PRELIMINARY STUDIES ON FLOW PAST A GATE WITH CYLINDRICAL LIPS

by

NIRMALENDU CHOUBEY

A MAJOR TECHNICAL REPORT

in

The Faculty

of

Engineering

Presented in Partial Fulfillment of the Requirements for
the Degree of Master of Engineering at
Sir George Williams University
Montreal, Canada

June, 1973

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

SYMBOLS AND PARAMETERS

a	Gate opening (ft.)
b	Trunnion height (ft.)
C_c	Contraction coefficient
C_{df}	Discharge coefficient (free flow)
C_{ds}	Discharge coefficient (submerged flow)
d	Diameter of circular cylindrical lip (in.)
d_o	Diameter of orifice (in.)
D	Internal diameter of pipe (in.)
F_t	$\left(\frac{\text{Average velocity at section } t}{\sqrt{g \times H_t}}\right)$ Froude No.
F_2	$\left(\frac{U_2}{\sqrt{g \times H_2}}\right)$ Froude No.
g	Force due to gravity (ft./sec.^{2})
h	Head at separation point (ft.)
Δh	Head difference across orifice meter
H_0	Stagnation head at intake (ft.)
H_1	Head at intake (ft.)
H_2	Head immediately downstream of the gate (ft.)
H_t	Head far downstream of the gate (ft.)
K	Flow coefficient
Q_a	Flow measured by orifice meter (cfs)
Q_{th}	Theoretical flow (cfs/ft.)
R_d	$\left(\frac{U_a \times d}{12 x \eta}\right)$ Reynolds No.
R_D	$\left(\frac{v \times D}{12 x \eta}\right)$ Reynolds No.
U_a	Average velocity at the slot (fps)
U_1	Average velocity ahead of the gate (fps)

U_2	Average velocity in contracted or expanded jet immediately downstream of the gate (fps)
v	Average velocity in pipe (ft./sec.)
W	Channel width (ft.)
β	Ratio of orifice to pipe diameter
η	Kinematic viscosity of water (ft.^{2}/sec.)
Θ	Any angle (degree)
Θ_1	Lip angle (degree)
Φ	An arbitrary function
$\frac{a}{H_1}$	Blockage

ABSTRACT

Nirmalendu Choubey

PRELIMINARY STUDIES ON FLOW PAST A
GATE WITH CYLINDRICAL LIPS

Existing literature related to characteristics of flow past a sluice gate fitted with a cylindrical lip (Fig. 1) is very limited. The distinguishing feature of a sluice gate fitted with cylindrical lip is the uncertainty about the location of the point of separation. For a cylinder the point of separation can move far downstream when the Reynolds number of the flow is large. An effect of this downstream shift in the separation point is to increase the area of flow and hence the discharge coefficient for the gate.

In the present investigation, a simple flume was fabricated to study the effects of gate lips on the coefficient of discharge of the sluice gates. The data reported presently is related to the preliminary studies in which a cylindrical lip was mounted on the gates. Both free and submerged conditions of flow were included during the investigations.

ACKNOWLEDGEMENTS

I wish to thank Dr. A.S. Ramamurthy for suggesting the project related to flow past sluice gates fitted with cylindrical lips. The assistance of the lab technician Mr. Louis Stankevicius is thankfully acknowledged.

INTRODUCTION

Previous Studies:

Normally, discharge underneath a gate of any shape is related to discharge from an equivalent two-dimensional slot. The contraction coefficient C_c, described as the ratio of the depth of contracted stream-to-gate opening, was first approximately measured by Rayleigh[1]. He analyzed the efflux from a slot in the wall of an infinite reservoir. Later, Von Mises[2] applied jet contraction in a slot to the sluice gate discharge problem. He made assumptions of constant velocity along the free streamline and constant pressure across the jet at infinity. The effect of gravity and boundry shear were neglected. Pajer[3] was the first one to consider the effect of gravity. His work was later followed by several others, including Benjamin[4] and Larock[5]. Some investigators applied the relaxation techniques and others formulated a non-linear integral equation to arrive at the solutions to the problem of flow past a sluice gate.

Due to curved boundaries associated with radial gates, it has not been possible to adopt the Schwartz-Christoffel theorem to determine the contraction coefficient. In the absence of a comprehensive theory, much of the existing experimental work cannot be generalised. Some systematic hydraulic model tests have been conducted by Metzler[6], Toch[7], and Babb[8]. These tests provide some guidance with regard to the characteristics of gate flow. Toch[7] studied several lip angles for a tainter gate (Fig. 2) during the course of his investigation. The contraction coefficient was found to be a function of the lip angle and not a function of the ratio of slot width to intake head. A critical appraisal of his work has been done by Henderson[9]. Recently Larock[10] has presented some analytical work and his results agree well with the experimental work done by others. He has included the effect of curvature and gravity on the flow.

In the present investigation, cylindrical lips (Fig. 6) of different sizes were fitted to the sluice gate to determine the discharge coefficient.

<u>Some Definitions</u>:

Steady, two-dimensional flow of water past a cylindrical gate lip is considered here.

As shown in Fig. 1, water flows underneath the cylindrical gate lip. In the rearward section of the curved boundry, the flow velocity starts to decrease and is accompanied by an adverse pressure gradient. This results in the separation of flow.

In the case of free flow, the loss of energy in the passage through the gate opening may be considered to be small. However, for the submerged flow a considerable part of the kinetic energy of the flow is dissipated by diffusion directly downstream from the gate. As the level of water at the tail end H_t (Fig. 1) is increased, hydraulic jump is formed. The jump moves progressively towards the gate and eventually submerges the gate opening. This is accompanied by an increase in the upstream and downstream heads H_1 and H_2 for the same rate of flow. Very soon a stage is reached where H_2 is only slightly lower than H_t and downstream surface waves are reduced to a minimum.

For the flow past the gate shown in Fig. 1, assume the energy at sections 1 and 2 is the same and that the pressure distribution is hydrostatic. From Bernoulli's equation (incompressible flow)

$$H_1 + \frac{U_1^2}{2g} = H_2 + \frac{U_2^2}{2g} \qquad \ldots(1)$$

Since U_1 is small, neglect $\frac{U_1^2}{2g}$

then $U_2 = \sqrt{2g(H_1 - H_2)}$ $\qquad \ldots(2)$

is the velocity along the separated streamline.

Define $Q_{th} = a\sqrt{2g(H_1 - H_2)}$ $\qquad \ldots(3)$

where "a" is the slot height.

Using this definition of the theoretical discharge, the coefficient of discharge C_{ds} can be set as

$$C_{ds} = \frac{Q_a}{Q_{th}} = \frac{Q_a}{a\sqrt{2g(H_1 - H_2)}} \text{ (submerged flow)} \qquad \ldots(4)$$

$$C_{df} = \frac{Q_a}{Q_{th}} = \frac{Q_a}{a\sqrt{2g(H_1 - a)}} \text{ (free flow)} \qquad \ldots(5)$$

In C_{df} definition H_2 has been replaced by "a".

EQUIPMENT AND PROCEDURE

The Test Flume:

A steel flume 18" x 15" (Fig. 3) was designed to study the characteristics of flow past sluice gates. The intake section was provided with a filter system to reduce the level of turbulence in the flow. The tail gate plates enabled one to vary the level of flow in the section of the flume which follows the hydraulic jump. Water was circulated by a centrifugal pump. The flow was metered by an orifice meter (Fig. 4). A plexiglass face plate (Fig. 5) was composed of two sections. The gate face and the gate lip were fastened to the steel gate of the flume. The gate could be raised or lowered to any desired height by a "jack screw" arrangement.

The Gate Lips:

Three cylindrical lips (Fig. 6) of diameters $2\frac{1}{4}$", 5", and 8" were used in the experiment. The gate face and lips were sealed at the side.

For setting the gate openings precisely 12" long, machined plexiglass strips were used. The widths of the gate slots chosen were 7/8" and 2" for each lip.

For controlling the downstream depth H_t (Fig. 1), wooden strips of known width were placed in the tail gate slot of the flume. This method was also used to avoid the discharge from overshooting the collecting tank.

Measurements:

The flow going through the gate Q_a was measured by recording the pressure difference in a mercury U-tube manometer connected to the two sides of the orifice meter (Fig. 4). A specimen claculation has been included in Appendix 1 to illustrate the computation procedure.

The head H_1 at the intake (Fig. 1) was measured by noting the level of water at the inside face of the gate. The head H_t far downstream of the gate (6.1 ft. from the gate) was measured by a point gage attached to a movable carriage mounted on horizontal rails (Fig. 7). The head H_2 (Fig. 1) was calculated from H_t (see Appendix 2) since the flow just downstream of the gate was strictly not two-dimensional. The gate opening a (Fig. 1) was measured by machined plexiglass strip of fixed width as described earlier.

Pressure measurements were taken by connecting peripheral pressure taps set at the lip center (Fig. 6). A flexible transparent plastic tubing connected the inclined manometer to the manifold which received the pressure tubes from the static taps of the gate lip.

Experimental Procedure:

At the beginning of each run, the gate opening was set to the desired height. The head H_1 at the intake section was maintained at the desired level by regulating the intake gate valve. When the state of steady flow was reached, the head difference across the orifice was noted to determine the discharge rate. For free flows H_1 was measured. Different levels of submergence were created, placing wooden strips (numbered) either individually or in combination in the tail gate slot of the flume. For each submergence, H_1 and H_t were measured. When the level of the flow was unsteady, an average reading was recorded. Since the velocity head at the intake was very small ($<\frac{1}{2}$"), the H_0 reading was taken to be close to H_1. All the wooden strips were taken out and higher H_1 for the free flow was achieved by regulating the gate valve. The above procedure was repeated for different levels of submergence for each of the three cylindrical lips.

Limited pressure measurements were taken to establish the fact that the flow did not separate ahead of the 90° location (point A in Fig. 6). Utmost care was taken to ensure that there were no air bubbles in the connecting tubes or any part of the measuring equipment. An inclined manometer was used to ensure precision in pressure measurements. A vacuum pump was used to suck the air bubbles.

All the relevant data has been recorded in Table 1.

DIMENSIONAL ANALYSIS

Using the notations shown in Fig. 1, important variables characterising the flow past a cylindrical gate lip are combined to give the functional relationship

$$\Phi \; [R_d, F, a/d, a/H_1, H_t/a, H_2/a] = 0 \qquad \ldots(6)$$

In equation (6), R_d and F are Reynolds number and Froude number respectively. For the flow conditions considered, the Froude number downstream of the gate was always more than one. Omitting for the time being the effects of F and including H_t and H_2 in the definition of C_{ds}, one can state

$$C_{df} \text{ (or } C_{ds}) = f[R_d, a/d, a/H_1]$$

In this presentation, it has not been possible to have overlapping ranges of R_d (Figs. 11a and 11b) to study its effects completely, due to equipment limitations.

DISCUSSION OF EXPERIMENTAL DATA

In all cases upstream of the gate, the flow was subcritical ($F<1$) while the flow downstream of the gate was supercritical. At the intake, the existence of a vortex was noticed. Possibly this was responsible for the flow out of the gate to be strictly not two-dimensional when cylindrical lips were mounted (Fig. 8).

Pressure Measurements:

Although the gate lips were provided with a liberal number of pressure taps around the curvature of the lips (Fig. 6), only a few nominal measurements of pressure were made to establish the fact that the flow was generally separating beyond the 90° location (point A in Fig. 6). For instance for the cylindrical gate lip, the pressure at B ($\Theta \approx 112.5°$) was nearly 10.58 in. of water while the pressure at A was nearly 4.9 in. of water for a particular flow rate (run 41) which is indicative of the deceleration from A to B. If the flow had separated ahead of A, generally the steady pressure at A and B would be nearly the same.

Effect of Gap-to-Diameter Ratio:

Fig. 9a indicates the variation of the coefficient of discharge C_{df} with the parameter a/d. It is observed that C_{df} is a very slowly varying (decreasing) function of a/d for the range covered [$0.1 < a/d < 0.9$]. C_{df} appears to be independent of the diameter of the gate lips tested. It is conceivable that the blockage ratio defined as a/H_1 will influence the discharge coefficient. For instance, one notices about 10% increase in C_{df} when a/H_1 is increased from 0.032 to 0.069 as indicated by points 44 and 46 respectively in Fig. 10a.

Fig. 9b indicates the variation of the coefficient of discharge C_{ds} with the parameter a/d. It is observed that in the submerged case, an envelope can be drawn to the data plotted and three distinct curves branch out depending on the diameters of the gate lips. The dependence of C_{ds} on a/H_1 is less marked (Fig. 10b) when compared to free flow (Fig. 10a) case.

Effect of Gate Opening to Intake Head Ratio:

Figs. 10a and 10b indicate the variation of the coefficients of discharge C_{df} and C_{ds} with the parameter a/H_1. It is seen that the curves rise to the right, meaning that the lesser the blockage, the higher is the coefficient of discharge. It can also be seen that except when the blockage is very large ($a/H_1 < 0.06$), the value of C_{ds} is nearly constant (Fig. 10b). Observe that a similar remark cannot be made about C_{df}, since blockage effect and R_d effect cannot be separated as in the submerged case.

Effect of Reynolds No.:

Figs. 11a and 11b indicate the variation of the coefficient of discharge with Reynolds numbers. The range of parameters covered did not permit overlapping regions in R_d vs. C_{df} and C_{ds} graphs for different lip sizes although the data points are plotted as a function of R_d.

In the range of $5.5 < R_d \times 10^{-5}$ and $R_d \times 10^{-5} < 2.5$, the trends of discharge coefficients for both the free and the submerged flows appear to be the same. In the range of $2.5 < R_d \times 10^{-5} < 5.5$, the variations of the discharge coefficient appear to be limited to the free flow case only.

For a fixed diameter of lip and gate opening, changes in R_d were brought about by changes in mean gap velocity U_a (Fig. 1). This immediately indicates that changes in R_d are associated with changes in blockage for free case only. Note that for the submerged case, blockage can be changed independent of R_d. In view of the above comment a reexamination of the four graphs A, B, C, and D (Figs. 11a and 11b) indicate that variation of blockage in graphs A and B is much larger than variation of blockage for the data plotted in graphs C and D. (See also Table 1. The number on the graphs indicates the run number in the table.)

Note that in Figs. 11a and 11b the discharge coefficients C_{df} and C_{ds} are consistently higher when the gate opening is smaller. This may very well be due to the following reason. It is conceivable that the flow separation occurs approximately at the same angle in the downstream section for a given size of the gate lip when the gate opening is varied over a small range. If this is true, the "run up" denoted by the climbing of the flow associated with the delayed separation while remaining constant will become prominent for smaller gate openings.

SUMMARY AND CONCLUSION

1. The small flume and the instrumentation designed for flow past sluice gates was satisfactory in terms of its performance to provide some preliminary data.

2. When flow separates in the rearward section of the cylindrical lip, the conventional contraction coefficient C_c appeared to assume values in excess of unity. Pressure measurements on the surface of the lip were taken to confirm the fact that flow indeed separated in the rearward part.

3. C_{df} and C_{ds} are decreasing functions of a/d. However, the size of the cylindrical lip appeared to influcence C_{ds}.

4. Except when the blockage is very large ($a/H_1 < 0.06$), the value of C_{ds} is nearly constant.

SUGGESTION FOR FURTHER WORK

The objective of this work was to design a simple flume to study the characteristics of flow past a sluice gate. To improve the reliability of data, the following recommendations are made:

1. The flow measurements should be done by a water manometer (improved sensitivity).

2. A more efficient filter system should be provided at the intake system (reduce large-scale eddy flow).

3. A larger upstream reservoir is to be provided to increase the area for settling the incoming flow.

4. A collapsible tubing should be used for sealing the gate to reduce time for sealing the inside edges of the gate.

5. Attempts should be made to measure turbulent fluctuations by hot-wire anemometer to study the unsteady characteristics of the flow fluid.

6. Lips of different roughness should be used to find the effect of roughness on the coefficient of discharge.

EXPERIMENTAL DATA

Run No.	Cyl. Lip Dia. a in.	Flow Type Free-F Subm-S	Gate Openg. a in.	Flow per Unit Width Q_a cfs/ft.	Head at Intake H_1 ft.	Head Downst. H_2 ft.	a/H_1	a/d	R_d $x10^{-5}$	C_{df} or C_{ds}
1	2¼	F	2	0.967	0.788	--	0.21	0.885	1.019	0.92
2	2¼	S	2	0.967	1.065	0.532	0.1550	0.885	1.019	0.992
3	2¼	S	2	0.967	1.28	0.715	0.1300	0.885	1.019	0.966
5	2¼	F	2	1.266	1.61	--	0.1030	0.885	1.311	0.79
6	2¼	S	2	1.266	1.54	0.486	0.1800	0.885	1.311	0.925
7	2¼	S	2	1.266	1.82	0.720	0.0914	0.885	1.311	0.91
9	2¼	F	7/8	0.510	0.69	--	0.1058	0.389	1.2	1.11
10	2¼	S	7/8	0.510	0.762	0.317	0.0962	0.389	1.2	1.3
11	2¼	S	7/8	0.510	0.968	0.512	0.0755	0.389	1.2	1.29
12	2¼	S	7/8	0.510	1.175	0.717	0.0621	0.389	1.2	1.29
13	2¼	F	7/8	0.745	1.65	--	0.0442	0.389	1.755	1.012
14	2¼	S	7/8	0.745	1.54	0.233	0.0474	0.389	1.755	1.11
15	2¼	S	7/8	0.745	1.9	0.696	0.0385	0.389	1.755	1.11

T A B L E 1

EXPERIMENTAL DATA (continued)

Run No.	Cyl. Lip Dia. a in.	Flow Type Free-F Subm-S	Gate Openg. a in.	Flow per Unit Width Q_a cfs/ft.	Head at Intake H_1 ft.	Head Downst. H_2 ft.	a/H_1	a/d	R_d $x10^{-5}$	C_{df} or C_{ds}
17	5	F	2	1.292	0.822	--	0.2016	0.4	2.973	1.2
18	5	S	2	1.292	1.115	0.261	0.1489	0.4	2.973	1.051
19	5	S	2	1.292	1.361	0.54	0.1220	0.4	2.973	1.072
20	5	F	2	1.680	1.640	--	0.101	0.4	3.866	1.038
21	5	S	2	1.680	1.804	0.3316	0.0920	0.4	3.866	1.041
22	5	F	2	1.545	1.310	--	0.1266	0.4	3.555	1.085
26	8	F	2	1.574	1.460	--	0.1136	0.25	5.802	1.04
27	8	S	2	1.574	1.675	0.412	0.099	0.25	5.802	1.053
28	8	S	2	1.574	1.805	0.578	0.0917	0.25	5.802	1.069
30	8	F	2	1.800	1.870	--	0.0889	0.25	6.636	1.034
32	8	S	2	1.800	2.870	0.37	0.0800	0.25	6.636	1.037
33	8	F	7/8	0.686	0.980	--	0.0745	0.1092	5.750	1.230
35	8	S	7/8	0.686	1.395	0.6	0.0524	0.1092	5.750	1.31

T A B L E 1 (continued)

EXPERIMENTAL DATA (continued)

Run No.	Cyl. Lip Dia. a in.	Flow Type Free-F Subm-S	Gate Openg. a in.	Flow per Unit Width Q_a cfs/ft.	Head at Intake H_1 ft.	Head Downst. H_2 ft.	a/H_1	a/d	R_d $\times 10^{-5}$	C_{df} or C_{ds}
36	8	S	7/8	0.686	1.581	0.785	0.0461	0.1092	5.750	1.31
37	8	F	7/8	1	1.840	--	0.0397	0.1092	8.383	1.265
39	8	S	7/8	1	2.140	0.29	0.0340	0.1092	8.383	1.255
40	8	S	7/8	1	2.250	0.503	0.0324	0.1092	8.383	1.290
41*	5	S	7/8	0.734	1.970	0.962	0.0370	0.175	3.85	1.250
42*	5	S	7/8	0.494	1.362	0.876	0.0535	0.175	2.59	1.212
43	5	S	7/8	0.820	2.100	0.798	0.0347	0.175	4.30	1.225
44	5	F	7/8	0.953	2.260	--	0.0323	0.175	5.00	1.100
45	5	F	7/8	0.886	1.655	--	0.0441	0.175	4.65	1.200
46	5	F	7/8	0.714	1.066	--	0.0685	0.175	3.74	1.222
47	5	F	7/8	0.440	0.494	--	0.1479	0.175	2.31	1.160

* Run No. 41: pressure at A 4.9 at B 10.6 (in. of water)
Run No. 42: pressure at A 6.7 at B 9.66 (in. of water) (see Fig. 6)

Note: Run numbers not included are repeat.

T A B L E 1 (continued)

DEFINITION SKETCH

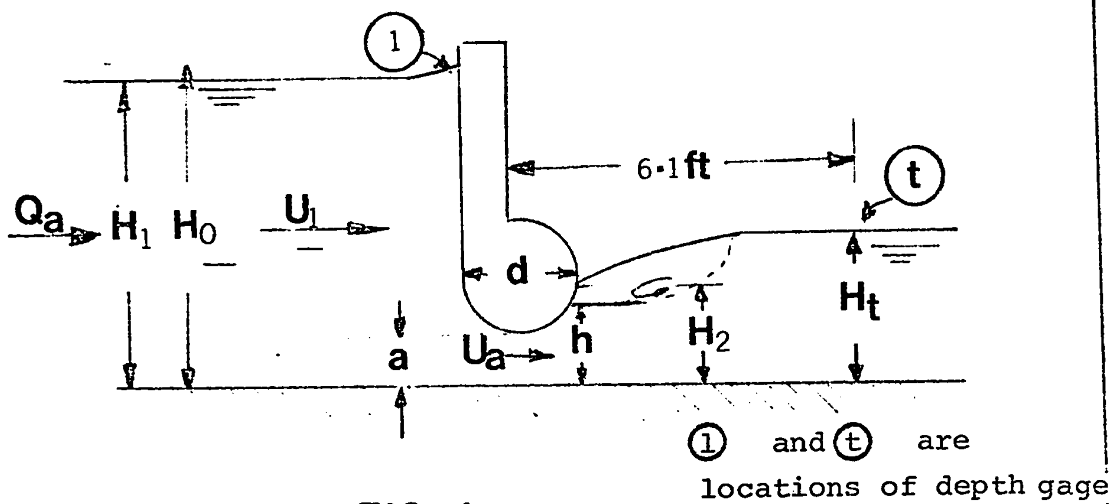


FIG. I

Range of Parameters:

Q_a	Flow (cfs/ft.)	0.44 - 1.8
a	Gate opening (in.)	7/8 - 2
H_1	Intake head (ft.)	0.494 - 2.26
H_t	Tail head (ft.)	0.447 - 1.166
R_d	Reynolds number ($x10^{-5}$)	1.019 - 8.383
d	Lip diameter (in.)	2¼ - 8
	Coefficient of Discharge:	
C_{df}	Free	0.79 - 1.265
C_{ds}	Submerged	0.91 - 1.3

TAINTER GATE

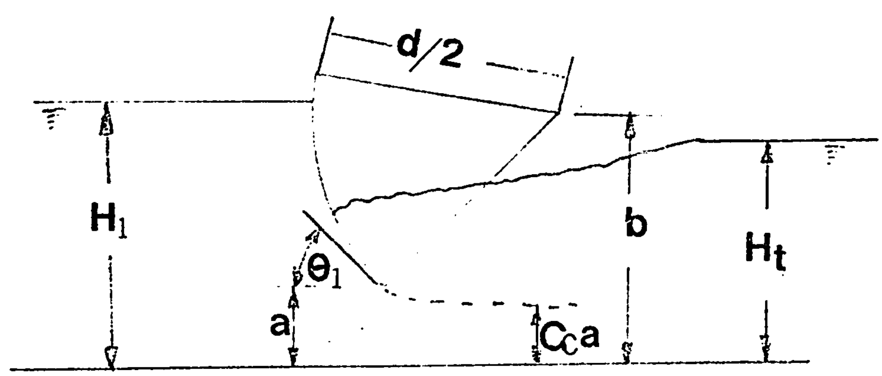


FIG. 2

EXPERIMENTAL SET-UP

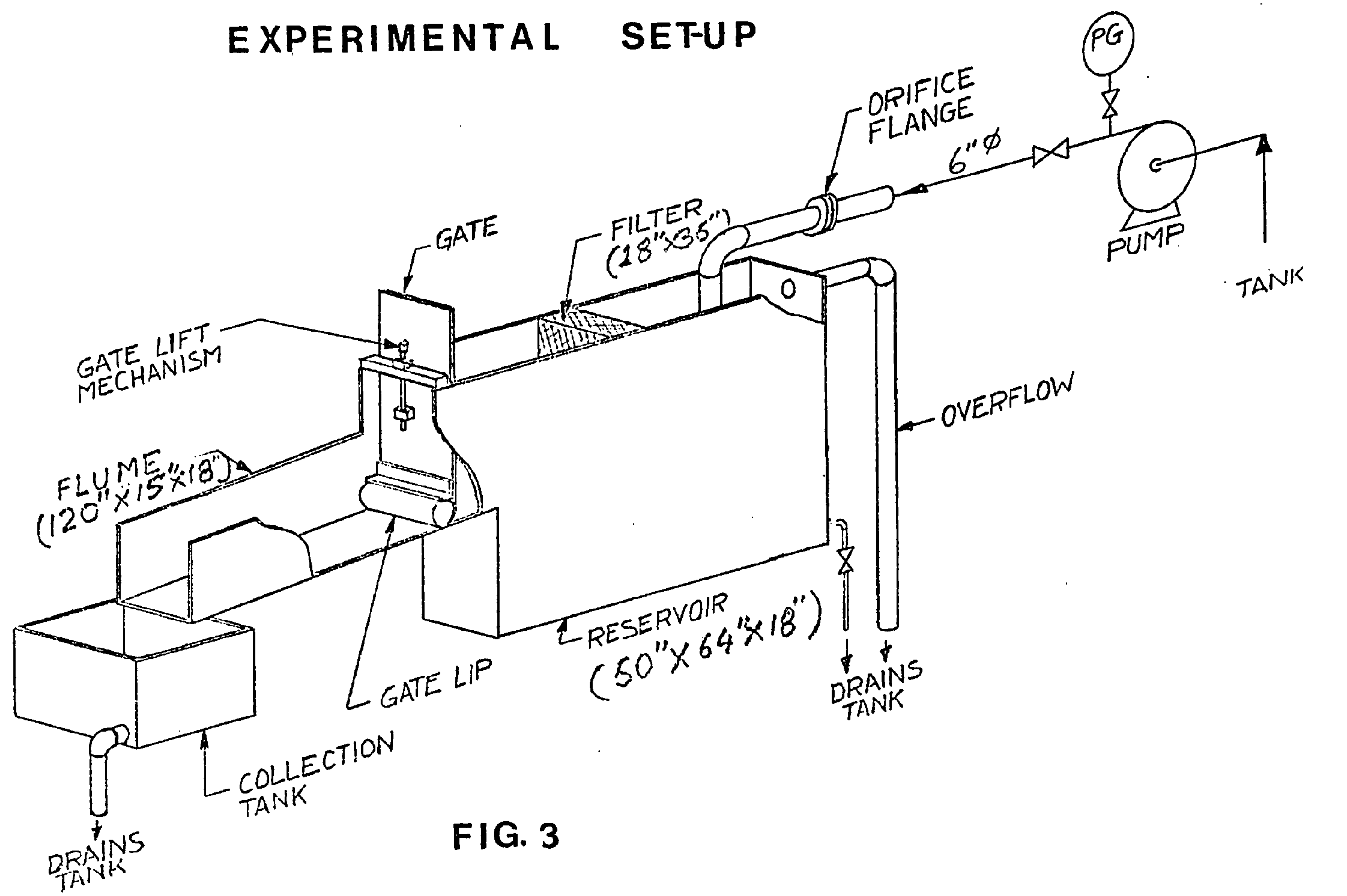


FIG. 3

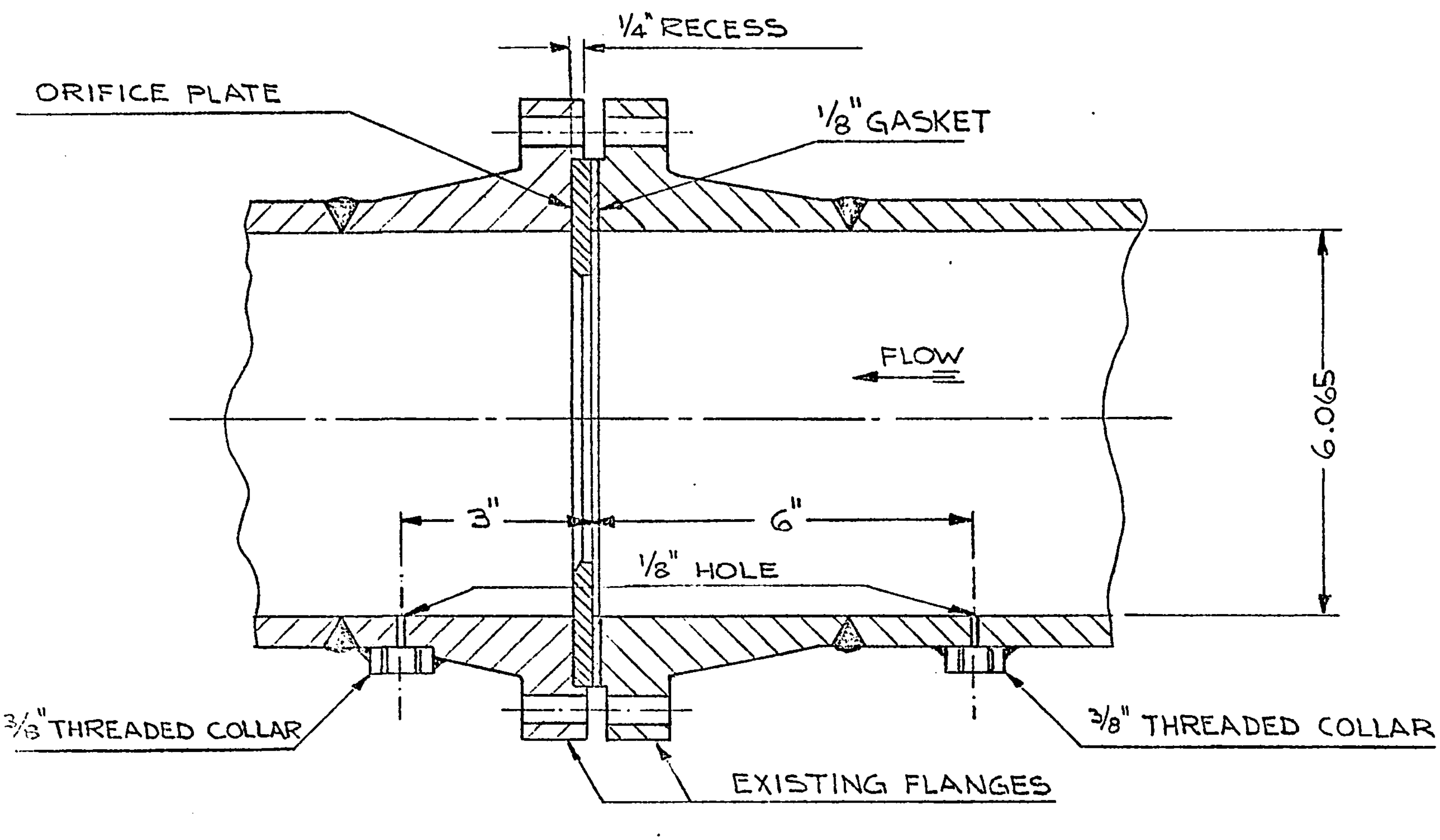


FIG. 4

FLANGE WITH ORIFICE PLATE

SHEET: 1

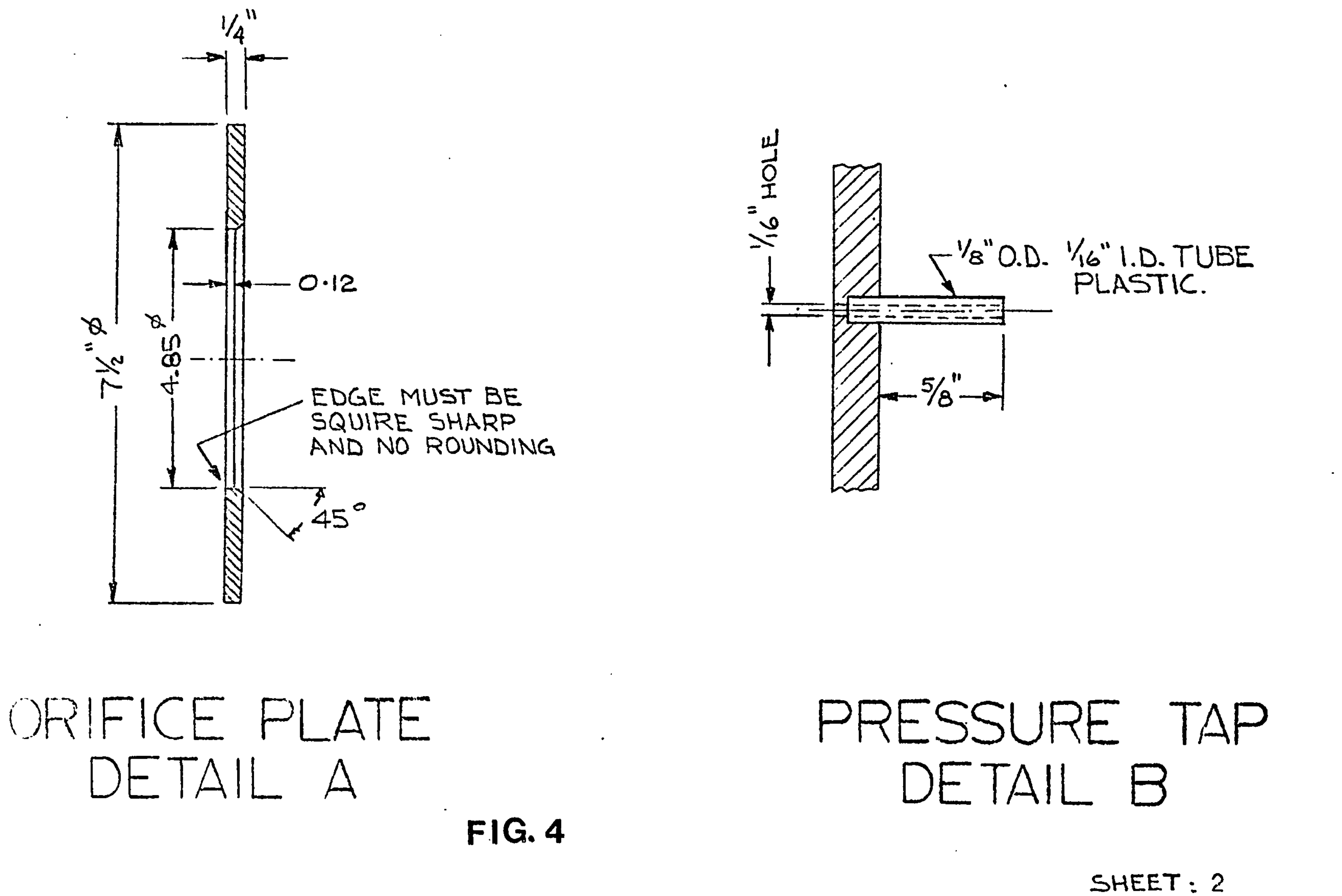

1/4"
0·12
7 1/2" ⌀
4.85 ⌀
EDGE MUST BE SQUIRE SHARP AND NO ROUNDING
45°
ORIFICE PLATE DETAIL A
1/16" HOLE
1/8" O.D. 1/16" I.D. TUBE PLASTIC.
5/8"
PRESSURE TAP DETAIL B
SHEET : 2

FIG. 4

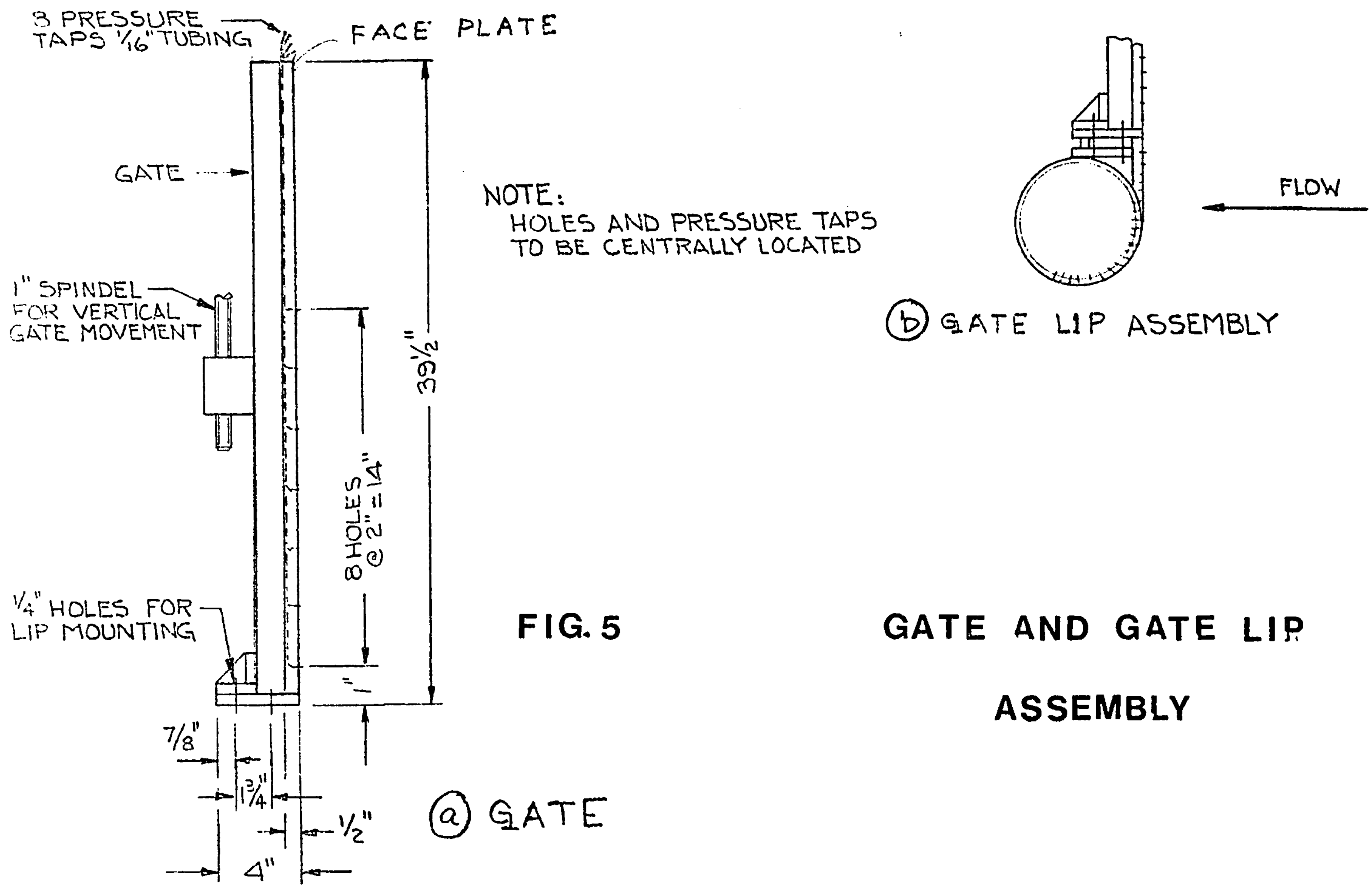
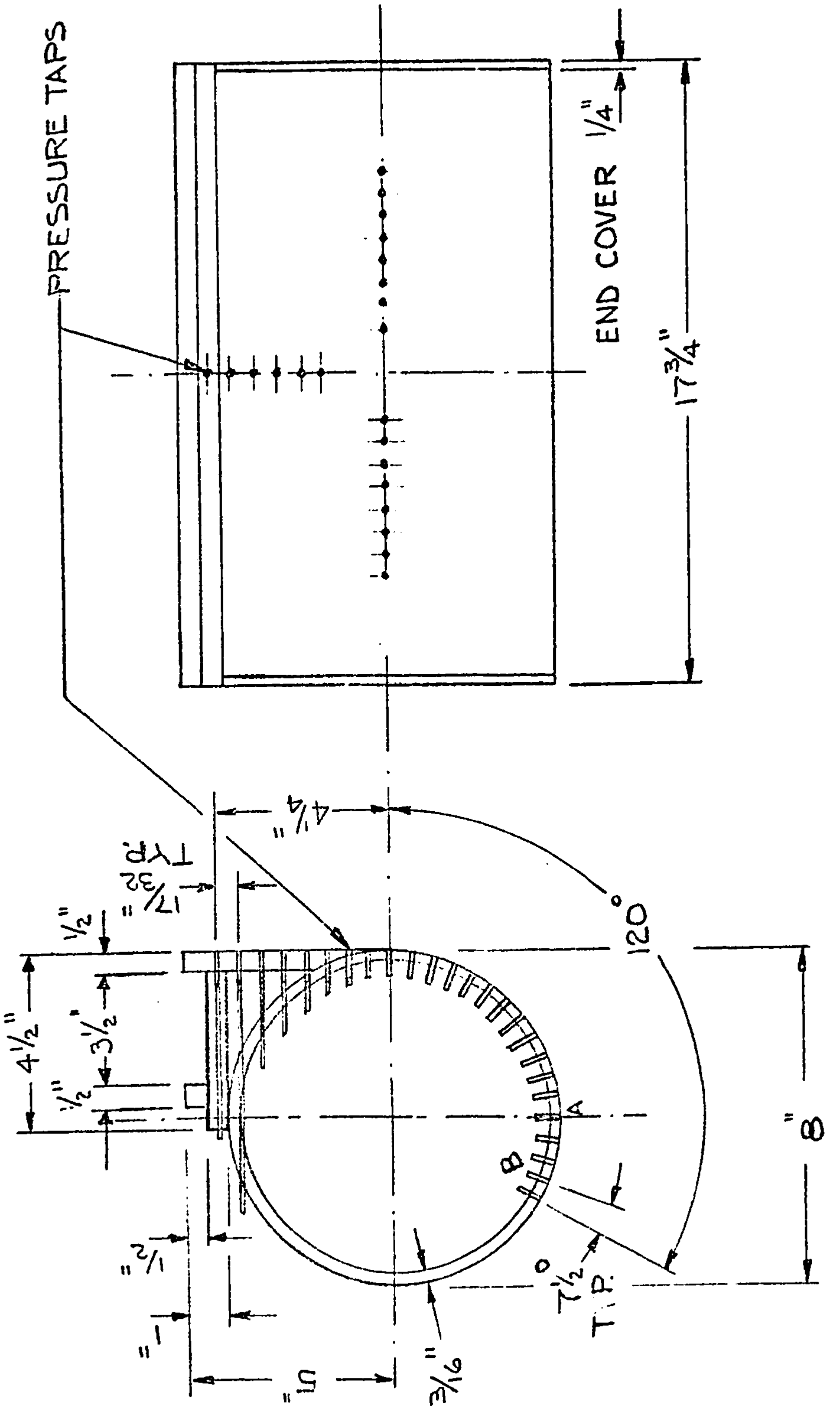


FIG. 5

GATE AND GATE LIP ASSEMBLY



8" GATE LIP

MATERIAL : PLEXIGLASS

FIG. 6

POINT GAGE

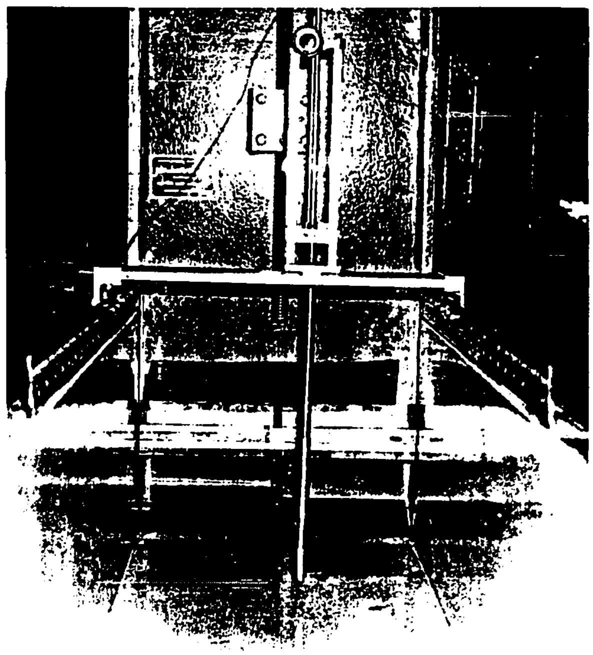


FIG. 7

FLOW UNDERNEATH
CYLINDRICAL LIP

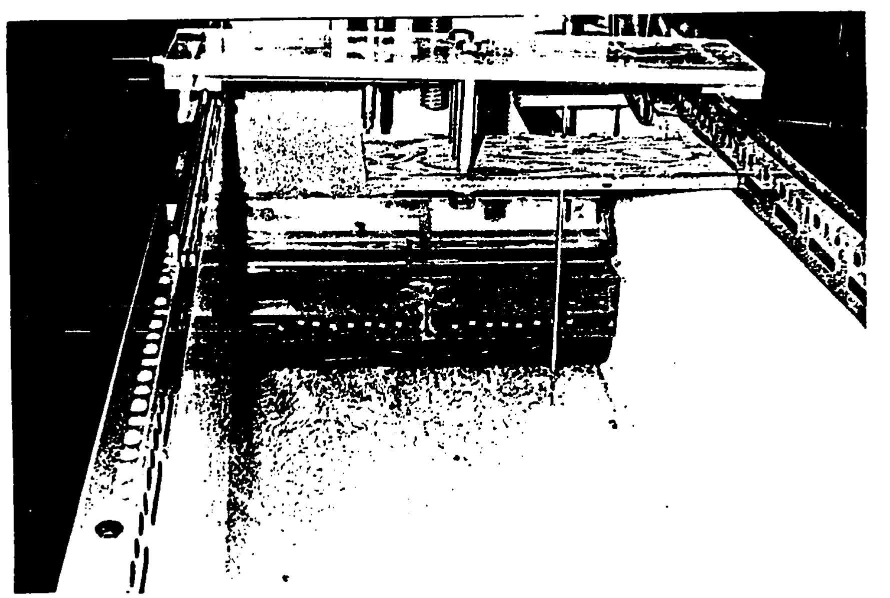


FIG. 8

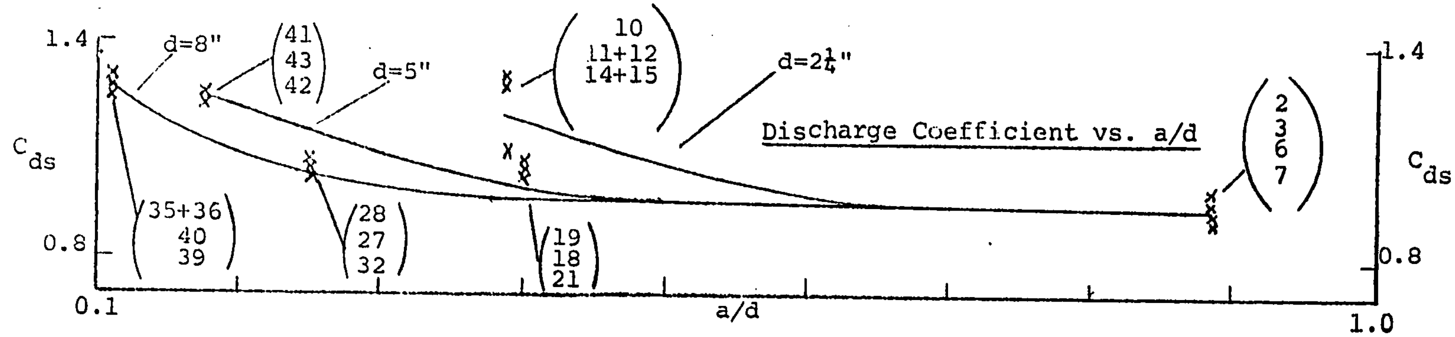
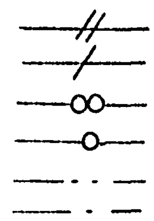
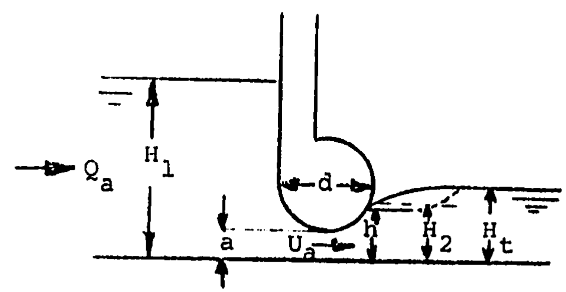


Fig. 9b (Submerged Flow)

Size (in.)	Slot Height (in.)
8	2
8	7/8
5	2
5	7/8
2¼	2
2¼	7/8

Legend





$$C_{ds} = \frac{Q_a}{a\sqrt{2g(H_1-H_2)}}$$

$$C_{df} = \frac{Q_a}{a\sqrt{2g(H_1-a)}}$$

$$R_d = \frac{U_a d}{\eta x 12}$$

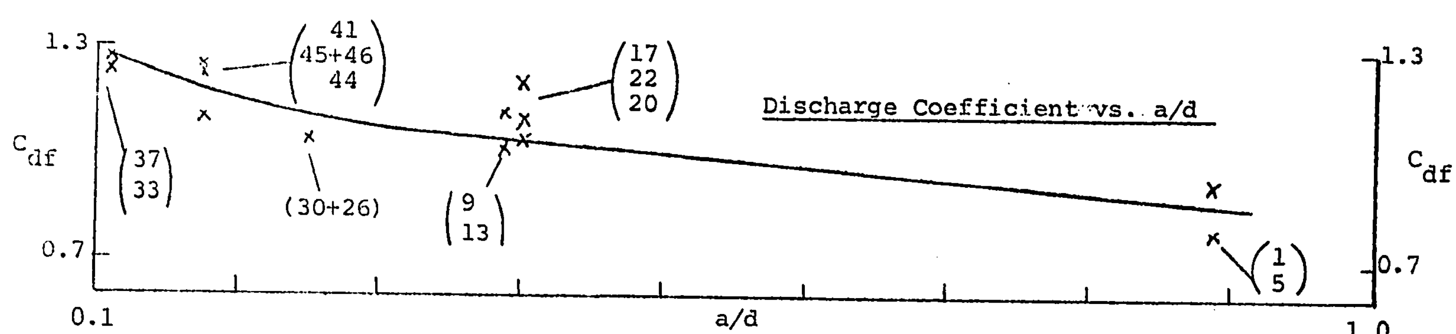


Fig. 9a (Free Flow)

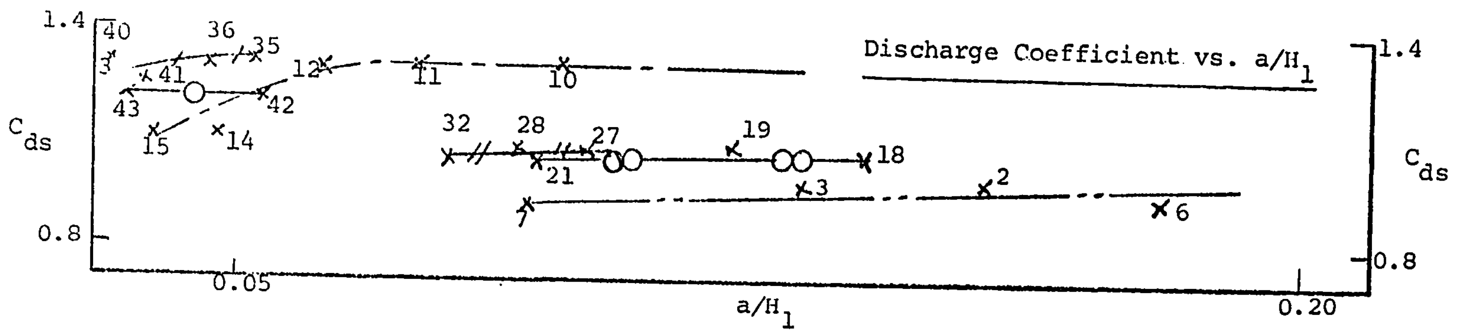
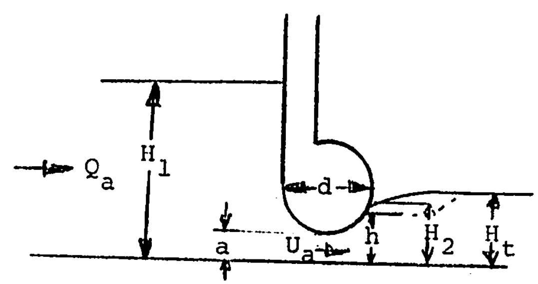


Fig. 10b (Submerged Flow)

Size (in.)	Slot Height (in.)	Legend
8	2	—//—
8	7/8	—/—
5	2	—OO—
5	7/8	—O—
$2\frac{1}{4}$	2	— - —
$2\frac{1}{4}$	7/8	— · —



$$C_{ds} = \frac{Q_a}{a\sqrt{2g(H_1-H_2)}}$$

$$C_{df} = \frac{Q_a}{a\sqrt{2g(H_1-a)}}$$

$$R_d = \frac{U_a\, d}{\eta x 12}$$

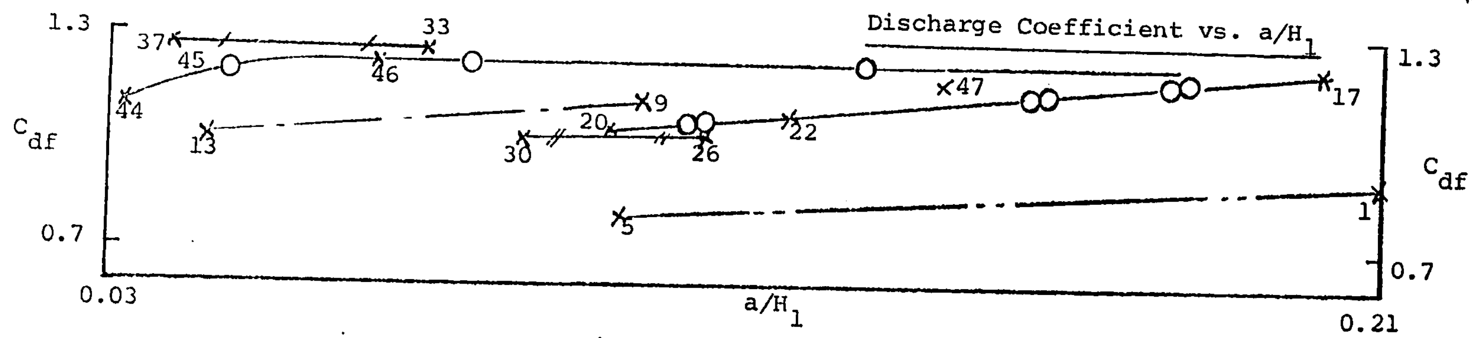


Fig. 10a (Free Flow)

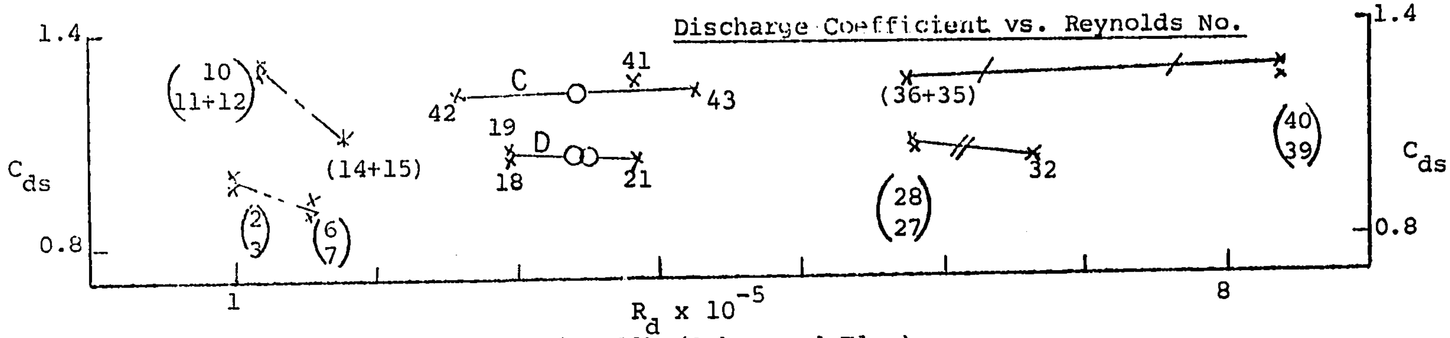
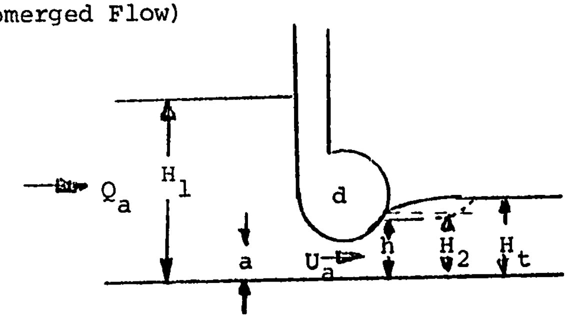


Fig. 11b (Submerged Flow)

Size (in.)	Slot Height (in.)	Legend
8	2	—//—
8	7/8	—/—
5	2	—OO—
5	7/8	—O—
2¼	2	——- - ——
2¼	7/8	—— - ——



$$C_{ds} = \frac{Q_a}{a\sqrt{2g(H_1-H_2)}}$$

$$C_{df} = \frac{Q_a}{a\sqrt{2g(H_1-a)}}$$

$$R_d = \frac{U_a\ d}{\eta x 12}$$

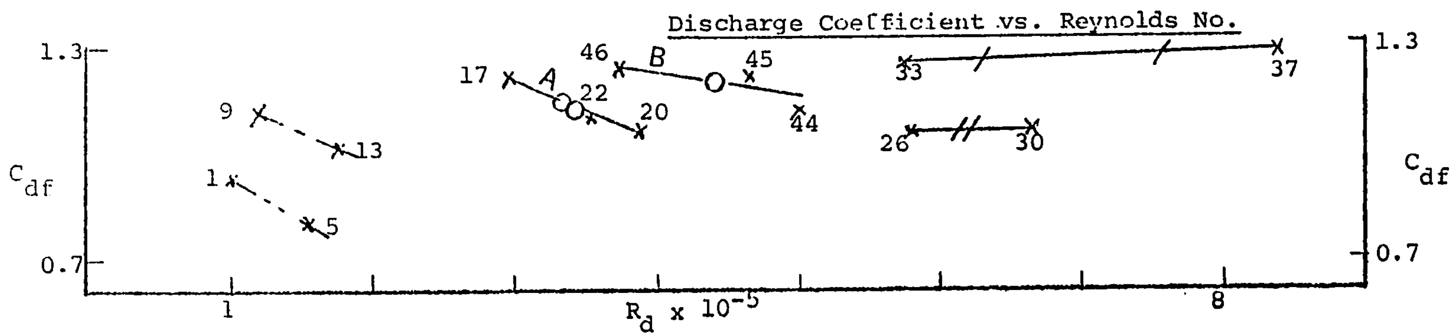
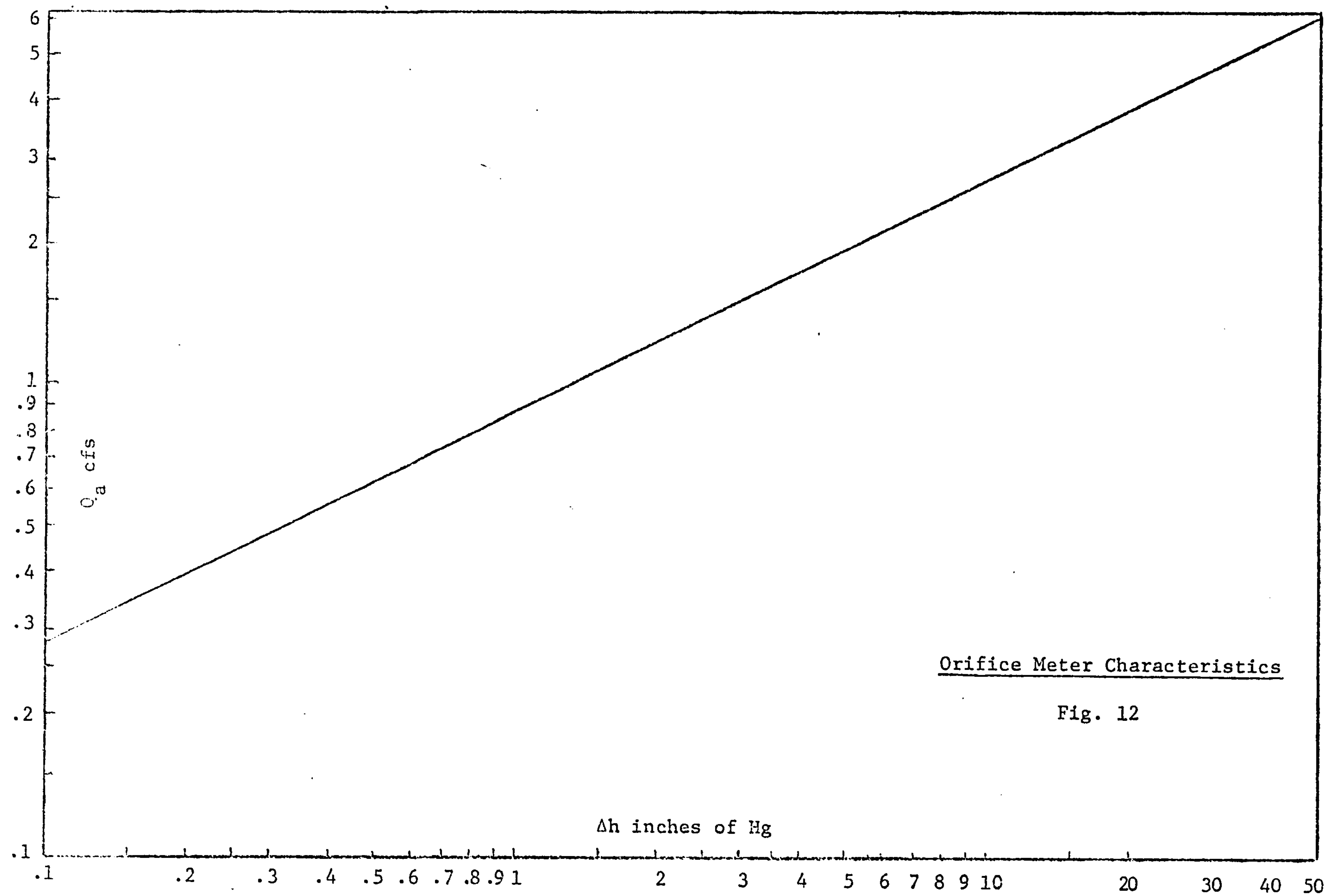


Fig. 11a (Free Flow)



Orifice Meter Characteristics

Fig. 12

APPENDIX I

Computation of Orifice Meter Discharge vs. Head Loss Relationship:

Assume Q_a = 2 cubic feet per second (cfs) in the flow discharged through the orifice. To find the resulting difference of head in mercury manometer:

$$\text{velocity (v)} = \frac{\text{flow (cfs)}}{\text{pipe area (ft.}^2)} = \frac{2}{0.2007} = 9.9652 \text{ ft./sec.}$$

$$R_D \text{ (Reynolds number)} = \frac{v x D}{\eta} [\text{use } \eta = 1.059 \times 10^{-5}] \text{ in ft.}^2/\text{sec.}$$

$$= \frac{9.9652 \times 6.065}{1.059 \times 10^{-5} \times 12} = 4.7560 \times 10^5$$

From Ref. (11) Table 5

at $\beta = 0.8$ $\quad K = 0.8087$ at $R_D = 1 \times 10^5$

$K = 0.7948$ at $R_D = 5 \times 10^5$

By interpolation, assuming linear relationship

$$K = 0.7957 \text{ at } R_D = 4.7560 \times 10^5$$

using relationship

$$\sqrt{2g\Delta h} = \frac{Q_a}{\frac{\pi d_0^2}{4} \times K} \quad \text{[with proper units]}$$

for our case of Q_a = 2 cfs Δh: 5.2396 in. of Hg.

Above results were used to form a graph (log log) shown in Fig. 12 to be used to get values of Q_a for various values of Δh.

APPENDIX II

Computation of C_{df}, C_{ds}, and R_d:

To compute C_{df} in run No. 1:

Diameter of lip = 2¼ in.

Gate opening a = 2 in. = 0.166 ft.

Head difference across orifice meter Δh = 2.05 + 0.65

= 2.7 in. of Hg

From Q_a vs. Δh graph Q_a = 1.45 cfs

Width of channel = 18 in. = 1.5 ft.

Hence flow/width = $\frac{1.45}{1.5}$ = 0.967 cfs ft.

Head of water measured at intake H_1 = 100-76 = 24 cm

= 24 x 0.03281 ft.

= 0.788 ft.

$$Q_{th} = a\sqrt{2g(H_1 - a)}$$

$$= 0.166 \sqrt{2 \times 32.2 \times (0.788 - 0.166)}$$

$$= 1.05$$

Hence $C_{df} = \frac{Q_a}{Q_{th}} = \frac{0.967}{1.05} = 0.92$

To compute C_{ds} in run No. 2:

Diameter of lip = 2¼ in.

Gate opening a = 2 in. = 0.166 ft.

Head difference across orifice meter Δh = 2.05 + 0.65

= 2.7 in. of hg

From Q_a vs. Δh graph (Fig. 12) Q_a = 1.45 cfs

Width of channel = 18 in. = 1.5 ft.

Hence flow/width $= \frac{1.45}{1.5} = 0.967$ cfs/ft.

Head at intake $H_1 = 100-67.5 = 32.5$ cm $= 1.065$ ft.

Head far downstream $H_t = 12.6+10.1 = 22.7$ cm $= 0.746$ ft.

$$F_t^{\,2} = \left[\frac{\text{velocity}}{\sqrt{g \times \text{head}}}\right]^2 = \frac{0.967 \times 0.967}{32.2 \times 0.746^3} = 0.07$$

By application of continuity and momentum equation between point 2 and t, it can be shown (Fig. 12) that

$$\frac{H_2}{H_t} = \sqrt{1 + 2\,F_t^{\,2}\left(1 - \frac{H_t}{a}\right)} \quad \text{where } F_t^{\,2} = \frac{Q_a^{\,2}}{g\,H_t^{\,3}}$$

By using above relationship

$$\frac{H_2}{H_t} = \sqrt{1 + 2 \times 0.07\left(1 - \frac{0.746}{0.166}\right)} = 0.714$$

$$H_2 = 0.714\,H_t = 0.714 \times 0.746 = 0.532 \text{ ft.}$$

$$C_{ds} = \frac{Q_a}{Q_{th}} = \frac{0.967}{0.166\sqrt{2 \times 32.2\,(1.065 - 0.532)}} = 0.992$$

To compute Reynolds No. (R_d) in run No. 1:

$$R_d = \frac{\text{lip diameter} \times \text{average velocity at the slot}}{12 \times \text{kinematic viscosity of fluid}}$$

Lip diameter = 2.25 in.

$$\text{Velocity at the slot} = \frac{\text{flow through orifice meter (cfs)}}{\text{channel width (ft.)} \times \text{gate opening (ft.)}}$$

$$= \frac{1.45}{1.5 \times 0.166}$$

Kinematic viscosity of water $= 1.09 \times 10^{-5}$ ft.^{2}/sec.

$$\text{Hence } R_d = \frac{2.25 \times 1.45}{12 \times 1.09 \times 10^{-5} \times 1.5 \times 0.166} = 1.019 \times 10^5$$

REFERENCES

1. Rayleigh, L., Notes on Hydrodynamics, Phil. Mag. (5) 2, 441, 1876.

2. Dailey and Harleman, Fluid Dynamics, Addision Wesley Co., Mass., 1966.

3. Pajer, G., Über den Strömungsvorgang an einer Unterströmten Scharfkantigen Planschütze, Z. Angew. Math. Mech. 17, 259, 1937.

4. Brooke, B., On the Flow in Channels when Rigid Obstacles are Placed in the Stream, J. Fluid Mechanics I, 227, 1956.

5. Larock, B.E., Gravity Affected Flow from Planar Sluice Gates, Proceedings of ASCE HY4 Paper No. 6674, July 1969.

6. Metzler, D.E., A Model Study of Tainter Gate Operation, Thesis State University of Iowa, Iowa City, 1948.

7. Toch, A., Discharge Characteristics of Tainter Gates, Paper No. 2739, Transactions ASCE Vol. 120, pg. 290, 1955.

8. Babb, A., Moayer, M., and Amorocho, J., Discharge Coefficients of Radial Gates, University of California, Davis, Water Science and Engineering, Paper 1013, 1966.

9. Henderson, F.M., Open Channel Flow, The Macmillan Co., New York, Chapter 6, 1966.

10. Larock, B.E., A Theory for Free Outflow Beneath Radial Gates, Journal of Fluid Mechanics, Vol. 41, Part 4, pp. 841-864, printed in Great Britain, 1970.

11. Fluid Meters--Their Theory and Application, Fifth edition, published by ASME, 1959.

12. Chow, V.T., Open Channel Hydraulics, McGraw Hill Book Co., pg. 60, 1959.