on the relationships that must exist among the pertinent variables because of their dimensions. Dimensional analysis gives qualitative rather than quantitative relationships, but when combined with experimental procedures it may be made to supply quantitative results and accurate prediction equations. (Murphy, 1950, p. 17)

The technique of dimensional analysis has been applied in this case to find a set of quantities that can be applied to other geometrically similar models. This analysis is also applied to find an expression for discharge through the device.

The flow through a system is affected by the dimensions of the system, the properties of the fluid and the applied forces. The variables that might effect this problem are listed below.

1. Dimensions defining the geometry of the system e.g., throat opening, d, bed width, b, and radius of the cover sections, r.

2. Flow characteristics e.g., rate of flow, Q, depth at any section, h, piezometric head at the throat, h_t.

3. Fluid properties e.g., density, ρ , elastic modulus, e, specific weight, γ , surface tension, δ, and viscosity, μ .

The viscous forces become less important at high Reynold's numbers. The scope of this study is limited to a small range of flow and the temperature variation is limited to about 5° F., so viscous forces will be assumed constant for the limited range and, therefore, will be neglected. Surface tension and elastic modulus are also not expected to affect this problem. The ratio, g, of specific weight to density will be used as an independent variable in place of these two quantities. Radius, r, is constant for this study so it is assumed that it will not affect the discharge for different throat openings. If the effect of radius, r, on discharge is to be considered, it will require several models with different radii so r is eliminated from the list of variables affecting discharge. Throat area A_t, a product of b and d, has been used as an independent variable replacing both b and d. This implies that the velocity of approach is neglected. Differential head $\Delta h = h_i - h_t$ is used as an independent variable in place of h_i and h_t. This process of elimination of variables results in only four variables which result in the following functional relationship.

$$f\,(Q,\ A_t,\ g, \Delta h) = 0 \tag{21}$$

There are two basic dimensions and four variables so from the principles of dimensional analysis there will be two π terms taking A_t as the repeating variable the functional relationship of these π terms can be written as

$$\phi\left(\frac{Q}{\sqrt{g}\ A_t^{5/4}},\ \frac{\Delta h}{\sqrt{A_t}}\right) = 0 \tag{22}$$

which can also be written as

$$\frac{Q}{\sqrt{g}\ A_t^{5/4}} = \phi'\left(\frac{\Delta h}{\sqrt{A_t}}\right) \tag{23}$$

Equation (23) is a functional relationship of π terms. The determination of this function must be done by experiment.

Head loss

The modified venturi section is designed to be used in canals which have a low allowable head loss, consequently it follows that it should have a low resistance to flow. The converging section changes the pressure head to velocity head while the diverging section converts the velocity head to pressure head. This recovery is not complete and there is a loss of energy in the passage of water through the section. The head loss is considered to be the differential head between point 1, just upstream from the section and point 5, just downstream from the section (see Figure 9), and thus includes the normal friction loss in this length of channel. The velocity head, though small, is added to the depth to obtain the energy at the section. The expression for head loss can be written from Bernoulli's theorem as

$$H_L = y_1 + \frac{v_1^2}{2g} - (y_5 + \frac{v_5^2}{2g}) \qquad (24)$$

Where

H_L = Head loss through the section

y_1, y_5 = Depths at points 1 and 5 respectively

$\frac{v_1^2}{2g}$, $\frac{v_5^2}{2g}$ = Velocity head at points 1 and 5 respectively.

PROCEDURE

Description of apparatus

The experimental work for this thesis has been done at the Utah Water Research Laboratory in 3 feet x 3 feet x 200 feet flume. The modified venturi section, as shown in Figures 3 and 5 was built from 1/8 inch thick steel sheet. The semicircular surface that comes in contact with water has a radius of 2.5 feet and is tangential to a plane surface which makes an angle of 45 degrees with the horizontal. On the downstream side the semicircular surface is tangential to a plane surface that makes an angle of 20 degrees with the horizontal. The overall length of the device is 10 feet 7 inches.

The top cover section was supported by a frame 1 1/2 inches x 1 1/2 inches steel angles, with 1 1/4 inches x 1 1/4 inches steel angles to stiffen the frame. The cover section was stiffened by three 1/2 inch pipes running longitudinally (see Figures 5 and 7). Transverse steel plates, 1/8 inch x 1 1/2 inches were welded to provide rigidity to the structure. A rubber gasket was fastened on the sides of the strucutre by screws to minimize the leakage.

The top cover section was hinged at the downstream and the upstream end was raised and lowered by a car jack. The top cover section was built in the shop of Utah Water Research Laboratory by Mr. Kenneth Steele and his staff.

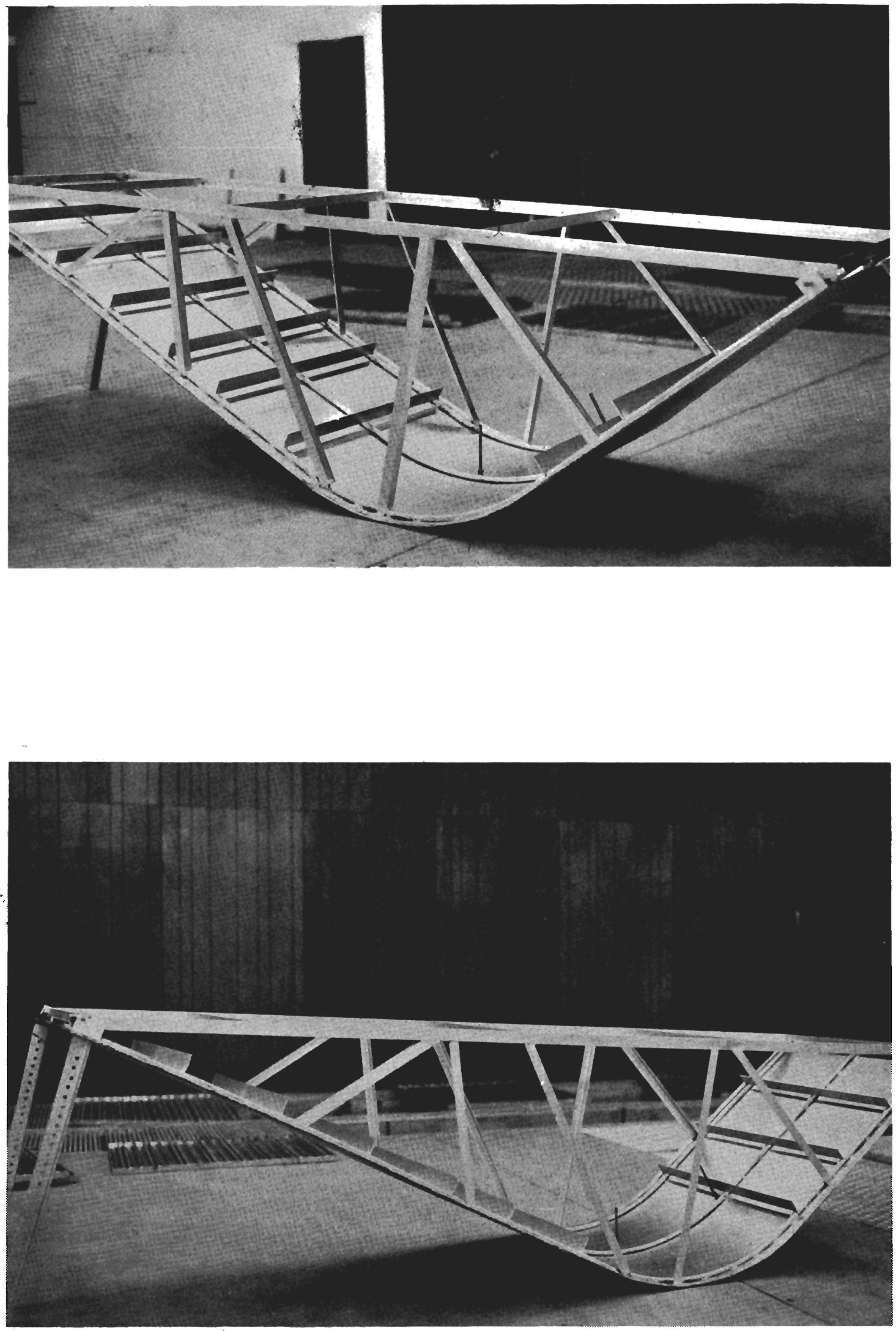

Figure 5. Test model.

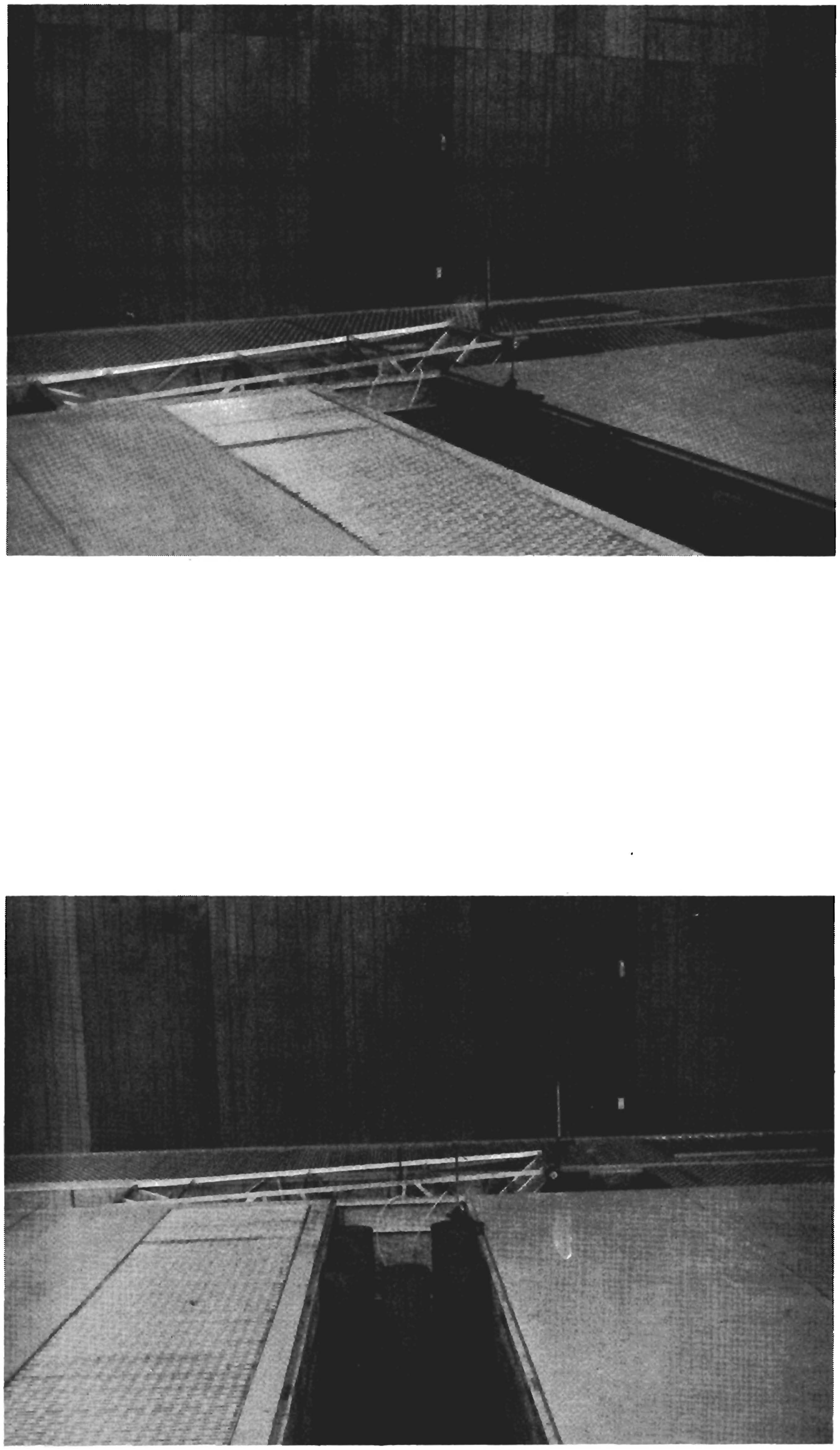

Figure 6. Laboratory arrangement.

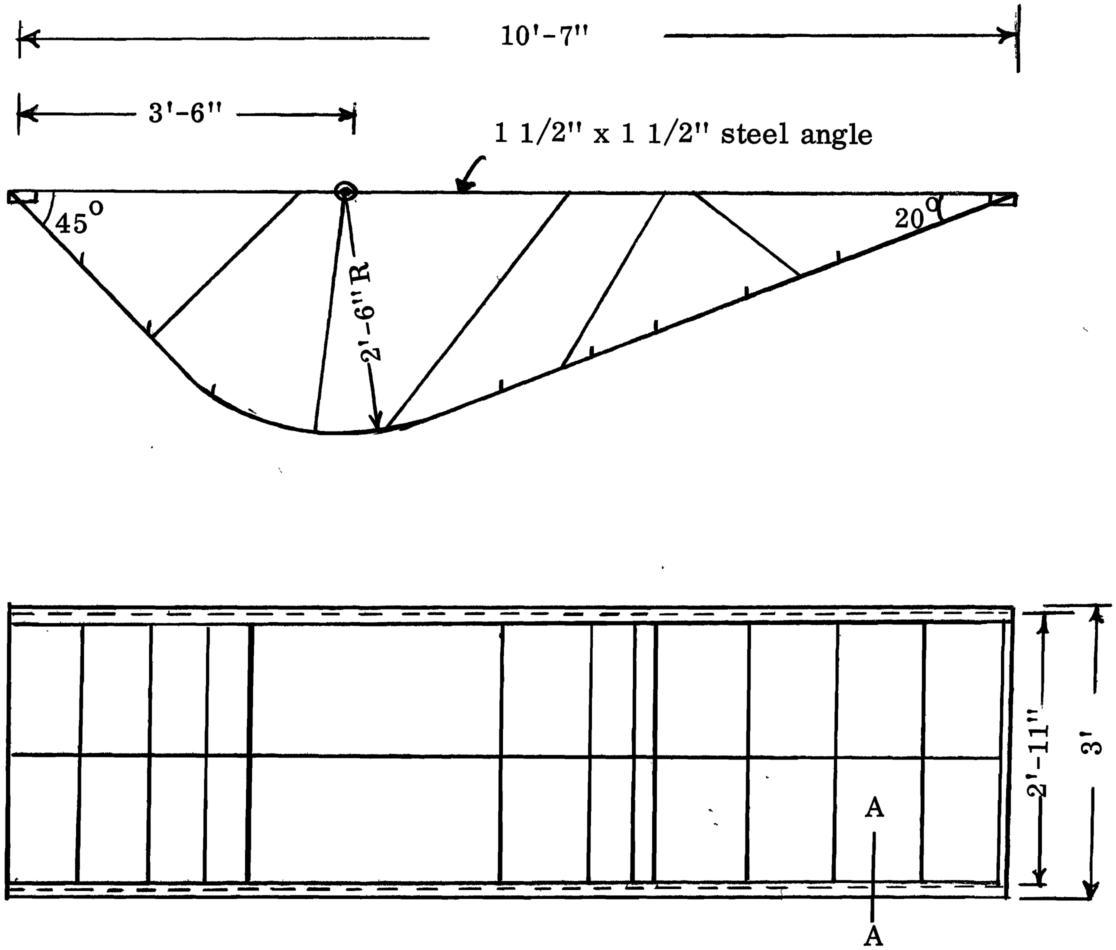

Figure 7. Details of top cover section.

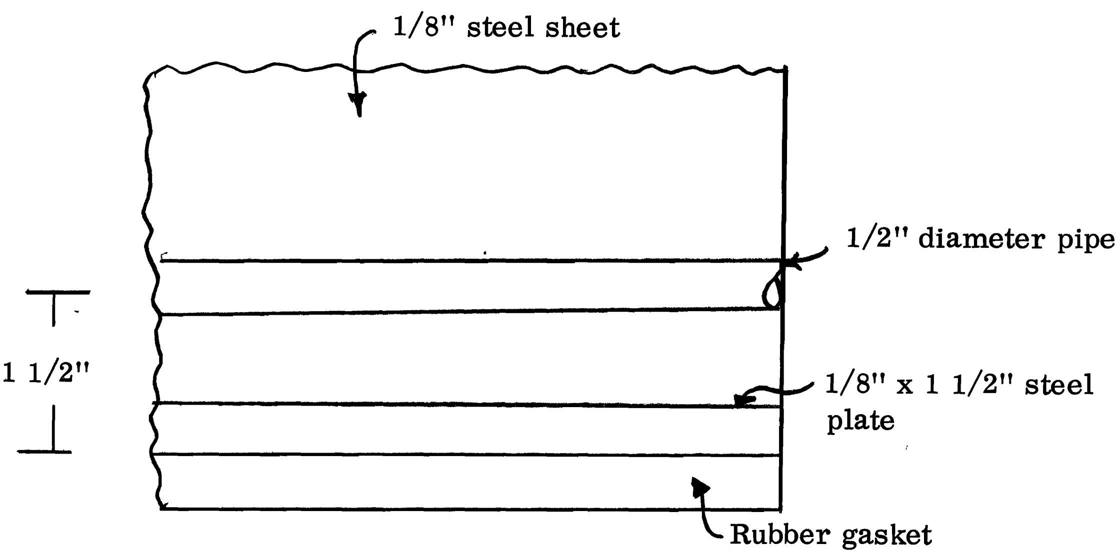

Figure 8. Section at A-A.

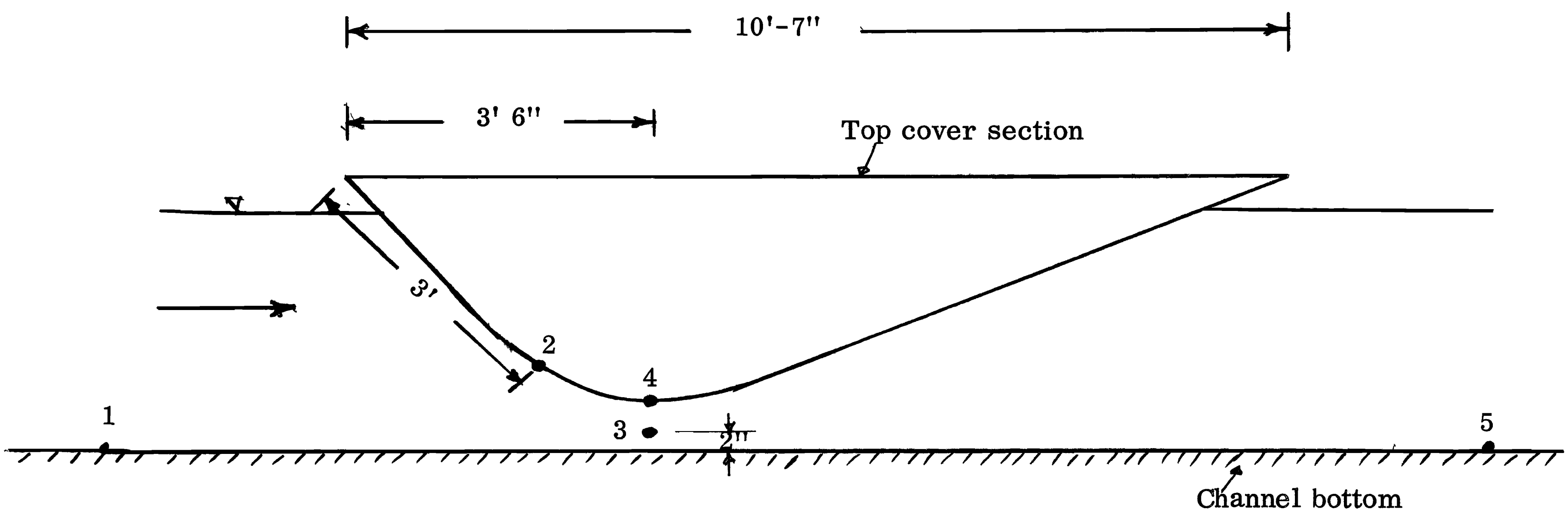

Figure 9. Location of points for piezometric connections.

The measurements were taken in five stilling wells. Two of the wells were connected to holes in the top cover section (see Figure 9). Inlets to the other three wells were located just upstream of the section, at the throat section in the side of the channel, and just downstream from the section. The inlets were connected to the stilling wells by one-half inch outside diameter poly flo tubing.

The water supply consisted of two pipe lines of diameters 12 and 8 inches. The pipe lines were controlled by valves to regulate the flow at the head of the test flume. The supply pipes were connected to the reservoir formed by the dam on Logan River upstream from the Water Research Laboratory. Water from the supply pipes was run in the flume and made to pass through the modified venturi section installed about 150 feet downstream from the supply. The water level in the stilling wells was read by a hook gage. The same gage was used for all the stilling wells. A 12 inch Parshall flume downstream from the device was used to measure the flow. The discharge was obtained from tables in "Measuring Water with Parshall Flumes." The water was discharged back into Logan River.

Experimental procedure

A certain discharge flowing at a certain depth constituted a series. A series consisted of several trials till the water level in all stilling wells was fairly constant. The discharge was varied by changing the valve opening consequently, the upstream depth also varied. Sufficient time was allowed for water to come to equilibrium. The velocity in the flume could be reduced by installing a number of wooden overflow boards across the flume downstream from the device. Thus the device could be tested for very low velocities. The tests were continued by progressively reducing the flow until the differential head was approximately 0.06 feet, then the throat opening was increased, or the velocity was changed by changing the overflow boards.

The throat opening was measured with a point gage. The point gage measured the depth for taps 3 and 4 on the top cover section. The throat opening was obtained from this measurement by allowing for the thickness of the cover sheet.

To eliminate the wave action, gratings used to cover the flumes in the laboratory were used as baffles. These gratings were placed at three sections across the flume and this reduced the waves considerably.

RESULTS AND DISCUSSION

Results from numerical solution

Results from the numerical solution are presented as a flownet in Figure 10. This flownet was obtained by plotting the x and y coordinates from the finite differences network. The complete solution as given by the program also includes the velocities and angles of the flow at each of the grid points.

The uppermost streamline gives the theoretical shape for the top cover section of the modified venturi section which will result in a velocity distribution with mild enough adverse pressure gradients to prevent separation in an idealized inviscid flow. This shape will offer no resistance to inviscid flow for a particular upstream depth and velocity. Field conditions, however, will be considerably different as the upstream depth and velocity will fluctuate considerably depending on discharge. The top cover section is to be hinged about the downstream section, so the shape of modified venturi section will be different at different throat openings. Considering these limitations the top cover section has not been built according to this design. The shape of modified venturi section used in this thesis is shown in Figure 3.

Equation of discharge

In the section on dimensional analysis the following functional relationship of π terms was obtained.

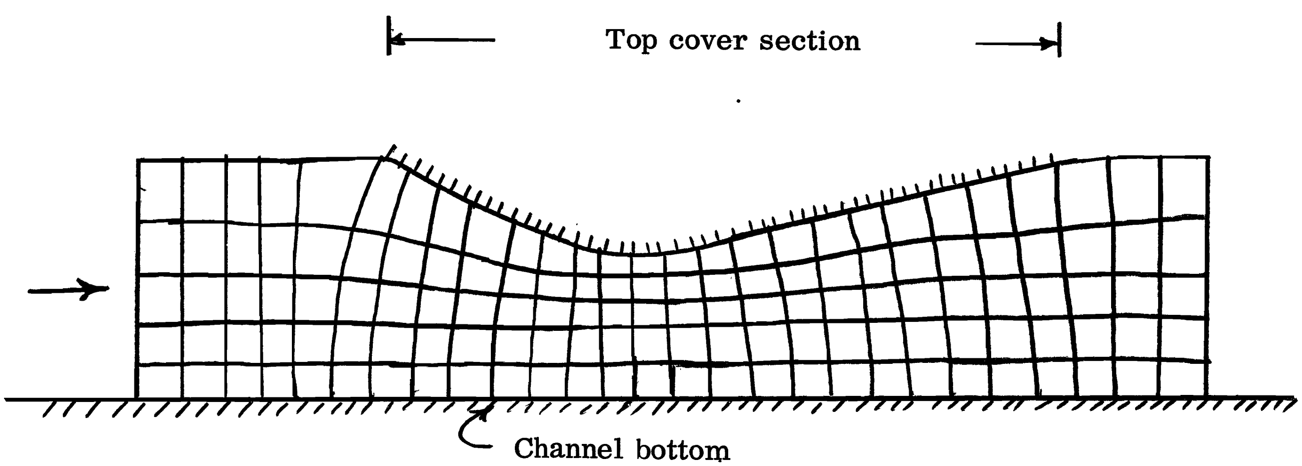

Figure 10. Flow net from numerical solution.

$$\frac{Q}{\sqrt{g}\ A_t^{5/4}} = \phi\left(\frac{\Delta h}{\sqrt{A_t}}\right) \tag{25}$$

In this section these π terms have been combined to give an equation for discharge.

When $\frac{Q}{\sqrt{g}\ A_t^{5/4}}$ is plotted against $\frac{\Delta h}{\sqrt{A_t}}$, data for all throat openings plot on the same parabolic curve (see Figure 11). If $\frac{Q}{\sqrt{g}\ A_t^{5/4}}$ is plotted against $\left(\frac{\Delta h}{\sqrt{A_t}}\right)^{1/2}$ instead of $\frac{\Delta h}{\sqrt{A_t}}$, a straight line results (see Figure 12). From this plot, the equation relating the π terms of equation (25) can be derived. The resulting equation is:

$$\frac{Q}{\sqrt{g}\ A_t^{5/4}} = C_\alpha\left(\frac{\Delta h}{\sqrt{A_t}}\right)^{1/2} \tag{26}$$

or

$$Q = C_\alpha A_t\sqrt{g\Delta h} \tag{27}$$

or

$$Q = C_D\ A_t\sqrt{2g\Delta h} \tag{28}$$

Equation (28) is the equation for discharge through the modified venturi section and is identical with the equation for discharge through a venturi meter. Figure 12 gives an average value of C_D = 1.00.

From Equation (28) the expression for coefficient of discharge C_D can be written as

$$C_D = \frac{Q}{A_t\sqrt{2g\Delta h}} \tag{29}$$

Figure 13 shows the relation between discharge and the quantity $A_t\sqrt{2g\Delta h}$. The data for throat openings of 6, 7, 8 and 9 inches plot on the same curve giving an average value of $C_D = 1.00$. The data for throat opening of 5 inch do not follow the above graph. This discrepancy might be the result of experimental error in measuring the throat opening, or a difference in downstream control conditions.

The relation of discharge Q to $\frac{\Delta h}{d}$, the ratio of differential head to throat opening, is a family of parabolic curves, one for each throat opening (Figure 14). A plot of Q vs. $\sqrt{\frac{\Delta h}{d}}$ results in a family of straight lines for different throat openings (Figure 15). The latter set of curves can be used to find the discharge for various throat openings for the shape of the modified venturi section used in this study.

Coefficient of discharge

In the equation for discharge the coefficient of discharge C_D accounts for factors which were not considered in the derivation of the equation. The expression for C_D can be written as

$$C_D = \frac{Q}{A_t\sqrt{2g\Delta h}}$$

The expression for coefficient of discharge obtained from Bernoulli's theorem and continuity equation can be written as

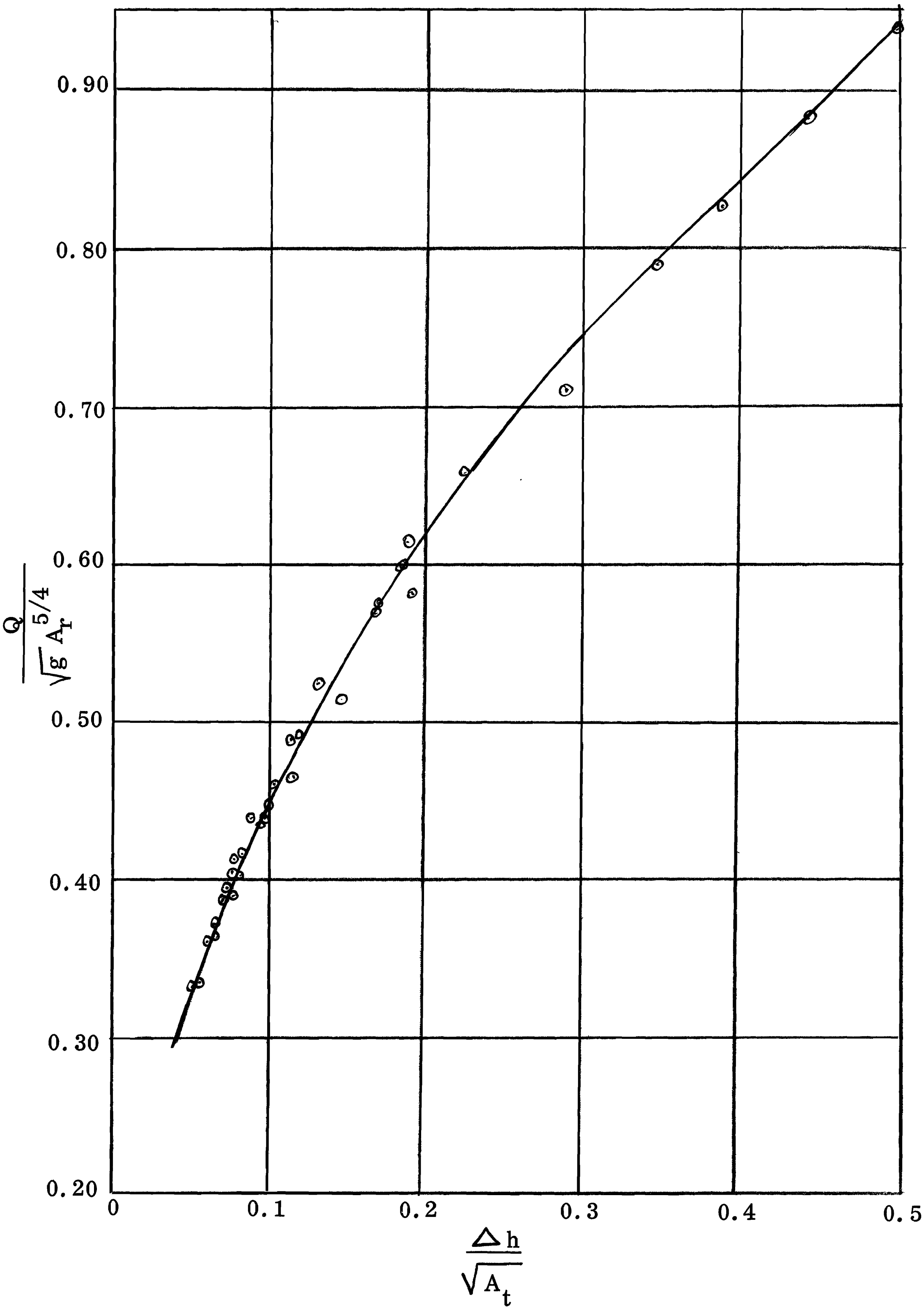

Figure 11. $\frac{Q}{\sqrt{g}\ A^{5/4}}$ as a function of $\frac{\Delta h}{\sqrt{A_t}}$.

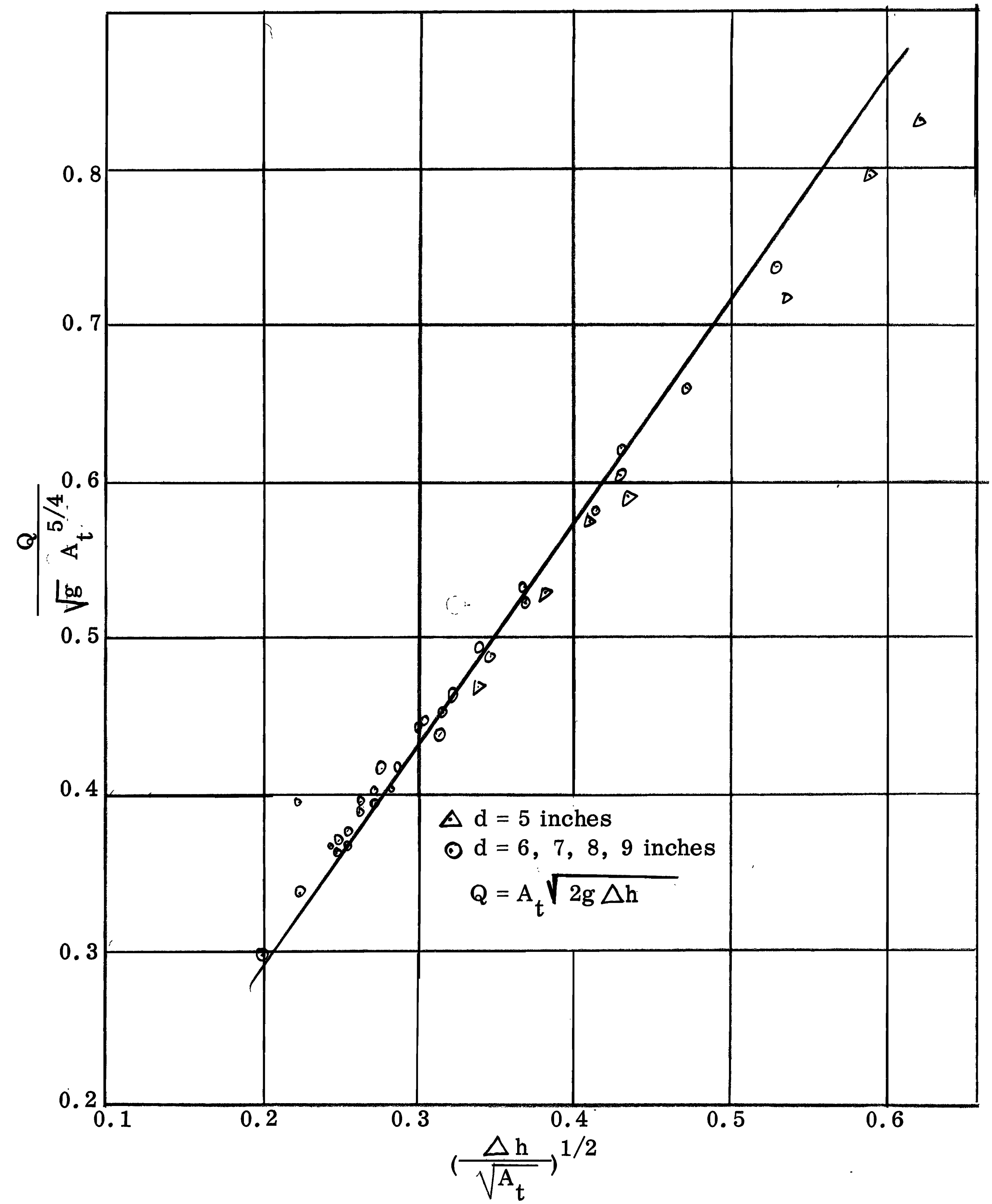

Figure 12. Empirical equation for discharge.

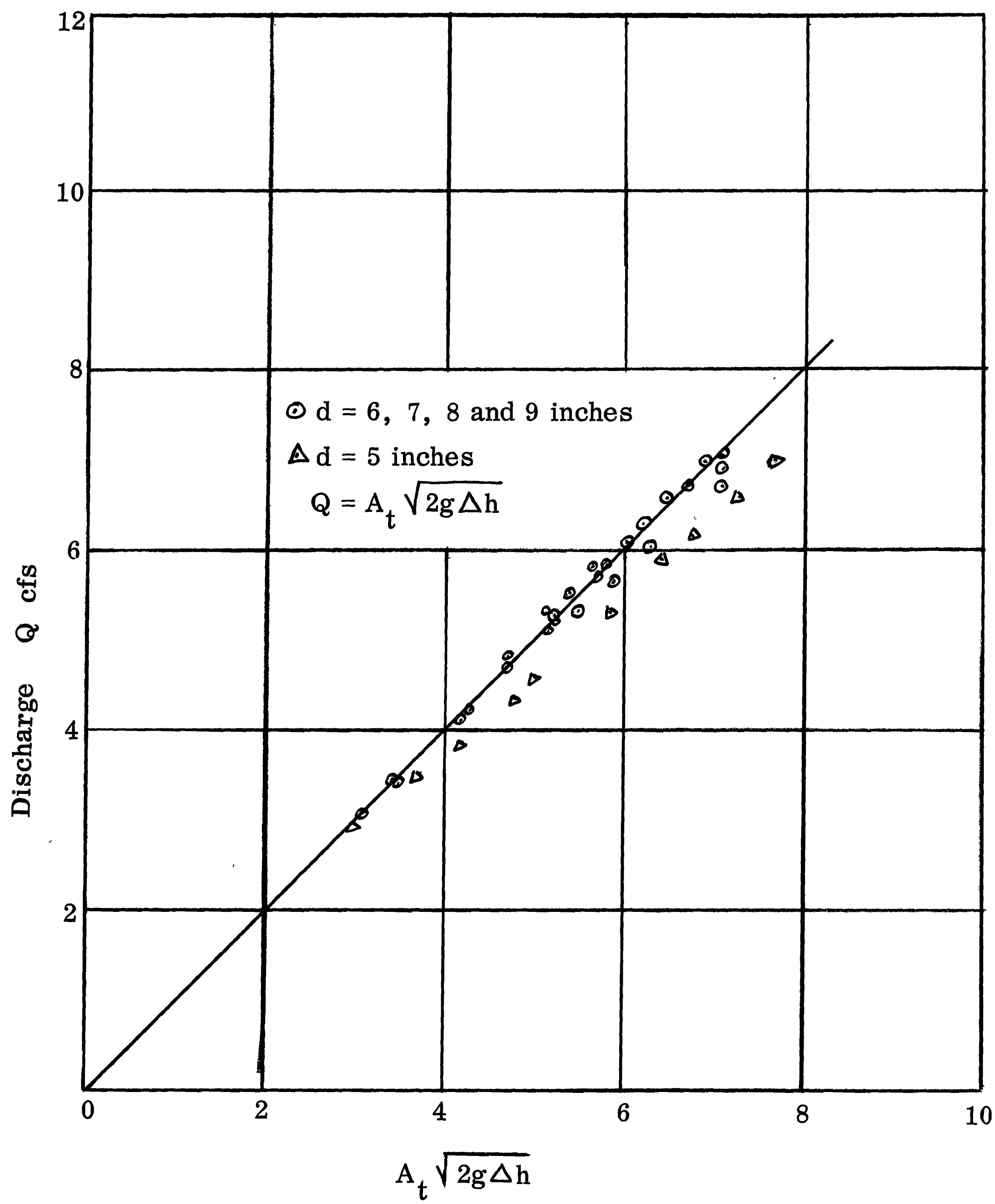

Figure 13. Relation between discharge and quantity $A_t \sqrt{2g \Delta h}$.

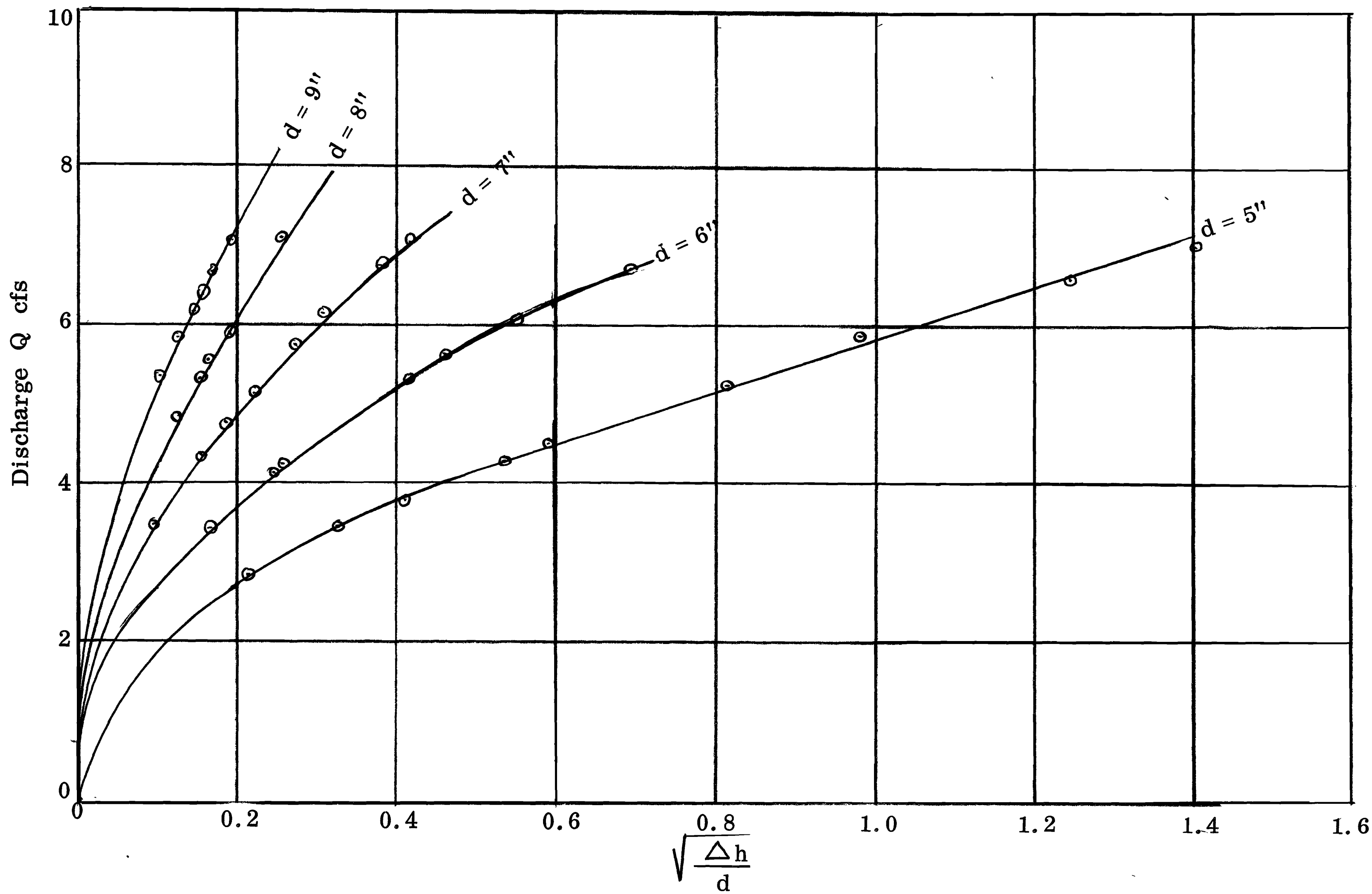

Figure 14. Discharge as a function of differential head.

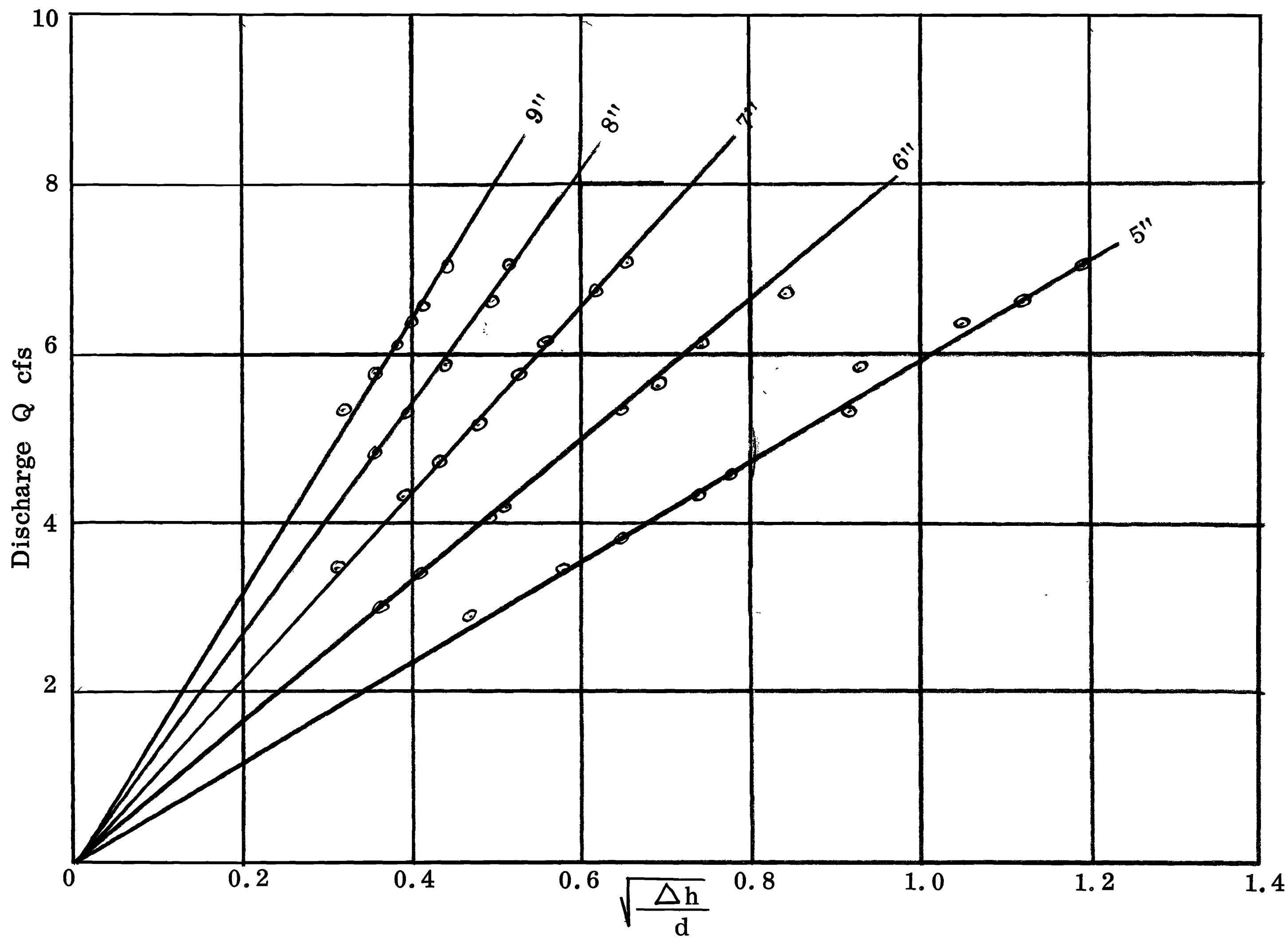

Figure 15. Q as a function of $\sqrt{\frac{\Delta h}{d}}$.

$$C_q = \frac{Q\sqrt{1 - (\frac{A_t}{A_x})^2}}{A_t\sqrt{2g\Delta h}} \qquad (30)$$

The comparison of Equations (29) and (30) results in the following relationship between C_D and C_q.

$$C_D = \frac{C_q}{\sqrt{1 - (\frac{A_t}{A_x})^2}} \qquad (31)$$

Both of these coefficients have been determined in this study.

The coefficient of discharge has been based on differential head between points 1 and 3 and points 1 and 4 (see Figure 9). Figures 16 through 20 show the coefficient of dishcarge as a function of discharge and is based on differential head between points 1 and 3. The values of C_D and C_q based on differential head between points 1 and 4 can be found in Table 2 (see Appendix).

The curves in Figures 16 through 20 have been compared with Skjerseth's (1951) data for the model of 24.5 inches width. The value of coefficient of discharge is comparatively higher in this study than those obtained by Skjerseth. When comparing these curves it should be understood that the size, shape and the surface of circular transition were different. The locations of the taps where piezometric head was measured is also different and this is a major factor affecting the coefficient of discharge. There is also the question of absolute accuracy of the flow measurements in all tests.

For the limited range of flow, the coefficient of discharge tends to decrease with an increase in discharge and differential head for a particular

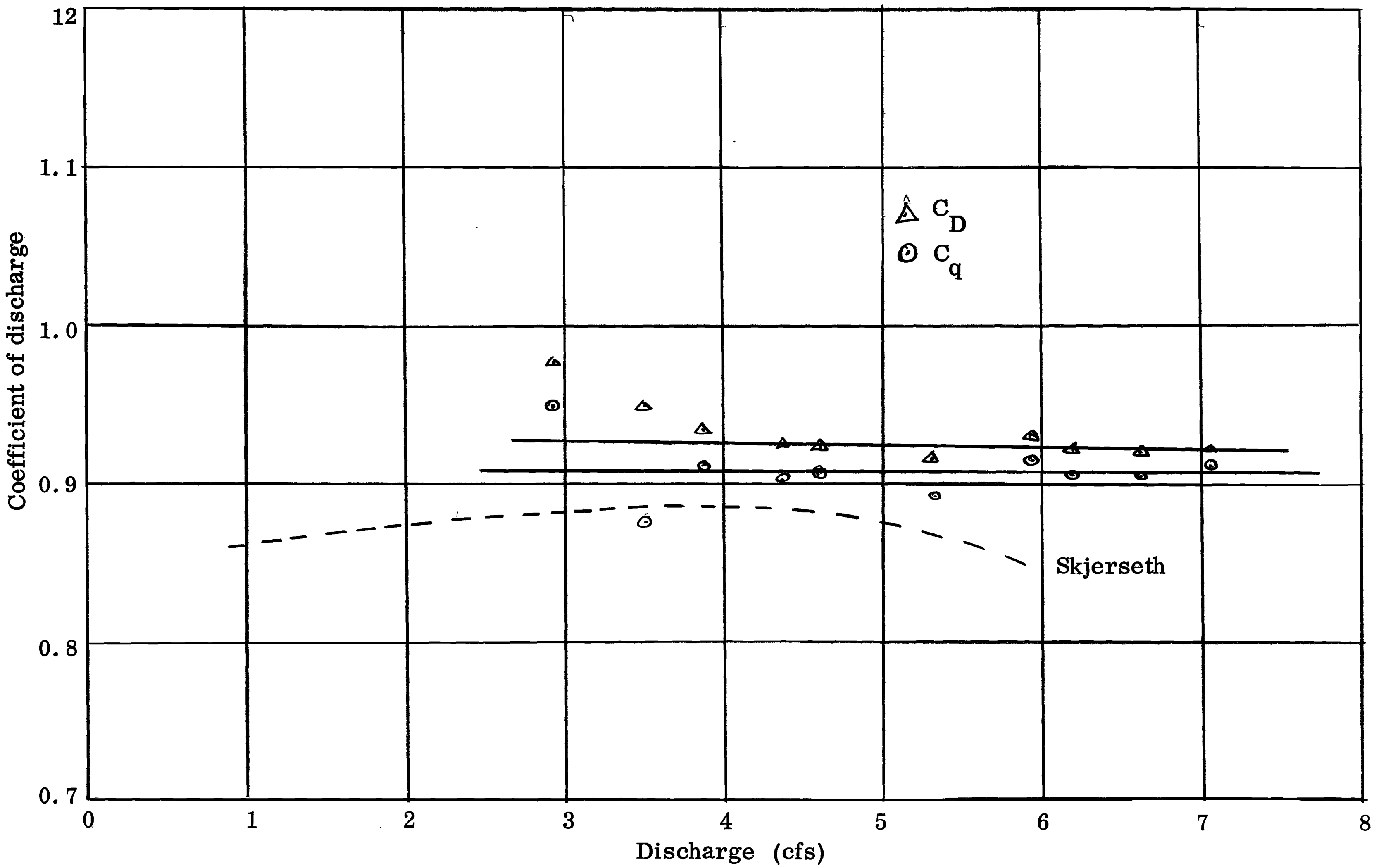

Figure 16. Coefficient of discharge for a 5 inch throat opening.

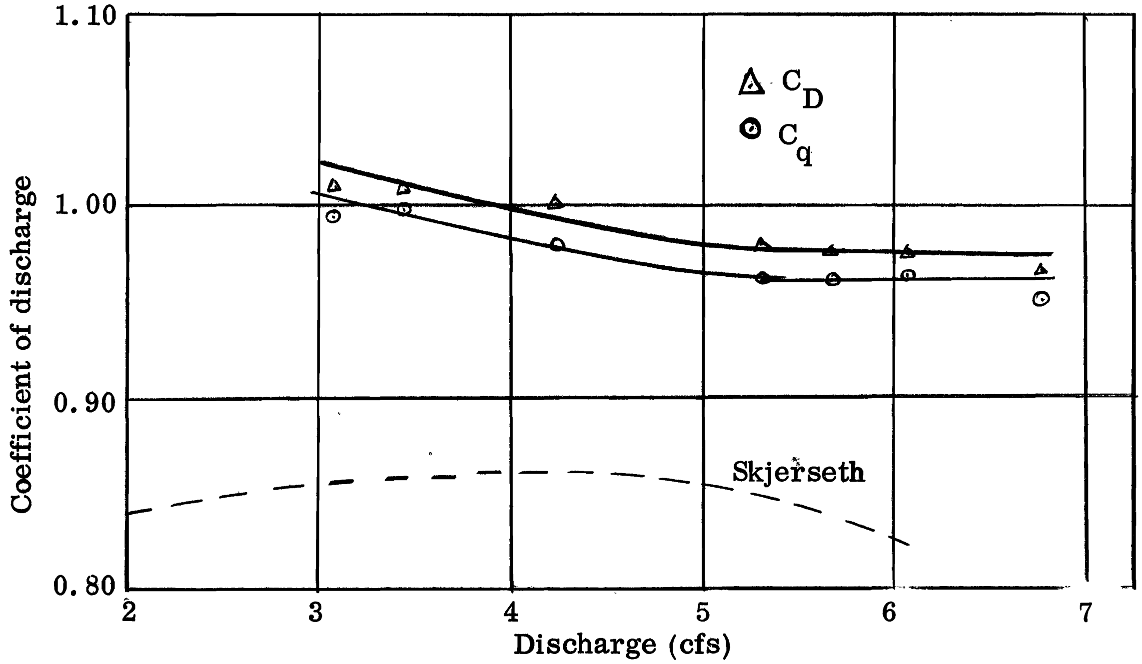

Figure 17. Coefficient of discharge for a 6 inch throat opening.

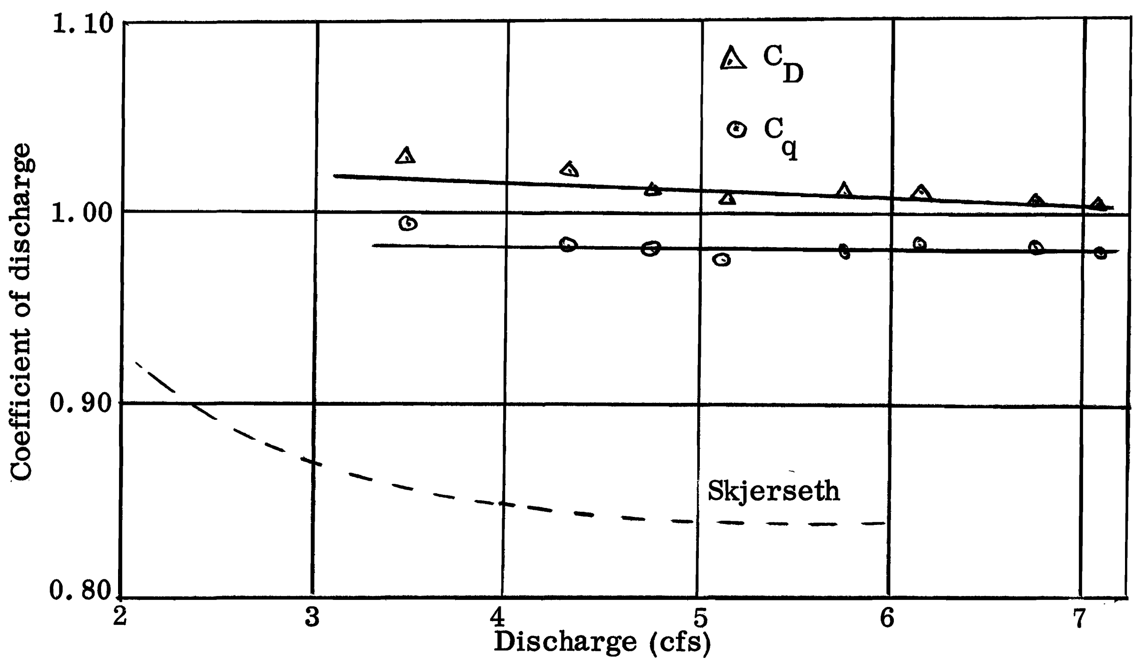

Figure 18. Coefficient of discharge for a 7 inch throat opening.

throat opening. Figures 21 and 22 show that the coefficient of discharge tends to increase with an increase in throat opening. The coefficient of discharge is comparatively constant at higher throat openings.

The coefficients of discharge, based on observations which had a differential head of less than 0.1 feet, have been plotted in Figures 16 through 20. These observations have not been given much weight in drawing the curves because the possibility of experimental error is a maximum at very small differential heads.

A plot of throat velocity, V_t, against the differential head Δh, shows that the data for all throat openings plot on the same parabolic curve (see Figure 23). When V_t is plotted against $\sqrt{\Delta h}$, data for all throat openings except the throat opening of 5 inches plot on the same straight line (Figure 24) which results in the following relationship,

$$V_t = 8.1 \sqrt{\Delta h} \qquad (32)$$

<u>Head loss</u>

Head loss through the section is calculated from the following relationship

$$H_L = Y_1 + \frac{V1^2}{2g} - (Y_5 + \frac{V_5^2}{2g}) \qquad (33)$$

Figures 25 through 29 show head loss as a function of differential head between points 1 and 3 (see Figure 9). The relationship of head loss to differential head is dependant on the throat opening and discharge. The maximum head loss

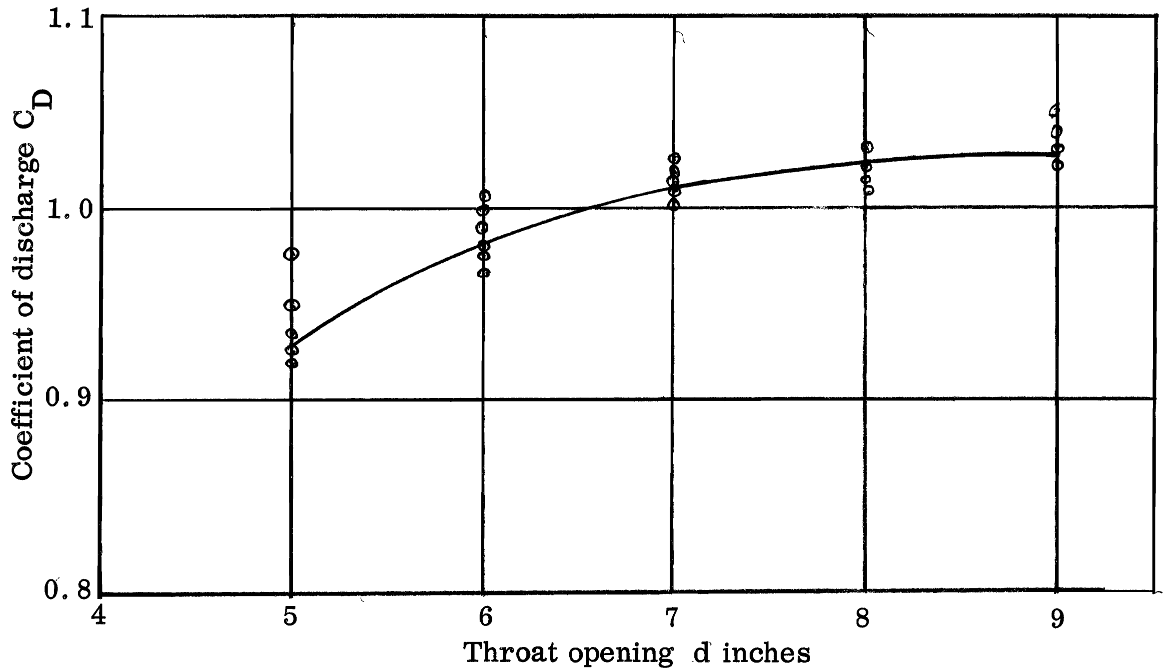

Figure 21. Coefficient of discharge C_D for various throat openings.

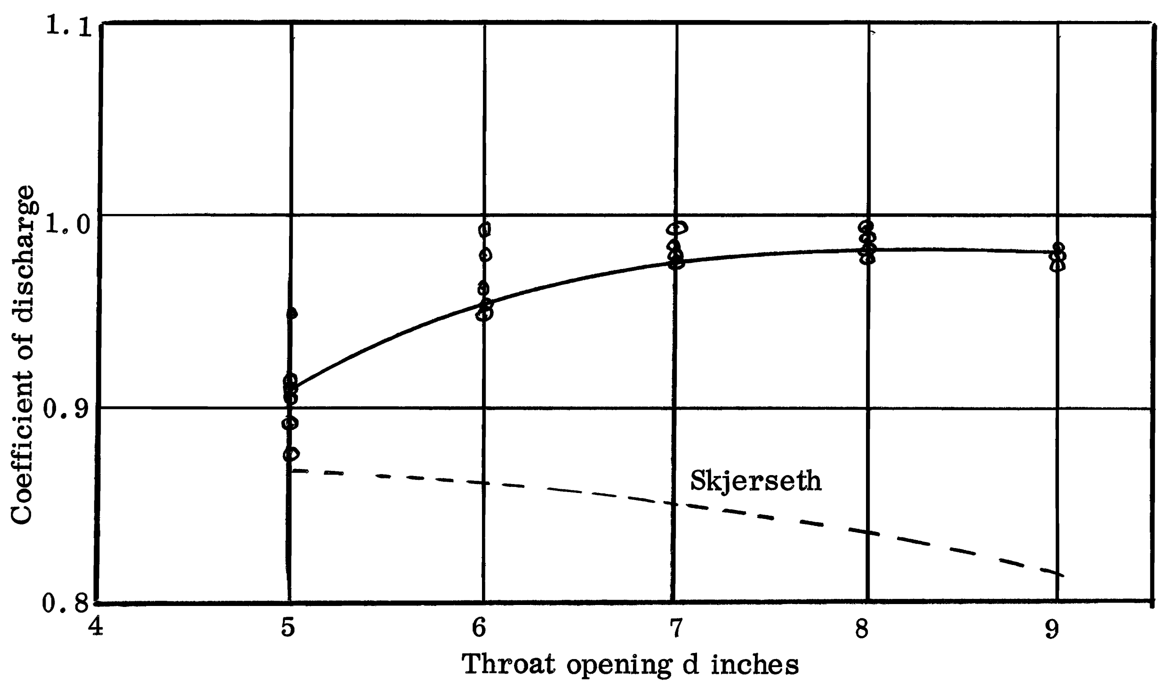

Figure 22. Coefficient of discharge C_q for various throat openings.

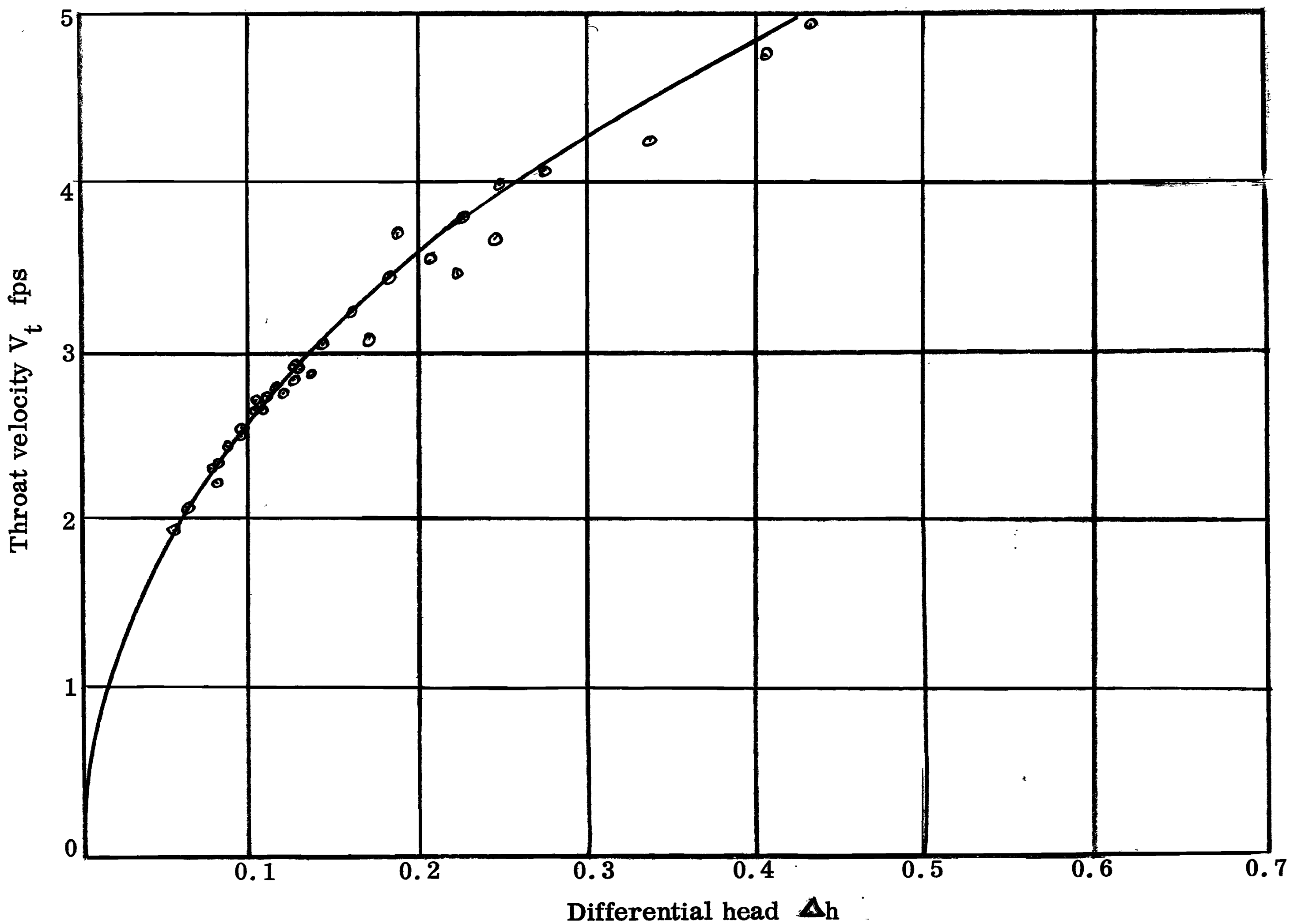

Figure 23. Throat velocity as a function of differential head.

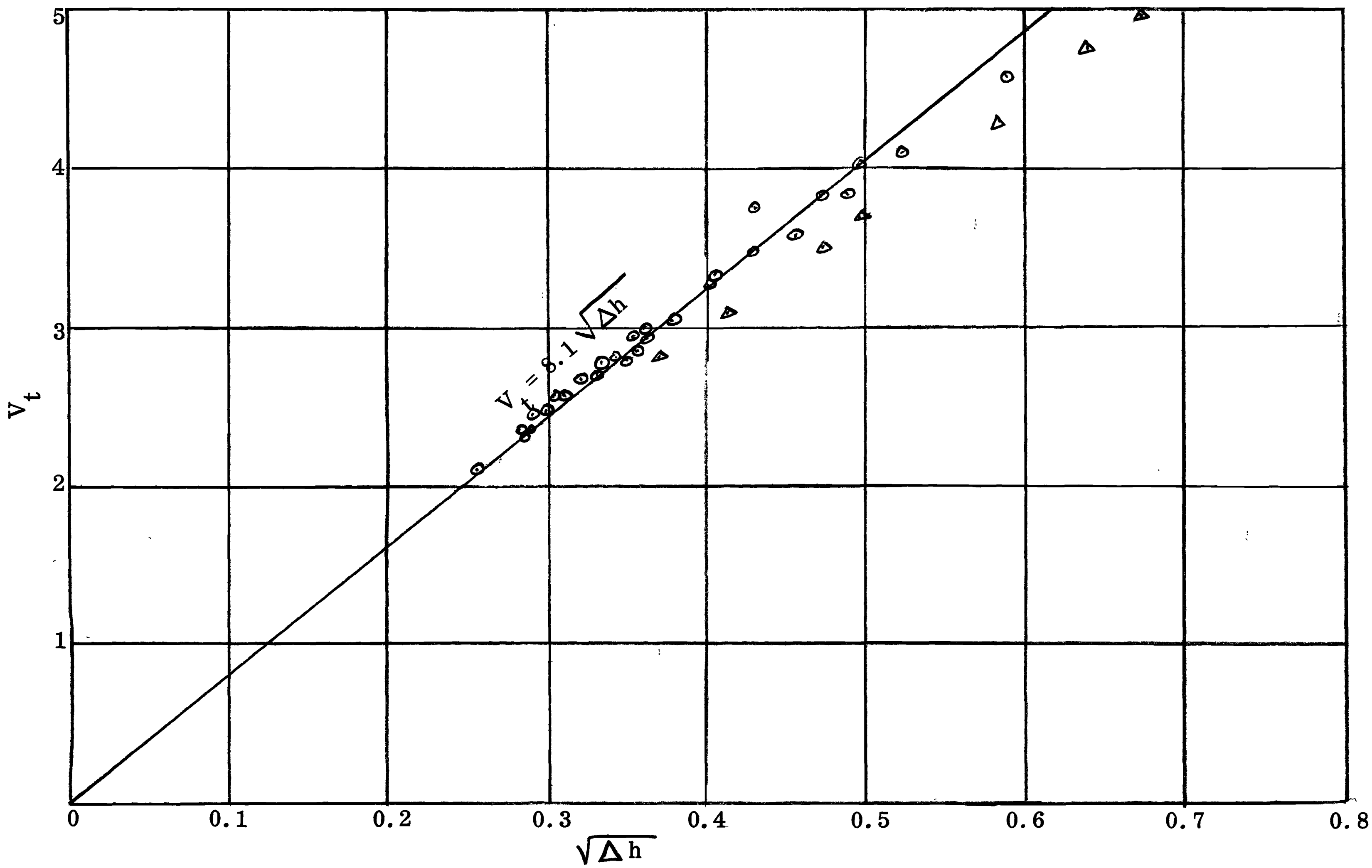

Figure 24. Relationship of throat velocity to differential head.

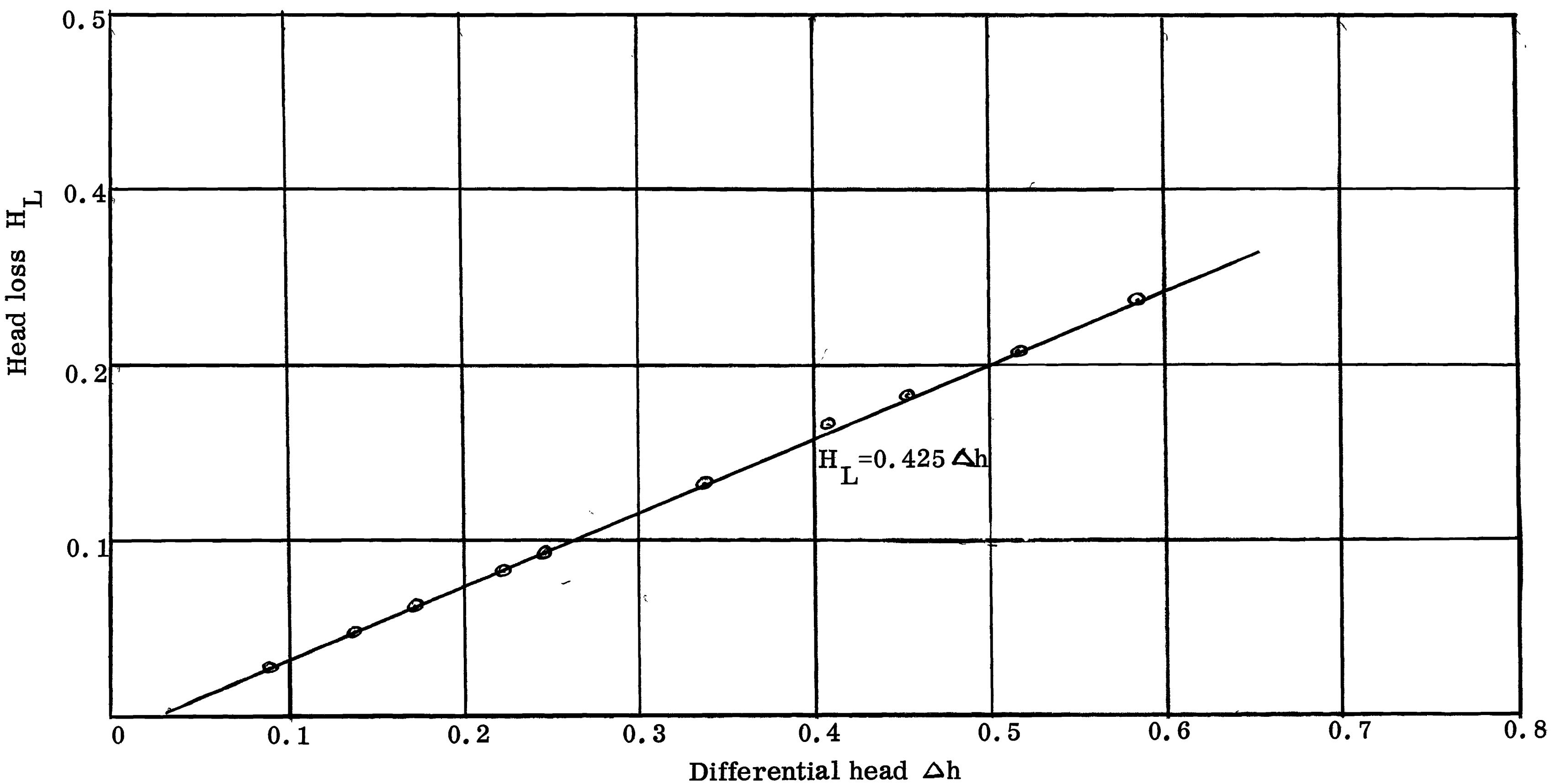

Figure 25. Head loss for a 5 inch throat opening.

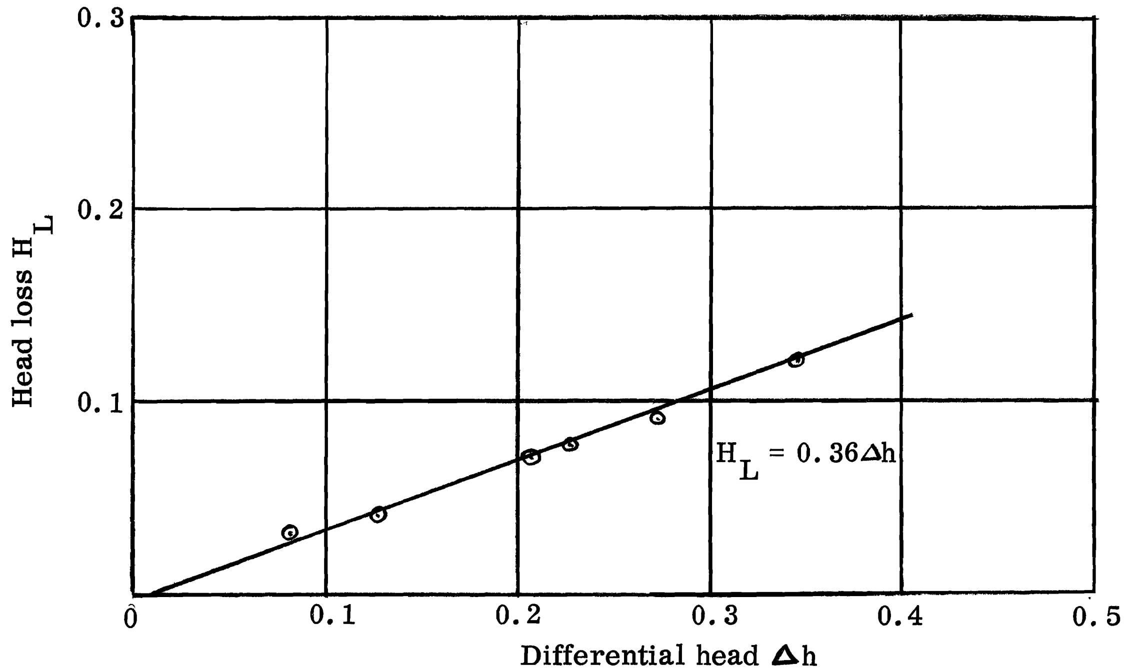

Figure 26. Head loss for a 6 inch throat opening.

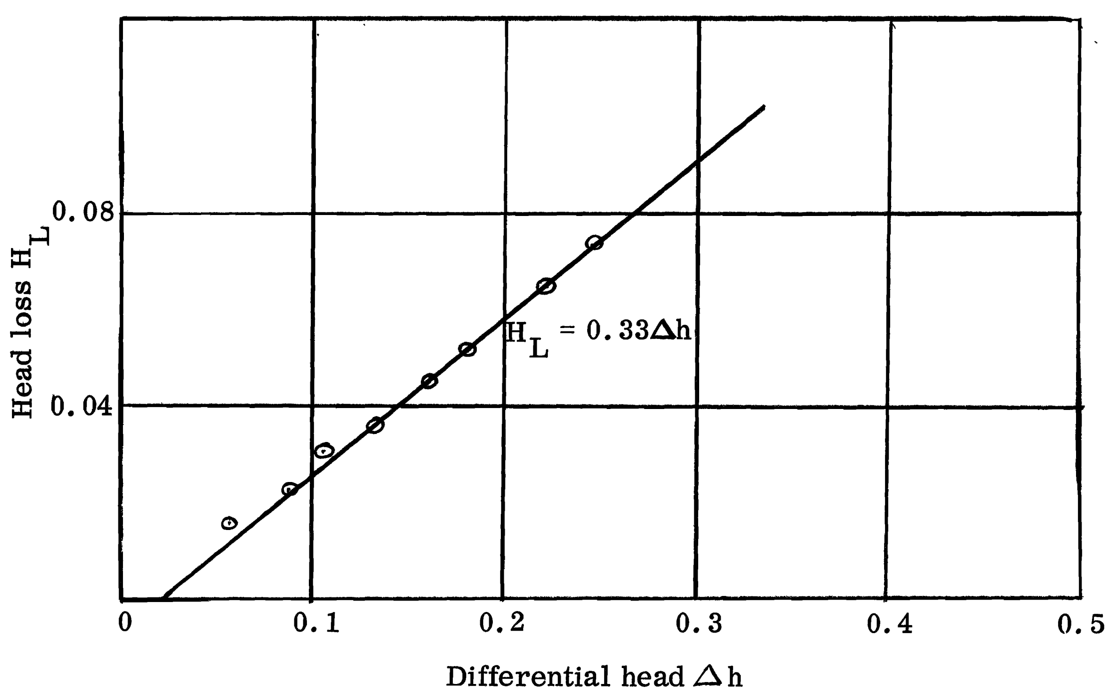

Figure 27. Head loss for a 7 inch throat opening.

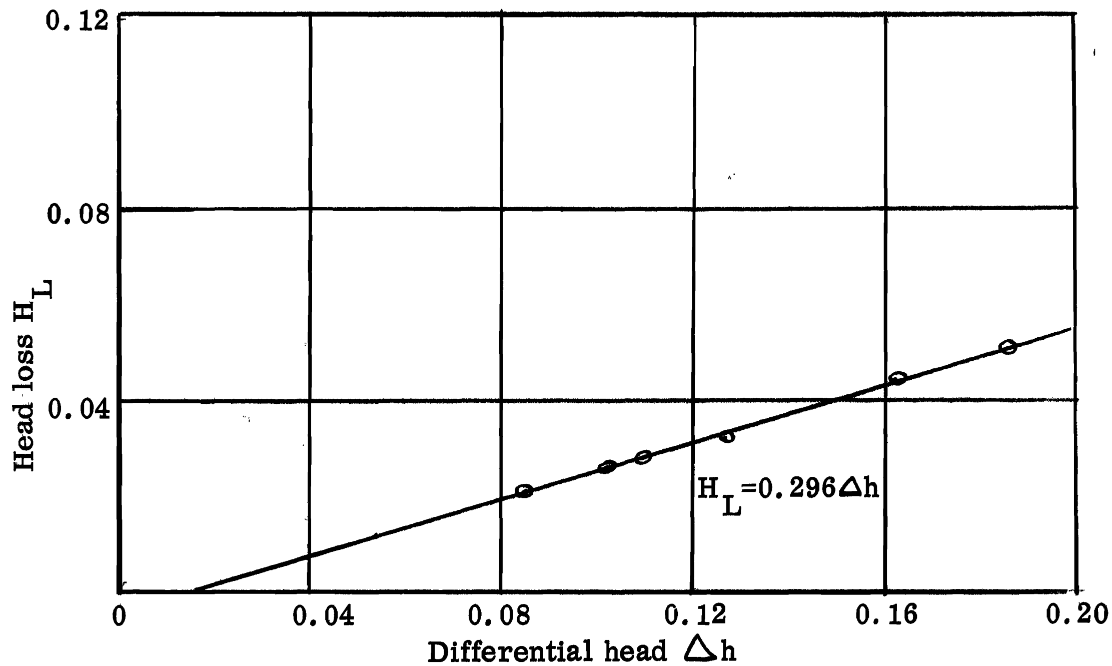

Figure 28. Head loss for an 8 inch throat opening.

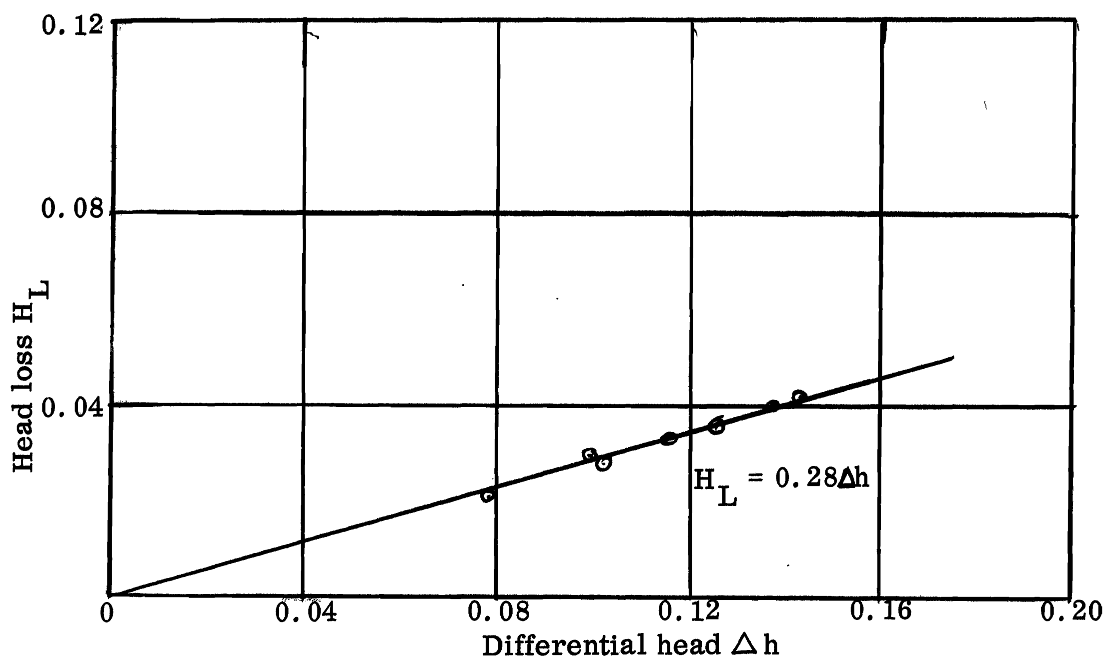

Figure 29. Head loss for a 9 inch throat opening.

occurs at the smallest throat openings and large flows. The head loss is about 43 percent of the differential head at a 5 inch throat opening and reduces to less than 30 percent for a 9 inch throat opening.

Figure 30 shows the ratio of head loss to differential head, $\frac{H_L}{\Delta h}$, as a function of throat opening. This ratio decreases with the increasing throat opening till it tends to be constant, but this observation is difficult to make from the limited range of this study.

This head loss is for a rectangular flume with straight approach. In wider canals, the canal has to be constricted for installing the modified venturi section. Trapezoidal canals also require a rectangular flume for the installation of this section. In both of these cases there will be additional head loss in the converging and diverging sections. This head loss is to be added to the head loss determined in this study.

Limitations of the study

The range of flow was limited by the capacity of the Parshall flume and the depth of the test flume. The maximum flow that could be measured with the Parshall flume was 7.10 cfs. There was no provision for accelerating the flow so the section could not be tested over a wide range of flow. It is believed that this section could be used to measure much larger flows.

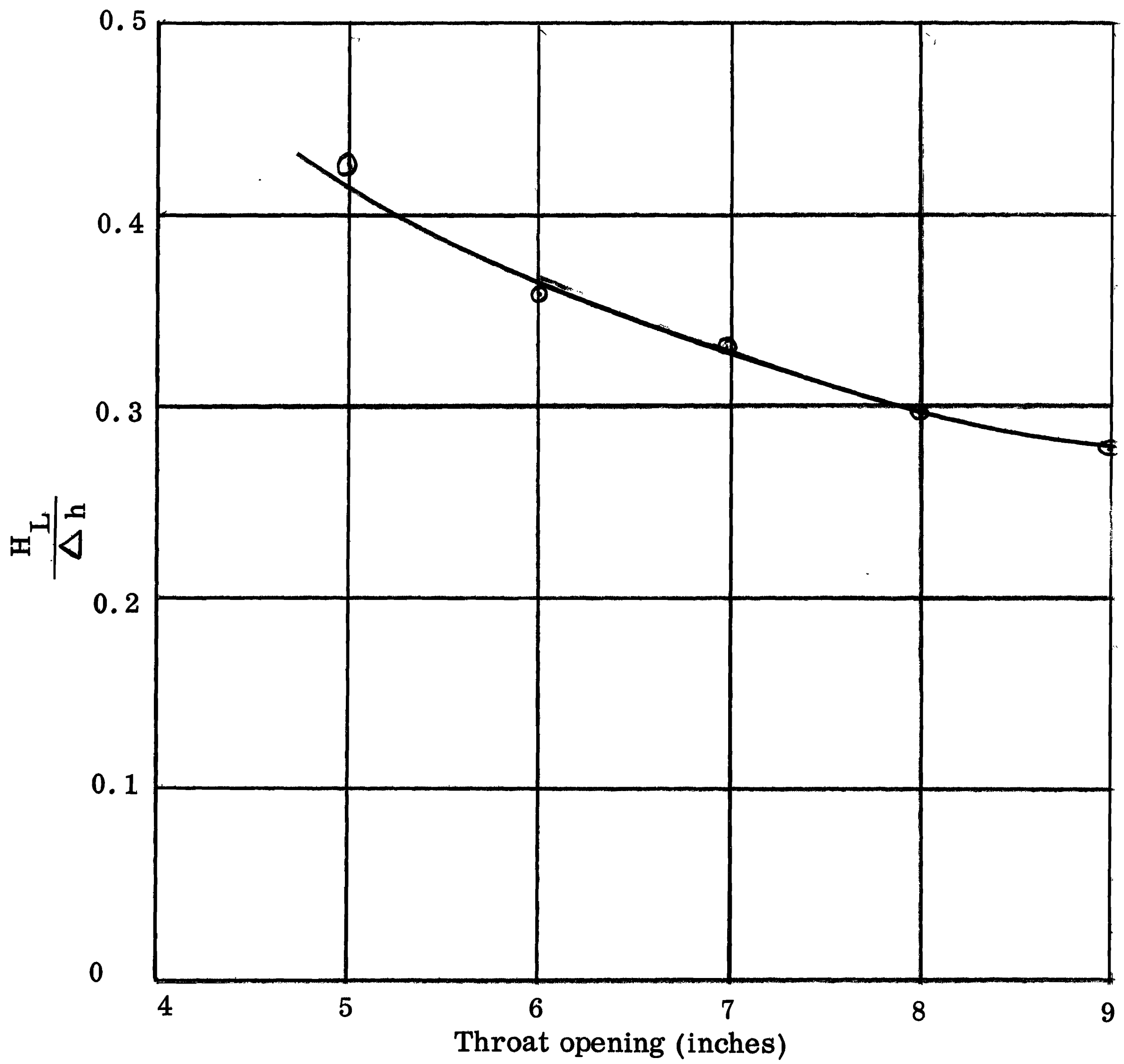

Figure 30. Head loss for various throat openings.

CONCLUSIONS

The modified venturi section studied in this thesis meets the requirements of a suitable water measuring device except for passing floating debris.

The provision of a hinge at the downstream side appears to be practical and offers the advantage of ease in changing the throat opening. The provision of the hinge will also reduce the cost of the top cover section.

The combination of taps 1 and 3 is considered to be the most practical combination for field application.

The equation for discharge obtained from dimensional analysis is as follows:

$$Q = C_D \ A_t\sqrt{2g\Delta h}$$

The average value of C_D is 1.00. The actual values of coefficients of discharge for various throat openings are given in Table 2.

For the limited range of flow, the coefficient of discharge tends to decrease with an increase in discharge and differential head for a particular throat opening. The coefficient of discharge tends to increase with an increase in throat opening. The coefficient of discharge becomes comparatively constant at higher throat openings.

Head loss has been expressed as a function of differential head between points 1 and 3. The head loss varies from about 43 percent of the differential head for a 5 inch throat opening to less than 30 percent of differential head for a 9 inch throat opening. For a given discharge the differential head decreases with the increase in throat openings, consequently the head loss also decreases. The throat opening can be adjusted to control the head loss and keep it below a certain desired limit.

The head loss through the section can be reduced if the divergence of the downstream side is more gradual. This can be done by reducing the downstream angle. An angle of about 12 degrees with the horizontal is recommended. This will tend to increase the overall length of the device but it is expected that the head loss will be reduced considerably.

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APPENDIX

Tables

Table 1. Dimensionless parameters for the device

Series	d	A_t	$\sqrt{A_t}$	$A_t^{5/4}$	Q	Δh	$\frac{\Delta h}{\sqrt{A_t}}$	$(\frac{\Delta h}{\sqrt{A_t}})^{1/2}$	$\frac{Q}{\sqrt{g}\ A_t^{5/4}}$	$A_t\sqrt{2g\ h}$
1	5"	1.248	1.117	1.319	5.93	0.407	0.348	0.590	0.790	6.36
2	5"	1.248	1.117	1.319	7.05	0.585	0.500	0.707	0.940	7.64
3	5"	1.248	1.117	1.319	6.62	0.518	0.443	0.666	0.882	7.21
4	5"	1.248	1.117	1.319	6.20	0.454	0.388	0 623	0.826	6.74
5	5"	1.248	1.117	1.319	5.33	0.337	0.288	0.537	0.710	5.82
6	5"	1.248	1.117	1.319	4.60	0.246	0.285	0.534	0.613	4.97
7	5"	1.248	1.117	1.319	2.92	0.089	0.076	0.275	0.389	2.99
8	5"	1.248	1.117	1.319	3.50	0.136	0.116	0.341	0.466	3.69
9	5"	1.248	1.117	1.319	3.86	0.171	0.146	0.382	0.515	4.12
10	5"	1.248	1.117	1.319	4.36	0.223	0.191	0.437	0.582	4.71
11	6"	1.486	1.22	1.641	6.76	0.345	0.283	0.532	0.731	7.05
12	6"	1.486	1.22	1.641	6.09	0.274	0.225	0.474	0.658	6.26
13	6"	1.486	1.22	1.641	5.69	0.228	0.187	0.432	0.615	5.85

Table 1. Continued

Series	d	A_t	$\sqrt{A_t}$	$A_t^{5/4}$	Q	Δh	$\frac{\Delta h}{\sqrt{A_t}}$	$\left(\frac{\Delta h}{\sqrt{A_t}}\right)^{1/2}$	$\frac{Q}{\sqrt{g}\, A_t^{5/4}}$	$A_t\sqrt{2g\Delta h}$
14	6"	1.486	1.22	1.641	5.32	0.207	0.170	0.413	0.575	5.44
15	6"	1.486	1.22	1.641	4.25	0.126	0.104	0.322	0.460	4.24
16	6"	1.486	1.22	1.641	3.45	0.082	0.0663	0.257	0.373	3.435
17	6"	1.486	1.22	1.641	4.13	0.122	0.100	0.316	0.447	4.18
18	6"	1.486	1.22	1.641	3.09	0.065	0.0533	0.227	0.334	3.05
19	7"	1.77	1.331	2.08	3.50	0.057	0.0426	0.206	0.295	3.38
20	7"	1.77	1.331	2.08	4.77	0.109	0.0816	0.284	0.402	4.68
21	7"	1.77	1.331	2.08	6.78	0.224	0.168	0.410	0.572	6.69
22	7"	1.77	1.331	2.08	6.16	0.182	0.136	0.368	0.520	6.05
23	7"	1.77	1.331	2.08	5.76	0.160	0.120	0.346	0.486	5.66
24	7"	1.77	1.331	2.08	5.17	0.130	0.0975	0.314	0.436	5.10
25	7"	1.77	1.331	2.08	4.35	0.089	0.0666	0.250	0.366	4.24
26	7"	1.77	1.331	2.08	7.10	0.247	0.185	0.430	0.600	7.05

Table 1. Continued

Series	d	A_t	$\sqrt{A_t}$	$A_t^{5/4}$	Q	Δh	$\frac{\Delta h}{\sqrt{A_t}}$	$\left(\frac{\Delta h}{\sqrt{A_t}}\right)^{1/2}$	$\frac{Q}{\sqrt{g}\, A_t^{5/4}}$	$A_t\sqrt{2g\Delta h}$
27	8"	2.00	1.416	2.36	7.10	0.186	0.132	0.364	0.526	6.94
28	8"	2.00	1.416	2.36	5.32	0.102	0.0721	0.266	0.394	5.14
29	8"	2.00	1.416	2.36	6.63	0.163	0.115	0.339	0.492	6.49
30	8"	2.00	1.416	2.36	5.89	0.127	0.090	0.300	0.44	5.74
31	8"	2.00	1.416	2.36	5.52	0.110	0.0776	0.278	0.412	5.34
32	8"	2.00	1.416	2.36	4.88	0.084	0.0594	0.244	0.364	4.65
33	8"	2.00	1.416	2.36	5.29	0.103	0.0726	0.226	0.395	5.17
34	9"	2.275	1.51	2.80	5.35	0.079	0.0523	0.269	0.336	5.08
35	9"	2.275	1.51	2.80	5.82	0.095	0.063	0.248	0.366	5.57
36	9"	2.275	1.51	2.80	6.38	0.116	0.0768	0.277	0.402	6.16
37	9"	2.275	1.51	2.80	6.62	0.126	0.0834	0.288	0.416	6.42
38	9"	2.275	1.51	2.80	7.04	0.144	0.0952	0.308	0.442	6.85
39	9"	2.275	1.51	2.80	6.18	0.108	0.0715	0.267	0.389	5.95
40	9"	2.275	1.51	2.80	5.82	0.096	0.0635	0.252	0.366	5.60

ft.)

h_4	$h_1-h_3+0.011$	$\sqrt{\Delta h}$	C_D	C_q	$h_1-h_4+0.012$	$\sqrt{\Delta h}$	C_D	C_q	V_t
1.316	0.407	0.6380	0.930	0.915	0.447	0.6685	0.900	0.884	4.75
1.346	0.585	0.7648	0.922	0.912	0.645	0.8031	0.889	0.871	5.65
1.340	0.518	0.7205	0.920	0.905	0.565	0.7516	0.890	0.880	5.30
1.331	0.454	0.6738	0.922	0.907	0.491	0.7687	0.818	0.807	4.96
1.292	0.337	0.5805	0.915	0.892	0.358	0.5983	0.900	0.876	4.28
1.244	0.246	0.4960	0.925	0.907	0.259	0.5090	0.915	0.895	3.69
1.060	0.089	0.2983	0.978	0.950	0.096	0.3098	0.943	0.920	2.34
1.136	0.136	0.3688	0.950	0.876	0.142	0.3768	0.940	0.915	2.81
1.174	0.171	0.4135	0.935	0.911	0.178	0.4219	0.925	0.905	3.10
1.224	0.223	0.4724	0.925	0.905	0.234	0.4837	0.915	0.898	3.50
1.481	0.345	0.5873	0.965	0.950	0.367	0.6058	0.949	0.925	4.56
1.435	0.275	0.5234	0.975	0.963	0.293	0.5412	0.951	0.930	4.10
1.402	0.228	0.4881	0.975	0.960	0.257	0.5069	0.950	0.930	3.83

Table 2. Continued.

Series	d	Parshall Flume Piezometric hea			
		h	Q	h_1	h_3
14	6"	1.207	5.32	1.586	1.390
15	6"	1.040	4.25	1.391	1.276
16	6"	0.907	3.45	1.728	1.657
17	6"	1.021	4.13	1.909	1.798
18	6"	0.845	3.09	1.485	1.431
19	7"	0.916	3.50	1.536	1.490
20	7"	1.123	4.77	1.586	1.488
21	7"	1.414	6.78	1.793	1.580
22	7"	1.327	6.16	1.693	1.522
23	7"	1.270	5.76	1.630	1.481
24	7"	1.183	5.17	1.533	1.414
25	7"	1.056	4.35	1.388	1.310
26	7"	1.458	7.10	1.846	1.610

Table 2. Continued.

Series	d	Parshall Flume h	Q	Piexometric head h_1	h_3
27	8"	1.458	7.10	1.829	1.654
28	8"	1.207	5.32	1.550	1.459
29	8"	1.394	6.63	1.758	1.606
30	8"	1.290	5.89	1.640	1.524
31	8"	1.236	5.52	1.582	1.483
32	8"	1.140	4.88	1.475	1.402
33	8"	1.201	5.29	1.554	1.462
34	9"	1.212	5.35	1.549	1.481
35	9"	1.279	5.82	1.623	1.539
36	9"	1.358	6.38	1.710	1.605
37	9"	1.392	6.62	1.746	1.631
38	9"	1.449	7.04	1.813	1.680
39	9"	1.329	6.18	1.680	1.583
40	9"	1.280	5.82	1.623	1.539

Table 3. Head loss for the device

Series	d	Y_1	$\frac{V_1^2}{2g}$	$H_1=Y_1+\frac{V_1^2}{2g}$	Y_2	$\frac{V_2^2}{2g}$	$H_2=Y_2+\frac{V_2^2}{2g}$	$H_L=H_1-H_2$	Δh_{13}	Δh_{14}	$\frac{H_L}{V_1^2/2g}$	$\frac{Y_1}{d}$	$\frac{\Delta h}{Y_1}$
1	5"	2.336	0.0118	2.3478	2.170	0.0129	2.1829	0.1649	0.407	0.447	13.98	5.64	0.174
2	5"	2.564	0.0130	2.5770	2.325	0.0158	2.3408	0.2362	0.585	0.645	18.20	6.18	0.228
3	5"	2.478	0.0123	2.4903	2.269	0.0147	2.2837	0.2066	0.518	0.565	16.80	5.96	0.209
4	5"	2.395	0.0115	2.4065	2.212	0.0136	2.2256	0.1809	0.454	0.491	15.70	5.77	0.1891
5	5"	2.223	0.0094	2.2324	2.090	0.0112	2.1012	0.1312	0.337	0.358	14.00	5.37	0.1513
6	5"	2.076	0.0085	2.0845	1.982	0.0093	1.9913	0.0932	0.246	0.259	10.95	5.00	0.1185
7	5"	1.729	0.0050	1.7340	1.700	0.0051	1.7051	0.0289	0.089	0.096	5.78	4.17	0.0515
8	5"	1.852	0.0062	1.8582	1.803	0.0065	1.8095	0.0487	0.136	0.142	7.37	4.47	0.0735
9	5"	1.925	0.0070	1.9320	1.861	0.0074	1.8684	0.0636	0.171	0.178	9.10	4.64	0.0888
10	5"	2.031	0.0080	2.0392	1.947	0.0087	1.9557	0.0835	0.223	0.234	10.41	4.90	0.1100
11	6"	2.421	0.0135	2.4345	2.297	0.0149	2.3119	0.1226	0.345	0.367	9.10	4.87	0.1425
12	6"	2.301	0.0120	2.313	2.207	0.0131	2.2201	0.0921	0.274	0.293	7.69	4.14	0.1190
13	6"	2.232	0.0012	2.2432	2.152	0.0121	2.1641	0.0791	0.228	0.257	7.06	4.50	0.1020

Table 3. Continued.

Series	d	Y_1	$\frac{V_1^2}{2g}$	$H_1=Y_1+\frac{V_1^2}{2g}$	Y_2	$\frac{V_2^2}{2g}$	$H_2=Y_2+\frac{V_2^2}{2g}$	$H_L=H_1-H_2$	Δh_{13}	Δh_{14}	$\frac{H_L}{V_1^2/2g}$	$\frac{Y_1}{d}$	$\frac{\Delta h}{Y_1}$
14	6"	2.171	0.0104	2.1814	2.099	0.0111	2.1101	0.0713	0.207	0.225	6.85	4.37	0.0955
15	6"	1.976	0.0080	1.984	1.935	0.0084	1.9434	0.0406	0.126	0.140	5.07	3.98	0.0638
16	6"	2.313	0.0039	2.3169	2.282	0.0039	2.2859	0.0310	0.082	0.092	7.95	4.66	0.0355
17	6"	2.494	0.0045	2.4985	2.424	0.0050	2.429	0.0695	0.122	0.182	15.45	5.02	0.0490
18	6"	2.070	0.0035	2.0735	2.047	0.0039	2.0509	0.0226	0.065	0.072	6.45	4.17	0.0314
19	7"	2.121	0.0047	2.1257	2.105	0.0048	2.1098	0.0159	0.057	0.062	3.78	3.60	0.0268
20	7"	2.171	0.0078	2.1788	2.140	0.0086	2.1486	0.0302	0.109	0.116	3.87	3.68	0.0502
21	7"	2.378	0.0133	2.3913	2.311	0.0149	2.3259	0.0654	0.224	0.247	4.91	4.02	0.0944
22	7"	2.278	0.0119	2.2899	2.225	0.0133	2.2383	0.0516	0.182	0.202	4.34	3.86	0.080
23	7"	2.215	0.0117	2.2267	2.169	0.0122	2.1812	0.0455	0.160	0.175	3.89	3.76	0.0722
24	7"	2.118	0.0097	2.1277	2.081	0.0107	2.0917	0.0360	0.130	0.140	3.70	3.58	0.0614
25	7"	1.973	0.0079	1.9809	1.950	0.0086	1.9586	0.0223	0.089	0.095	2.82	3.34	0.0450
26	7"	2.431	0.0139	2.4449	2.355	0.0158	2.3708	0.0741	0.247	0.271	5.33	4.12	0.1015

Table 3. Continued.

Series	d	Y_1	$\frac{V_1^2}{2g}$	$H_1 = Y_1 + \frac{V_1^2}{2g}$	Y_2	$\frac{V_2^2}{2g}$	$H_2 = Y_2 + \frac{V_2^2}{2g}$	$H_L = H_1 - H_2$	Δh_{13}	Δh_{14}	$\frac{H_L}{V_1^2/2g}$	$\frac{Y_1}{d}$	$\frac{\Delta h}{Y_1}$
27	8"	2.414	0.014	2.428	2.361	0.0156	2.3766	0.0514	0.186	0.271	3.67	3.62	0.077
28	8"	2.135	0.0107	2.1457	2.107	0.011	2.118	0.0277	0.102	0.117	2.59	3.20	0.0477
29	8"	2.343	0.0138	2.3568	2.297	0.0141	2.3111	0.0457	0.163	0.189	3.32	3.52	0.0695
30	8"	2.225	0.0108	2.2358	2.191	0.0125	2.2035	0.0323	0.127	0.145	3.00	3.34	0.057
31	8"	2.167	0.0112	2.1782	2.137	0.0115	2.1485	0.0297	0.110	0.130	2.65	3.25	0.0507
32	8"	2.060	0.0096	2.0696	2.038	0.0099	2.0479	0.0217	0.084	0.097	2.26	3.09	0.0406
33	9"	2.139	0.0105	2.1495	2.111	0.0108	2.1218	0.0277	0.103	0.121	2.64	3.21	0.0482
34	9"	2.134	0.0109	2.1449	2.113	0.0111	2.1241	0.0208	0.079	0.097	1.91	2.85	0.037
35	9"	2.208	0.0120	2.220	2.181	0.0123	2.1933	0.0267	0.095	0.113	2.222	2.94	0.043
36	9"	2.295	0.0134	2.3084	2.262	0.0137	2.2757	0.0327	0.116	0.129	2.44	3.06	0.0506
37	9"	2.331	0.0139	2.3449	2.294	0.0144	2.3084	0.0365	0.126	0.146	2.62	3.11	0.0540
38	9"	2.398	0.0149	2.4129	2.356	0.0154	2.3714	0.0415	0.144	0.168	2.79	3.19	0.0600
39	9"	2.265	0.0129	2.2779	2.235	0.0133	2.2483	0.0296	0.108	0.128	2.30	3.02	0.0477
40	9"	2.208	0.0120	2.2200	2.182	0.0123	2.1943	0.0257	0.096	0.111	2.14	2.94	0.0435

List of symbols in computer program

NS = Number of streamlines

NP1 = Number of potential drops to front of top cover section

NP2 = Number of potential drops to end of top cover section

NP3 = Total number of potential drops

INIT = If greater than 0 field is not initialized

YIN = Upstream depth

VINT = Leaving velocity

VIN = Incoming velocity

W = Over relaxation factor

ERR = Error parameter

MAX = Maximum number of iterations permitted

```
*JOBID,*MEAS,10050607
      COMMON Y(40,16),V(33),NS1,NP31,INIT,H,YIN,VIN,NP,FNS1,NP1P,NP2P,
     $FNP,FNP32,W,NP11,NP21,A2,ERR,MAX,NS,NP1,NP2,NP3,VINT,X(40,16)
   10 READ(5,100) NS,NP1,NP2,NP3,INIT,YIN,VIN,VINT,W,ERR,MAX
  100 FORMAT(5I5,3F10.5,2F10.6,I5)
      IF(NS.EQ.99) GO TO 99
      WRITE(6,103)NS,NP1,NP2,NP3,INIT,YIN,VIN,VINT,W,ERR,MAX
  103 FORMAT(1H ,5I5,3F10.5,2F10.6,I5)
      NS1=NS-1
      FNS1=NS1
      NP=NP2-NP1+1
      NP1P=NP1+1
      NP2P=NP2+1
      FNP=NP
      FNP32=NP3-NP2
      NP21=NP2-1
      NP11=NP1-1
      READ(5,101)(Y(I,NS), I=NP1P,NP2)
  101 FORMAT(8F10.5)
      WRITE(6,201)(Y(I,NS), I=NP1P,NP2)
  201 FORMAT(1H ,13F10.5)
      Y(NP3,1)=0.0
      Y(1,1)=0.0
      DELY=YIN/FNS1
      DO 3 J=2,NS
      Y(1,J)=Y(1,J-1)+DELY
    3 Y(NP3,J)=Y(NP3,J-1)+DELY
      NP31=NP3-1
      H=YIN+VINT*VINT/64.4
      A=YIN*VIN/FNS1
      A2=A*A
      CALL YCOORD
      CALL XBOND
      CALL XCOORD
      DO 1 I=1,NP3
      WRITE(6,102)(Y(I,J), J=1,NS)
      WRITE(6,102)(X(I,J), J=1,NS)
    1 WRITE(6,110)
  110 FORMAT(1H )
  102 FORMAT(1H ,13F8.3,3F9.3)
      CALL VANDAN
      GO TO 10
   99 STOP
```

Fortran IV program

```
      END
      SUBROUTINE  YCOORD
      COMMON Y(40,16),V(33),NS1,NP31,INIT,H,YIN,VIN,NP,FNS1,NP1P,NP2P,
     $FNP,FNP32,W,NP11,NP21,A2,ERR,MAX,NS,NP1,NP2,NP3,VINT,X(40,16)
      NS2=NS-2
      IF(INIT.GT.0)  GO TO 10
      DO 11 I=2,NP11
      DO 11 J=1,NS
   11 Y(I,J)=Y(1,J)
      Y(NP1,NS)=H
      DO 2 I=NP1,NP2
      II=I-NP11
      DO  2 J=1,NS1
    2 Y(I,J)=FLOAT(J-1)/FNS1*Y(I,NS)
      DO 3 I=NP2P,NP31
      Y(I,NS)=YIN
      DO 3 J=1,NS1
    3 Y(I,J)=FLOAT(J-1)/FNS1*Y(I,NS)
   10 NCOUNT=0
   20 SUM=0.0
      NCOUNT=NCOUNT+1
      DO 4 I=2,NP31
      DO 4 J=2,NS2
      YT=.05*(4.*(Y(I+1,J)+Y(I-1,J)+Y(I,J+1)+Y(I,J-1))+Y(I+1,J+1)+
     $Y(I+1,J-1)+Y(I-1,J-1)+Y(I-1,J+1))
      DIF=YT-Y(I,J)
      SUM=SUM+DIF*DIF
    4 Y(I,J)=Y(I,J)+W*DIF
      DO 15 I=2,NP31
   15 Y(I,NS1)=.25*(Y(I+1,NS1)+Y(I-1,NS1)+Y(I,NS)+Y(I,NS2))
   42 DO 7 I=NP2P,NP31
    7 CALL NEWRP(I,NCOUNT)
      IF(SUM.GT.50.0) GO TO 99
      IF(MOD(NCOUNT,10).NE.0) GO TO 29
      WRITE(6,150)NCOUNT,SUM
   29 IF(SUM.GT.ERR.AND.NCOUNT.LT.MAX) GO TO 20
      IF(SUM. GT. 99999.) GO TO 99
      WRITE(6,150)NCOUNT,SUM
  150 FORMAT(1H ,21HNUMBER OF ITERATIONS=,I5,5H SUM=,F15.5)
   99 RETURN
      END
      SUBROUTINE NEWRP(I,NCOUNT)
      COMMON Y(40,16),V(33),NS1,NP31,INIT,H,YIN,VIN,NP,FNS1,NP1P,NP2P,
```

```
     $FNP,FNP32,W,NP11,NP21,A2,ERR,MAX,NS,NP1,NP2,NP3,VINT,X(40,16)
      WW=.4
      NCT=0
      IP=I+1
      IM=I-1
      H128=128.8*H
      H16=16.1*H
      Y13=Y(IP,NS)-Y(IM,NS)
      Y132=Y13*Y13
      YPM=Y(IP,NS)+Y(IM,NS)+2.*Y(I,NS1)
   10 SY=4.*Y(I,NS)-YPM
      NCT=NCT+1
      SY2=SY*SY
      F=16.1*(H-Y(I,NS))*(SY2+Y132)-A2
      DF=H128*SY-(SY2+Y132+8.*Y(I,NS)*SY)*16.1
      DIF=F/DF
      Y(I,NS)=Y(I,NS)-DIF*WW
      IF(ABS(DIF).GT. .000005 .AND. NCT .LT.12) GO TO 10
      RETURN
      END
      SUBROUTINE XBOND
      COMMON Y(40,16),V(33),NS1,NP31,INIT,H,YIN,VIN,NP,FNS1,NP1P,NP2P,
     $FNP,FNP32,W,NP11,NP21,A2,ERR,MAX,NS,NP1,NP2,NP3,VINT,X(40,16)
      DO 1 J=1,NS
      F1=13.0/24.0
      F2=1.0/24.0
      NS2=NS-2
      NS3=NS-3
    1 X(1,J)=0.0
      DYB1=3.*Y(1,2)-1.8333333*Y(1,1)-1.5*Y(1,3)+.33333333*Y(1,4)
      DYT1=1.8333333*Y(1,NS)-3.*Y(1,NS1)+1.5*Y(1,NS2)-.3333333*Y(1,NS3)
      DYB2=3.*Y(2,2)-1.8333333*Y(2,1)-1.5*Y(2,3)+.33333333*Y(2,4)
      DYT2=1.8333333*Y(2,NS)-3.*Y(2,NS1)+1.5*Y(2,NS2)-.3333333*Y(2,NS3)
      DYB3=3.*Y(3,2)-1.8333333*Y(3,1)-1.5*Y(3,3)+.33333333*Y(3,4)
      DYT3=1.8333333*Y(3,NS)-3.*Y(3,NS1)+1.5*Y(3,NS2)-.3333333*Y(3,NS3)
      X(2,1)=.5*(DYB1+DYB2)
      X(2,NS)=.5*(DYT1+DYT2)
      DO 2 I=4,NP3
      I1=I-1
      I2=I-2
      DYB4=3.*Y(1,2)-1.8333333*Y(1,1)-1.5*Y(1,3)+.33333333*Y(1,4)
      DYT4=1.8333333*Y(I,NS)-3.*Y(I,NS1)+1.5*Y(I,NS2)-.3333333*Y(I,NS3)
      X(I1,1)=X(I2,1)+F1*(DYB2+DYB3)+F2*(DYB1+DYB4)
```

```
      X(I1,NS)=X(I2,NS)+F1*(DYT2+DYT3)+F2*(DYT1+DYT4)
      DYB1=DYB2
      DYB2=DYB3
      DYB3=DYB4
      DYT1=DYT2
      DYT2=DYT3
    2 DYT3=DYT4
      X(NP3,1)=X(NP31,1)+.5*(DYB2+DYB3)
      X(NP3,NS)=X(NP31,NS)+.5*(DYT2+DYT3)
      DIF=.5*(X(NP3,NS)-X(NP3,1))/FLOAT(NP3)
      WRITE(6,100) DIF
  100 FORMAT(1H ,5HDIF =,F10.4)
      DO 4 I=2,NP3
      FI=I
      X(I,NS)=X(I,NS)-FI*DIF
    4 X(I,1)=X(I,1)+FI*DIF
      XT=X(NP3,1)
      DIF=(X(NP3,NS)-XT)/FLOAT(NS1)
      DO 3 J=2,NS1
    3 X(NP3,J)=XT+FLOAT(J)*DIF
      RETURN
      END
      SUBROUTINE XCOORD
      COMMON Y(40,16),V(33),NS1,NP31,INIT,H,YIN,VIN,NP,FNS1,NP1P,NP2P,
     $FNP,FNP32,W,NP11,NP21,A2,ERR,MAX,NS,NP1,NP2,NP3,VINT,X(40,16)
      FNS1=NS1
      DO 1 I=2,NP31
      XT=X(I,1)
      DIF=(X(I,NS)-XT)/FNS1
      DO 1 J=2,NS1
    1 X(I,J)=XT+FLOAT(J)*DIF
      NCOUNT=0
   10 SUM=0.0
      NCOUNT=NCOUNT+1
      DO 2 I=2,NP31
      DO 2 J=2,NS1
      XT=.05*(4.*(X(I+1,J)+X(I-1,J)+X(I,J+1)+X(I,J-1))+X(I+1,J+1)+
     $X(I+1,J-1)+X(I-1,J+1)+X(I-1,J-1))
      DIF=XT-X(I,J)
      SUM=SUM+DIF*DIF
    2 X(I,J)=X(I,J)+W*DIF
      IF(SUM.GT.50.0) GO TO 99
      IF(SUM.GT.ERR.AND.NCOUNT.LT.MAX) GO TO 10
```

```
      WRITE(6,100) SUM,NCOUNT
  100 FORMAT(1H ,4HSUM=,F12.5,25HNO. OF ITERATIONS FOR X =,I5)
   99 RETURN
      END
      SUBROUTINE VANDAN
      COMMON Y(40,16),V(33),NS1,NP31,INIT,H,YIN,VIN,NP,FNS1,NP1P,NP2P,
     $FNP,FNP32,W,NP11,NP21,A2,ERR,MAX,NS,NP1,NP2,NP3,VINT,X(40,16)
      REAL A(16)
      DPS=VIN*YIN/FNS1
      NP32=NP3-2
      NP33=NP3-3
      NS2=NS-2
      NS3=NS-3
      WRITE(6,110)
  110 FORMAT(1H1,35HVELOCITIES AND ANGLES OF FLOW FIELD)
      DO 1 J=1,NS
      A(J)=0.0
    1 V(J)=VIN
      WRITE(6,100)(V(J),J=1,NS)
      WRITE(6,100)(A(J),J=1,NS)
      WRITE(6,101)
  100 FORMAT(1H ,13F8.3,3F9.3)
  101 FORMAT(1H0)
      DYP=Y(3,2)-.3333333*Y(1,2)-.5*Y(2,2)-.16666667*Y(4,2)
      DYS=Y(2,3)-.333333*Y(2,1)-.5*Y(2,2)-.16666667*Y(2,4)
      V(2)=DPS/SQRT(DYP*DYP+DYS*DYS)
      V(1)=V(2)
      A(1)=0.0
      A(2)=ARSIN(V(2)*DYP)
      DO 2 J=3,NS2
      DYP=Y(3,J)-.3333333*Y(1,J)-.5*Y(2,J)-.16666667*Y(4,J)
      DYS=.666667*(Y(2,J+1)-Y(2,J-1))+.0833333*(Y(2,J-2)-Y(2,J+2))
      V(J)=DPS/SQRT(DYP*DYP+DYS*DYS)
    2 A(J)=ARSIN(V(J)*DYP)
      DYP=Y(3,NS1)-.333333*Y(1,NS1)-.5*Y(2,NS1)-.16666667*Y(4,NS1)
      DYS=Y(2,NS2)-.333333*Y(2,NS)-.5*Y(2,NS1)-.166666667*Y(2,NS3)
      V(NS1)=DPS/SQRT(DYP*DYP+DYS*DYS)
      A(NS1)=ARSIN(V(NS1)*DYP)
      DYP=Y(3,NS)-.333333*Y(1,NS)-.5*Y(2,NS)-.16666667*Y(4,NS)
      DYS=1.83333*Y(2,NS)-3.*Y(2,NS1)+1.5*Y(2,NS2)-.333333*Y(2,NS3)
      V(NS)=DPS/SQRT(DYP*DYP+DYS*DYS)
      A(NS)=ARSIN(V(NS)*DYP)
      WRITE(6,100)(V(J), J=1,NS)
```

```
      WRITE(6,100) (A(J), J=1,NS)
      WRITE(6,101)
      DO 3 I=3,NP32
      DYP=.666667*(Y(I+1,2)-Y(I-1,2))+.0833333*(Y(I-2,2)-Y(I+2,2))
      DYS=Y(I,3)-.333333*Y(I,1)-.5*Y(I,2)-.16666667*Y(I,4)
      V(2)=DPS/SQRT(DYP*DYP+DYS*DYS)
      A(2)=ARSIN(V(2)*DYP)
      DYP=.666667*(Y(I+1,1)-Y(I-1,1))+.0833333*(Y(I-2,1)-Y(I+2,1))
      DYS=1.833333*Y(I,1)-3.*Y(I,2)+1.5*Y(I,3)-.333333*Y(I,4)
      V(1)=DPS/SQRT(DYP*DYP+DYS*DYS)
      DO 6 J=3,NS2
      DYP=.666667*(Y(I+1,J)-Y(I-1,J))+.0833333*(Y(I-2,J)-Y(I+2,J))
      DYS=.6666667*(Y(I,J+1)-Y(I,J-1))+.08333333*(Y(I,J-2)-Y(I,J+2))
      V(J)=DPS/SQRT(DYP*DYP+DYS*DYS)
    6 A(J)=ARSIN(V(J)*DYP)
      DYP=.666667*(Y(I+1,NS1)-Y(I-1,NS1))+.0833333*(Y(I-2,NS1)
     $-Y(I+2,NS1))
      DYS=Y(I,NS2)-.33333*Y(I,NS)-.5*Y(I,NS1)-.1666667*Y(I,NS3)
      V(NS1)=DPS/SQRT(DYP*DYP+DYS*DYS)
      A(NS1)=ARSIN(V(NS1)*DYP)
      DYP=.666667*(Y(I+1,NS)-Y(I-1,NS))+.08333333*(Y(I-2,NS)-Y(I+2,NS))
      DYS=1.833333*Y(I,NS)-3.*Y(I,NS1)+1.5*Y(I,NS2)-.333333*Y(I,NS3)
      V(NS)=DPS/SQRT(DYP*DYP+DYS*DYS)
      A(NS)=ARSIN(V(NS)*DYP)
      WRITE(6,100) (V(J),J=1,NS)
      WRITE(6,100)(A(J),J=1,NS)
    3 WRITE(6,101)
      DYP=.333333*Y(NP3,1)-Y(NP32,1)+.5*Y(NP31,1)+.1666667*Y(NP33,1)
      DYS=1.833333*Y(NP31,1)-3.*Y(NP31,2)+1.5*Y(NP31,3)-.33333*Y(NP31,4)
      V(1)=DPS/SQRT(DYP*DYP+DYS*DYS)
      DYP=.33333*Y(NP3,2)-Y(NP32,2)+.5*Y(NP31,2)+.1666667*Y(NP33,2)
      DYS=Y(NP31,3)-.333333*Y(NP31,1)-.5*Y(NP31,2)-.1666667*Y(NP31,4)
      V(2)=DPS/SQRT(DYP*DYP+DYS*DYS)
      A(2)=ARSIN(V(2)*DYP)
      DO 7 J=3,NS2
      DYP=.333333*Y(NP3,J)-Y(NP32,J)+.5*Y(NP31,J)+.1666667*Y(NP33,J)
      DYS=.6666667*(Y(NP31,J+1)-Y(NP31,J-1))+.0833333*(Y(NP31,J-2)-
     $Y(NP31,J+2))
      V(J)=DPS/SQRT(DYP*DYP+DYS*DYS)
    7 A(J)=ARSIN(V(J)*DYP)
      DYP=.333333*Y(NP3,NS1)-Y(NP32,NS1)+.5*Y(NP31,NS1)+.1666667*
     $Y(NP33,NS1)
      DYS=Y(NP31,NS2)-.3333333*Y(NP31,NS)-.5*Y(NP31,NS1)-.16666667*
```

```
 $Y(NP31,NS3)
  V(NS1)=DPS/SQRT(DYP*DYP+DYS*DYS)
  A(NS1)=ARSIN(V(NS1)*DYP)
  DYP=.333333*Y(NP3,NS)-Y(NP32,NS)+.5*Y(NP31,NS)+.16666667*
 $Y(NP33,NS)
  V(NS)=VIN
  A(NS)=ARSIN(VIN*DYP)
  WRITE(6,100)(V(J),J=1,NS)
  WRITE(6,100)(A(J),J=1,NS)
  WRITE(6,101)
  DO 8 J=1,NS
  V(J)=VIN
8 A(J)=0.0
  WRITE(6,100)(V(J),J=1,NS)
  WRITE(6,100)(A(J),J=1,NS)
  RETURN
  END
  FUNCTION ARSIN(X)
  ARG=SQRT(1.0-X*X)
  ARSIN=ATAN(X/ARG)
  RETURN
  END
```

VITA

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Candidate for the Degree of

Master of Science

Thesis: Hydraulic Characteristics of a Modified Venturi Section

Major Field: Hydraulics

Biographical Information:

Personal Data: Born at Roorkee, India, March 26, 1943, Son of Rasheed Ahmad and Saeeda Khatoon, Unmarried.

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