Main Index

Norske Sivilingeniørers Forening

NORTH SEA FLOW METERING WORKSHOP

Stavanger, 5 - 7 November 1985

The Effects of Symmetric Steps and Gaps on Orifice Measurement

1.1

Lecturer: Mr. R. G. Teyssandier
Daniel Industries Inc

THE EFFECTS OF SYMMETRIC STEPS AND GAPS ON ORIFICE MEASUREMENT*

Dr. R. G. Teyssandier
Daniel Industries Inc.

INTRODUCTION

Recesses or protrusions within the near flow field of orifice meters can be found in a limited though significant number of installations. Recesses occur most commonly when the orifice and its associated piping are mounted with ring-type joints used in high pressure service. There are of course, other situations where recesses can occur such as a mismatch between a flange and a pipe, sealing rings on certain types of orifice fittings, etc. As a general rule, a recess is not considered to be a very significant condition. Protrusions, on the other hand, are another matter. Protrusions are always considered to be bad practice and are always thought to cause an error in measurement. Although protrusions are never designed into a system they do occur and are most commonly caused by the use of an undersized gasket.

Current standards supply limited guidance on either recesses or protrusions. Both U.S. (1) and international (2) standards restrict the use of gaskets to those which will be at most flush and generally below the pipe surface. The U.S. standards allows some recess in the vicinity of the plate for both flange and pipe taps (2 1/2 D upstream, 8D downstream). A recess of less than 6.4 mm (1/4 inch) is allowed for all β ratios. If the recess is greater (unspecified) than 6.4 mm (1/4 inch) this recess is allowed only for the following conditions: $\beta \leq 0.3$, D = 50mm; $\beta \leq 0.4$, D = 75mm; and $\beta \leq 0.5$, D = 100mm. The international standard addresses only corner tapped orifices and specifies an equation form which involves the depth and width of the recess. No information is given regarding flange taps.

The user of these standards will also note that these criteria address only the immediate vicinity of the plate. Other criteria (however unjustified) such as the pipe diameter tolerance are presumed to apply at other locations along the meter tube.

The published literature which forms the basis for the above specifications is somewhat limited in scope and number as will be discussed in the next section. The objective of this paper is to study systematically the effects of such recesses or protrusions at various locations for a small line size where effects would be. Four representative locations for the protrusions are considered. These are: in the vicinity of the plate on the upstream and on the downstream side, two diameters upstream of the plate and two diameters downstream of the plate.

*Sections of this paper have appeared as an ASME paper and as a Gas Processors Association Report.

PREVIOUS STUDIES

Beitler and Overbeck [3] investigated the effect of using a recessed flange before and after the plate. Recessed flanges are usually made with the pipe welded to the flange but without extending all the way to the face of the flange. This leaves a recess or a recess whose depth is typically equal to the pipe thickness. On the other hand, standard (non-recessed) flanges are made such that the pipe end is flush with the flange face. Combinations of both types of flanges were used by Beitler and Overbeck to determine whether the inlet or outlet recess was affecting the coefficient. The effect of the recess length was investigated. The flow rate through the test orifices was determined using a standard orifice (i.e. a comparison test). Both flange and pipe taps were used in these tests. The 51 mm (2-inch) line recessed flanges typically had a recess of 6 mm (0.25 inch) depth and 41 mm (1.625 inch) length. The results obtained using flange taps showed that C_d increases as a result of the recess. The deviation of C_d from the unrecessed flange case for $\beta \leq 0.4$ was less than 0.5%. The deviation increased generally with β, attaining a broad maximum of about 1.75% around $\beta = 0.63$ and dropped off to about 0.75% at $\beta = 0.75$. The authors were not surprised by these relatively substantial increases in C_d, since they expected the recess to increase the turbulence level ahead of the orifice and so decrease the contraction after the plate. However, the authors could not explain adequately why the deviation decreased for $\beta > 0.63$. The results for the pipe taps were generally similar but the deviation magnitude was slightly less at most values of β. The authors did similar experiments on 100 mm (4-inch) and 200 mm (8-inch) lines. For the 100 mm line, C_d increased monotonically with β starting at $\beta = 0.3$. The deviation amounted to 0.5% at $\beta = 0.5$, and rose to a maximum of 2.4% at $\beta = 0.75$. For this case the depth of the recess was kept at 6 mm and its length was 38 mm (1.5 inch) before the plate and 34 mm (1.34 inch) after the plate. The effect of using pipe taps instead of flange taps was similar to the 51 mm (2-inch) line case. For the 200 mm (8-inch) line, the trends were similar to those obtained in the 100 mm (4-inch) line. The deviatiation started at β = 05 and was less than 0.5% at $\beta = 0.6$ increasing to 2.5% at β = 08. The authors varied the length of the recess in the tests in the 100 mm (4-inch) line. They found that a recess of length equal to 6.4 mm (1/4 incn) or less had no effect on D_d. Beyond 6.4 mm (1/4 inch) the deviation increased with the recess length up to a value of 2% at 34 mm (1.34 inch). Experiments with a recess on one side of the plate showed that the downstream recess did not have any effect on C_d. Although the trends of the above tests are useful the fact that these were comparison tests (ie. to another reference orifice) tempers the conclusions drawn.

The second report found in the literature was by H. Bean [4]. He reported the results of some tests done by manufacturers of orifice meter equipment about 17 years earlier (in 1929). In most of these tests a reference orifice was used to determine C_d. Three β ratios: 0.31, 0.5 and 0.69 were investigated in a 100 mm (4-inch) line using flange, radius and pipe taps. The recess depth was 2.4 mm (0.094 inch) and its length was 39.6 mm (1.56 inch). For $\beta = 0.31$, no effect on C_d was observed. For $\beta = 0.5$, the deviations were: 0.6% for flange taps and 0.25% for both radius and pipe taps. For $\beta = 0.69$, the deviations were: 1.0% for flange taps, 0.5% for radius taps and 1.4% for pipe taps. Note again the use of a reference orifice.

McNulty and Spencer [5] investigated the effects of orifice plate carrier diameter (relative to the pipe diameter) in both rough and smooth pipes. A weigh tank system was used to determine the flow rate. The tests were done initially using a 100 mm (4-inch) line. Four orifice plates with β ratios of 0.45, 0.63, 0.74 and 0.84 were used in the study. The differential pressure was measured via corner taps of 4.8 mm (3/16 inch) diameter. The increase in the size of the carrier diameter relative to pipe diameter ranged from -2% to 14%, this corresponds to a protrusion or recess range of 1% and -7% of D (protrusions = 1 mm to -7.1 mm). Notice that a negative value indicates a recess. The results indicated that for $\beta < 0.63$, the pipe conditions and protrusions or recesses had no significant effect. For $\beta = 0.74$, C_d increased by 0.5% for recess of 5.5% of D (protrusion = -5.6 mm) and increased by 0.4% for recess of 2% of D (protrusion = -2 mm). For $\beta = 0.84$, the corresponding increase in C_d was about 1.5% for both recesses. For a protrusion of about 1.25% of D (protrusion = 1.3 mm), the increase in C_d was negligible for $\beta = 0.74$ and went up to 1.8% for $\beta = 0.84$. The authors gave curve fits for the deviation in C_d versus percentage change in carrier diameter. Due to the limited number of points (about 4), these fits should be viewed with caution. In a previous study McNulty and Spencer [6] presented some limited data for 51 mm (2 inch) and 150 mm (6 inch) pipes. This data obtained in the 152 mm line indicated that for an upstream ledge (with an effective protrusion of 4.67% of D), C_d increased by 0.5% for $\beta = 0.5$, 1.15% for $\beta = 0.6$, 2% for $\beta = 0.71$ and 6% for $\beta = 0.81$, while C_d did not change for the case with upstream recess of 2.5% D. The data obtained in the 51 mm (2-inch) line gave mixed results. The deviation of C_d with a protrusion of 1.85% D (0.94 mm) from C_d with the negligible recess of 0.375% D (0.2 mm) was -.16% for $\beta = 0.44$, -0.32% for $\beta = 0.39$, -1.125 for $\beta = 0.63$ and +3.7% for $\beta = 0.84$.

EXPERIMENTAL SET-UP AND TEST PROCEDURE

Three orifice plates with $\beta = 0.3$, 0.5 and 0.7 were tested in a 51 mm (2-inch) line using water as the working fluid. Figure 1 gives a diagrammatic sketch of the experimental set-up. Fully developed turbulent flow was insured by having a straight pipe run of 105 diameters upstream of the test section. The actual flow rate was determined by using a dynamic weigh tank and a timer (0.001 second resolution) triggered by the dynamic weight balance pointer. In the $\beta = 0.5$ and 0.7 tests reported here, 3000 pounds of water were collected while in the $\beta = 0.3$ tests, 2000 pounds were used. The differential pressure across the orifice plate was measured via a pair of flange taps 9.5 mm (3/8 inch) in diameter. Three D-P cells were used to insure redundancy. Each of the D-P cells was calibrated versus a deadweight tester and also differential mercury manometer. Calibrations were conducted once every two weeks or whenever a discrepancy appeared between readings of the three D-P cells.

In a typical test, the D-P cell output is fed into the computer, digitized and averaged. A total of 3000 samples were averaged for the $\beta = 0.5$ and $\beta = 0.7$ tests and 7000 samples for the $\beta = 0.3$ tests. These averages together with appropriate calibration curve constants, were used to obtain the mean pressure measured by each D-P cell. Agreement was generally within 0.05% or between for the D-P cells at the critical low end of the flow range. Whenever discrepancies were higher than that, the D-P cells were checked for air bubbles and/or recalibrated. The repeatability of the results for a number of representative configurations was checked and the data found to lie within a band of width equal to 0.15% of C_d. The test program lasted for about three months.

The test fixture is shown in Figure 2. Provisions were made for protrusions/recesses by using a number of rings. The width of each ring was 12.7 mm (0.5 inch). All the rings had the same outside diameter (to fit in provided locations in the fixture) while the inside diameter varied between different rings to provide different protrusions/recesses. The protrusions/recesses used in the study were 6.35, 5.3, 4.3, 3.2, 1.6, 0.15, 0, -0.15, -3.2 and -6.35 mm (0.25, 0.21, 0.17, 0.125, 0.0625, 0.006, 0, -0.006, -0.125 and -0.25 inches) respectively. A protrusion or recess of height equal to 0.15 mm represents the limit set by the ISO standard based on pipe diameter tolerance (a negative value indicates a recess). The test fixture was designed with a provision to change protrusions (rings) at the four locations. These locations were: 1) adjacent to the upstream face; 2) adjacent to the downstream face; 3) 2D upstream of the plate; and 4) 2D downstream of the plate. The fourth location was obtained by inverting the whole fixture. In this investigation, the height/depth of the proptrusion/recess was changed at one axial location while keeping the remaining locations in the flush configuration (zero protrusion). For each test the discharge coefficient was determined at 9-10 flow rates (Reynolds numbers) for $\beta = 0.7$ and 0.5 and at about 5 - 7 flow rates for $\beta = 0.3$.

RESULTS AND DISCUSSIONS

The results of this experimental program are displayed for each test in the form of a deviation of the measured discharge coefficient C_d from the corresponding base line coefficient C_{do}. This base line coefficient for each β ratio was obtained with no protrusions or recesses. These deviations are plotted versus $10^6/R_D$ where R_D is the pipe Reynolds number. The results will be presented in order from upstream to downstream results.

FAR UPSTREAM LOCATION

This region is located at 2 diameters upstream of the orifice plate. Figure 3a summarizes the test results for both the protrusions and recesses for $\beta = 0.3$. As shown by this figure all recesses at this location and β ratio had no noticable effect (defined by system repeatability) on the discharge coefficient. Protrusions into the flow stream, however, did show an effect. When the step was 3 mm into the flow stream an increase in discharge coefficient of about 0.2% was noted. The 6 mm step caused a 1% increase. As expected when the β ratio was increased to 0.5 the effect of the protrusion into the stream was magnified. (Figure 3b) For the same step (3 mm) as above the coefficient increased to about 1% and the maximum deviation for the 6 mm step was roughly four times (3.9% vs 1.0%) greater at this value of β. For the recesses, however, the changes were virtually not noticable with the maximum "apparent" change on the order of 0.15% at a 6 mm recess.

At the highest β tested (β = 0.7) the maximum step into the pipe (Figure 3c) caused about a 14% bias. The 3 mm step cited above resulted in about a 2.5% offset. A recess of 6 mm caused a positive bias of about 0.2%. This value being just outside of the overall repeatability figure might be subject to interpretation as to whether this was a true bias.

In all of the above cases the use of steps or gaps which fell within the 0.3% tolerance on diameter of the ISO standard resulted in deviations well within the repeatability of the experiments.

ZERO D UPSTREAM

In this configuration the protrusion or recess abuts the orifice plate itself forming a 13 mm (1/2 inch) perturbation in front of the plate. Figure 4a shows the deviations plotted for β = 0.3. The graph indicates that deviations are within a band of width = 0.10% C_{d_o} for protrusions = 1.6 mm (0.0625 inch) or less (well within laboratory repeatability). For protrusions equal to 3, 4 and 6 mm (0.125, 0.17 and 0.25 inch) the deviations are approximately 0.2, 0.6 and 1.6% above baseline. For recesses there was (as above) virtually no effect. For β = 0.5, the effects of protrusions became more pronounced while the recesses still had negligible effect as shown in Figure 4b. For a protrusion of 6 mm (0.25 in) deviations as high as 11.5% of C_{d_o} were measured. The deviation droped to 8% for a protrusion = 5 mm (0.21 inches), 5% for protrusion of 4 mm (0.17 inch) and continued with this trend down to 0.66% for protrusion of 1.6 mm (0.0625 inch). The deviation for a protrusion of 0.15 mm (0.006 inch) which is equal to the allowed pipe tolerance was negligible. Figure 4c shows similar results for β = 0.7. The protrusion effects even much more pronounced than those for β = 0.5. Deviations varied from 47.7% of C_{d_o} for a protrusion of 6 mm to 0.1% (or negligable) for protrusion of 0.15 mm. Recesses had some effect for this β; 0.9% for a value of -3 mm (-0.125 inch) and 0.77% for a value of -6 mm (-0.25 inch). It should be noted that neither the protrusion nor the recess effected the slope of the calibration curves.

The large increase in C_d at large upstream protrusions for large βs may be attributed to a nozzle type flow. For the extreme case of β = 0.7 and protrusion of 6 mm (0.25 inch), the flow stream in the pipe converges before arriving at the plate because of the relatively large annular protrusion. The length of the protrusion would also be expected to play an important part since it determines if the flow has a chance to reattach. If it does, it would affect the velocity profile in the vicinity of the plate. One can also consider this configuration to be a plate with a β = 0.9+ based on the diameter of the upstream ring (which may be considered as a very, very short upstream pipe). This definitely reduces the contraction of the jet and therefore it increases C_d. On the other hand, the reason for the increase of C_d due to large upstream recesses for the β = 0.7 case is not clear; however this behavior agrees with what was reported by Beitler and Overbeck [3] and by Bean [4] and with some of the results of McNulty and Spencer [6].

ZERO D DOWNSTREAM

The next location studied was that immediately downstream of the orifice plate. In contrast to the previous cases where it was possible to note some effect for mid-range and smaller β ratios no effects were noted for either protrusions or recesses downstream of the orifice plate. That being the case, detailed deviation results plotted vs. $10^6/R_D$ are given for β = 0.7 only (Figure 5). The deviation is about 5.25% for a protrusion of 6 mm (0.25 inch), 0.8% for protrusion = 4 mm (0.17 in) and 0.4% for protrusion = 3 mm (0.125 in). For protrusions = 1.6 mm (0.0625 inch) and less as well as for recesses up to 3 mm (0.125 inch), the effect is negligible. A deviation of -0.25% has been found for a recess of 6.35 mm (0.25 in).

In this line size (50 mm) it is not surprising that this protrusion/β combination showed a significant effect. As noted above there is a "false β" on the downstream side of roughly β = 0.9+ which would surely be responsible for downstream streamline shape. Beitler and Overbeck (3) reported negligible effects for downstream recesses; however, they had no data on the effect of downstream protrusions.

TWO DIAMETER DOWNSTREAM LOCATION

By inverting the fixture, it was possible to test the effect of having a protrusion or recess at 2 pipe diameters downstream of the plate. Since the effects noted at the immediate downstream location were minimal it was decided to only test the extreme protrusion (6.35 mm) and the extreme recess (6.35 mm) for the three βs. The results showed negligible effect for either a protrusion or a recess at this location. Figure 6 shows the detailed deviation results for one β only (β = 0.7) for protrusions of +6 mm and -6mm. Results for the other two βs show less effect and therefore are not shown.

SUMMARY AND CONCLUSIONS

From the above experimental program the following conclusions may be drawn.

1. At three of the locations studied, the presence of a protrusion caused the coefficient of discharge to increase. This deviation increased with both the protrusion height and the β ratios investigated. The only exception to this was the far downstream case (2D) where there was no effect.

2. Protrusions at 2D upstream of the plate can have considerable effect on Cd. The error variation trends are similar to the case of a protrusion directly upstream of the plate (see below) however, the magnitudes are smaller. For example, it can be inferred from the present data (by interpolation) that a protrusion of 6.3% D or smaller results in an error within the repeatability of the data for β=0.3%; while for β = 0.5, the protrusion should be kept at or below 1.7% D; and for β=0.7, the protrusion should not exceed 0.9% D to achieve this accuracy.

3. As expected, the protrusions directly upstream of the plate caused the most substantial deviations in Cd depending on the size of the protrusion and the β ratio of the orifice plate. For β = 0.3, errors were negligible for protrusions less then 5.8% D but were as high as 1.6% for protrusion = 12.5% D. For β

= 0.5%, the effects were substantially higher beyond a protrusion of 1.0% D reaching a value of 11.5% at protrusion = 12.5%. For β = 0.7, the effects were even much higher, and protrusions should be avoided or kept below 0.38% D to keep the error within the uncertainty of the data. For β = 0.3 and 0.5 the protrusions should be kept below 5.8% D and 1% D, respectively, to have similar accuracy.

4. Protrusions at a location directly downstream of the plate had much less effect than the previous two upstream cases. In fact, for β = 0.3 and 0.5, the effect was negligible even at the highest protrusions. For β = 0.7, the error was less then 0.5% for a protrusion 6.25% D and less, but values as high as 5% were obtained with a protrusion of 12.5% D. Based on the data presented in the paper it may be inferred that the protrusion should be kept below 3% D to keep the deviation within the repeatability of the data for this β.

5. A 2D downstream the only test run indicated that the 12.5% step did not have a significant effect.

6. As expected recesses had a substantially lower effect than protrusions. At 2D upstream of the plate for β = 0.3 and 0.5, the deviations was negligible while deviations of 0.32 and 0.22% were obtained for β = 0.7 with recesses = 6.25% D and 12.5% D, respectively. Since there is no logical explanation for the higher deviation for the smaller recess that data point is very suspect.

7. Similar to the results at 2D upstream, the data for both β = 0.3 and β = 0.5 showed no effect on coefficient for recesses up to 12.5% of diameter. At β = 0.7, however, deviation of about 0.8 to 0.9% were measured for recesses larger than 6.25% of diameter.

8. On the downstream of the plate, recesses up to 6.25% seemed to have no effect on Cd for all plates, while a recess of 12.5% D gave a reduction in Cd (negative deviation) of 0.25% for β = 0.7.

9. Recesses two diameters downstream of the plate showed no effect for all βs.

10. The ISO-5167 pipe diameter specification of ±0.3% over the 2D upstream length shows no effect for a 13 mm wide perturbation placed at the extremes of the specified length.

REFERENCES

1. American National Standard Institute "Orifice Metering of Natural Gas, and Other Related Hydrocarbon Fluids," Chapter 14 Manual of Petroleum Measurement Standards, American Petroleum Institute, ANSI/API-2530, 2nd edit, 1985.

2. International Organization for Standardization, Measurement of Fluid Flow by Means of Orifice Plates, Nozzles and Venturi Tubes Inserted in Circular Cross-section Conduits Running Full," ISO Standard 5167, ISO, Geneva, 1980.

3. Beitler, S. R. and Overbeck, J.E., "Determination of the Effects of Certain Installation Conditions on the Coefficient of Sharp Edged Orifices," ASME Transactions, Vol. 59, No. 2, Feb. 1937, p. 115.

4. Bean, H., "Indications of an Orifice Meter," American Gas Association Monthly, Issue of July-August, 1947.

5. McNulty, P. J. and Spencer, E. A., "Tests on Orifice Plates in a 4-inch Diameter Pipe; Effect of Pipe Roughness and Carrier Diameter," MERL Fluids Note No. 74, East Kilbride, Glasgow, Mechanical Engineering Research Laboratory, Jan. 1959.

6. McNulty, P. J. and Spencer, E. A., "Initial Tests on Two and Six-inch Orifice plates," MERL Fluids Note No. 61, East Kilbride, Glasgow, Mechanical Engineering Research Laboratory, 1958.

TEST RESULTS SUMMARY

$(C_D - C_{Do})/C_{Do} \times 100\%$

2D Upstream

Step Size % of Diameter	β =	0.30	0.5	0.7
12.5%		0.995	3.65	14.26
10.5		-	2.58	8.9
8.5		0.471	1.64	4.54
6.25		0.196	0.94	2.32
3.125		-	0.372	0.73
0.3		-0.055	0.035	0.034
-0.3		0.006	0	0.054
-6.25		-0.056	0.157	0.32
-12.5		-0.077	0.164	0.22

0 D Upstream

12.5		1.63	11.5	47.7
10.5			8.0	45.6
8.5		0.63	5.04	27.8
6.25		0.21	2.8	13.0
3.125			0.66	3.66
0.3		0.93	0.035	0.1
-0.3		-0.001	-0.002	0.066
-6.25		0.038	0.17	0.9
-12.5		0.039	0.033	0.77

0 D Downstream

12.5		0.04	0.165	5.25
8.5				0.8
6.25		-0.07	-0.047	0.4
3.125				-0.006
0.3		0.003	-0.005	0.016
-0.3		-0.054		0.044
-6.25		-0.07	-0.017	-0.08
-12.5		-0.19	-0.101	-0.25

SYMBOLS FOR FIGURES 3 AND 4

Symbol	HEIGHT (mm)	% of Diameter
✡	6.35	12.5
⍋	5.33	10.5
⧖	4.32	8.5
✱	3.18	6.25
⌧	1.59	3.125
◇	0.15	0.3
△	-0.15	-0.3
+	-3.18	-6.25
×	-6.35	-12.5

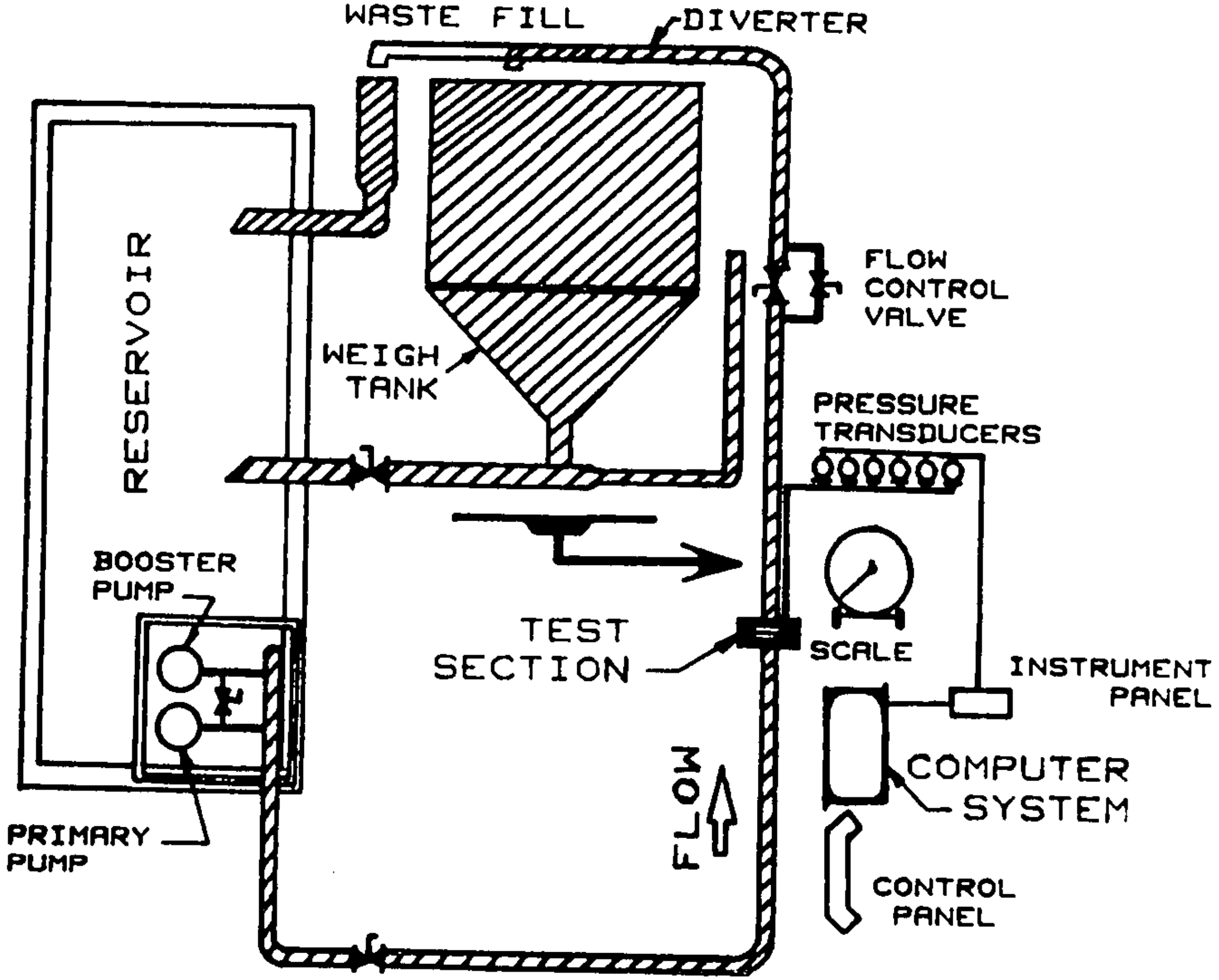

FIGURE 1 : SCHEMATIC OF EXPERIMENTAL FACILITY.

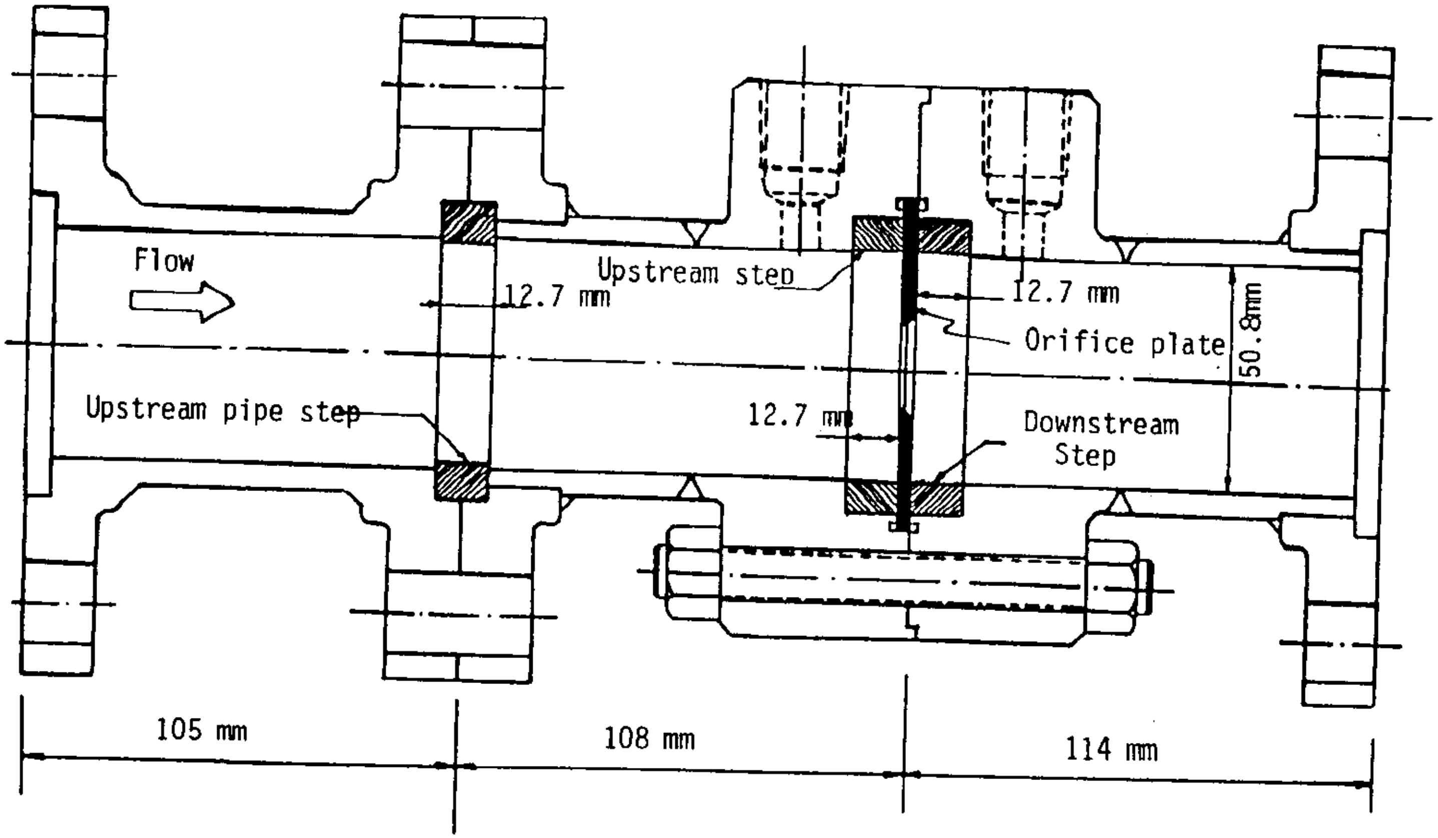

Figure 2: Test Fixture

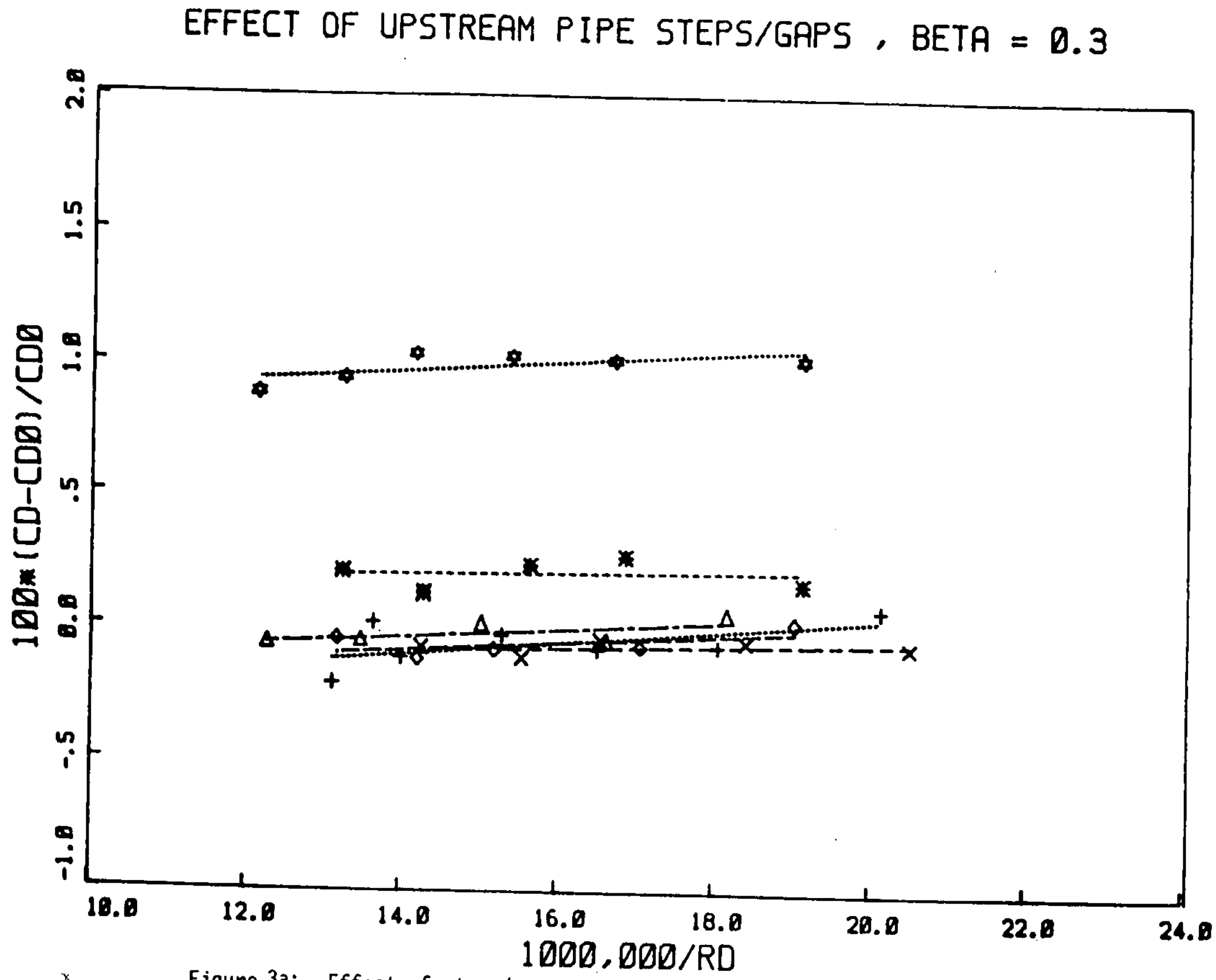

Figure 3a: Effect of steps/recesses at 2D upstream of the orifice plate for β = 0.3

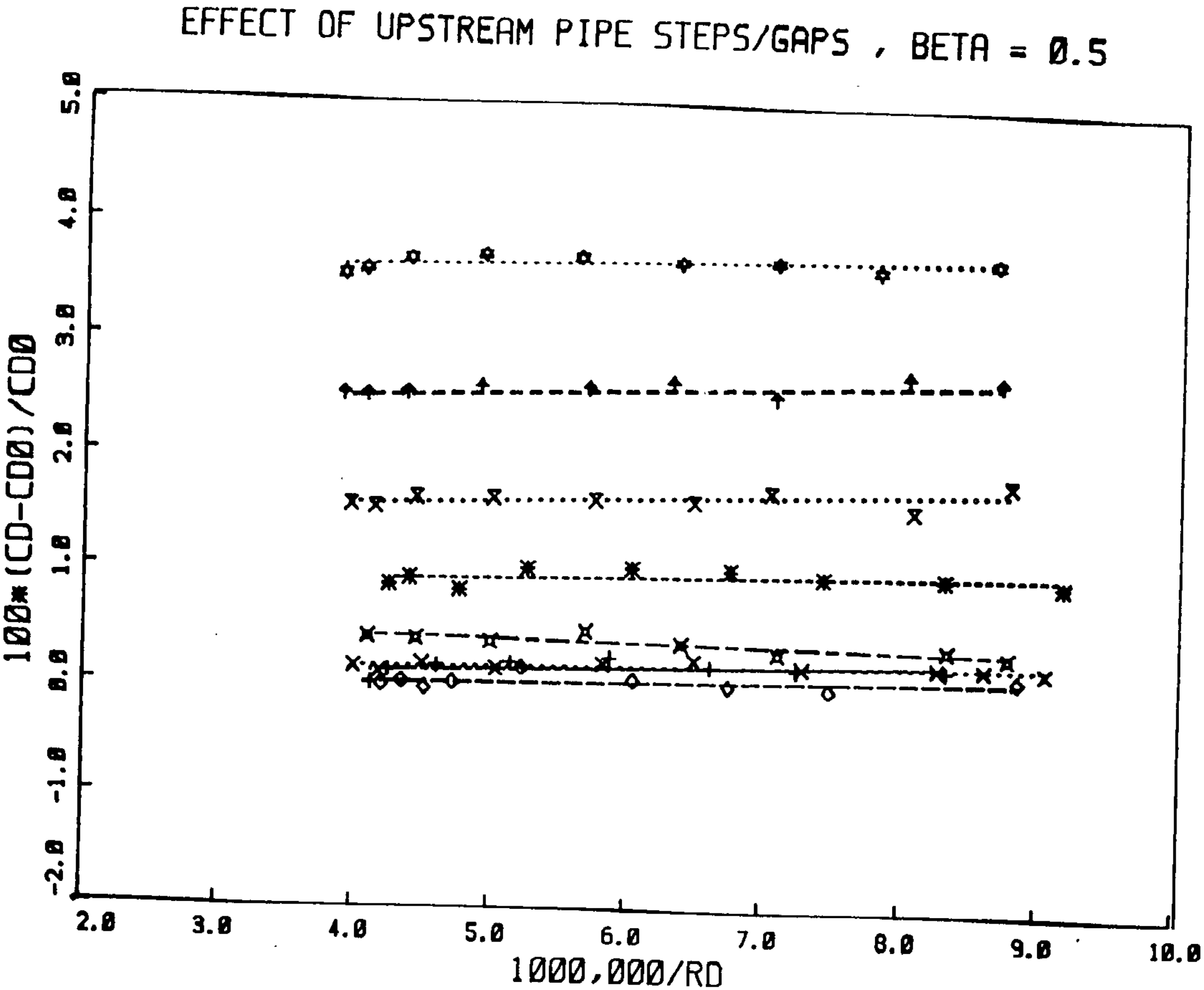

Figure 3b: Effect of steps/recesses at 2D upstream of the orifice plate for $\beta = 0.5$

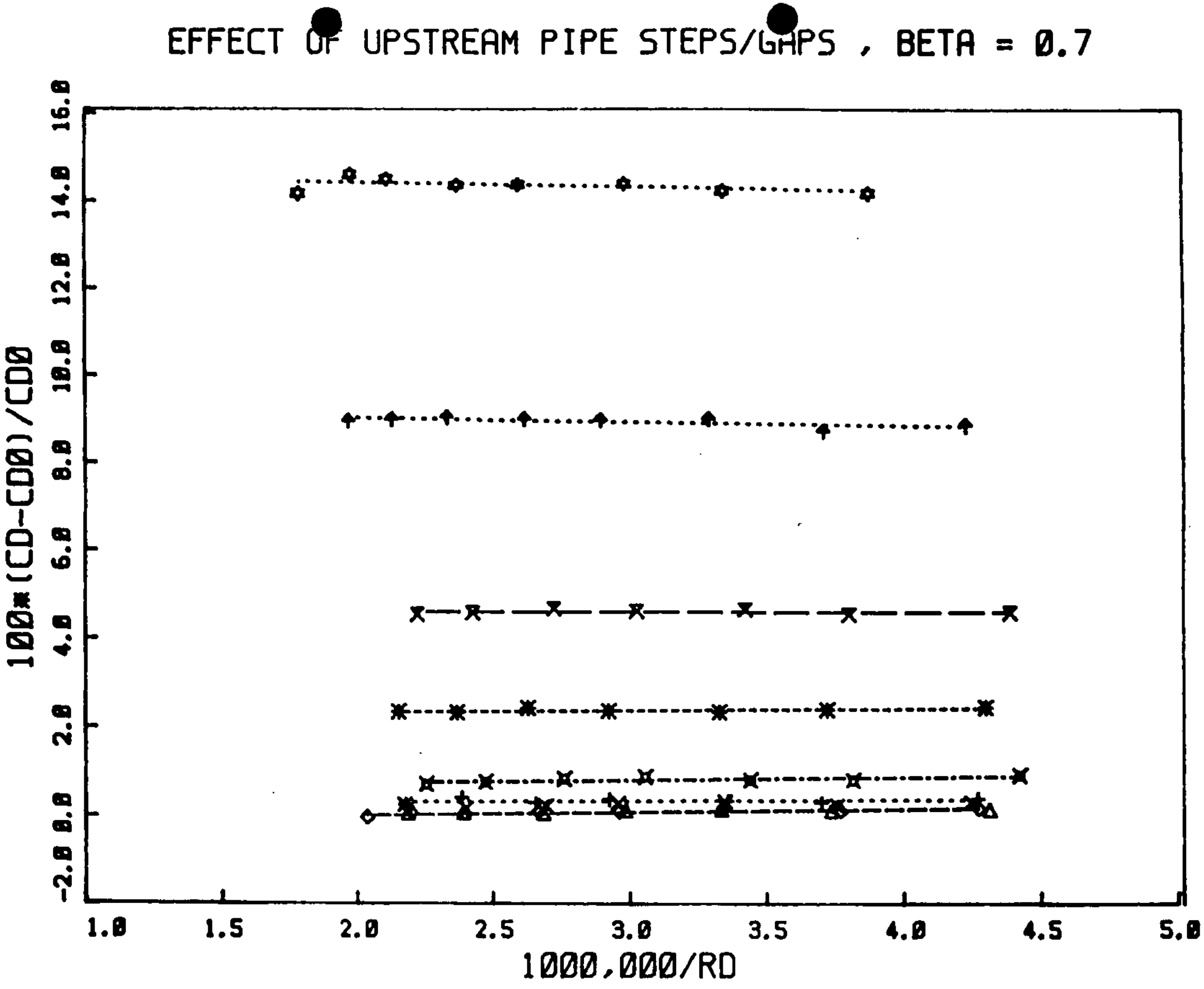

Figure 3c: Effect of steps/recesses at 2D upstream of the orifice plate for β = 0.7

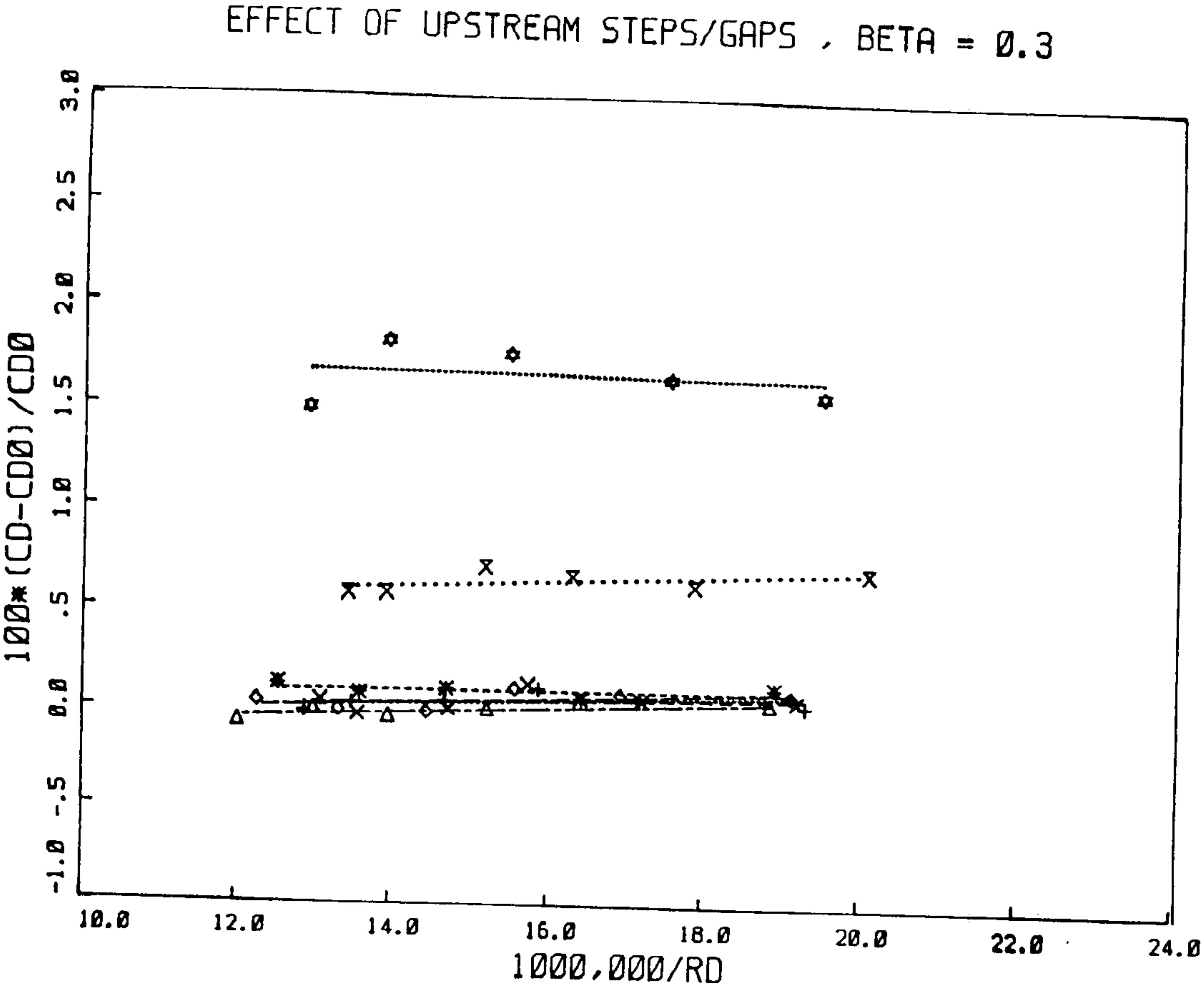

Figure 4a: Effect of Upstream Steps/Recesses at the Orifice for β = 0.3

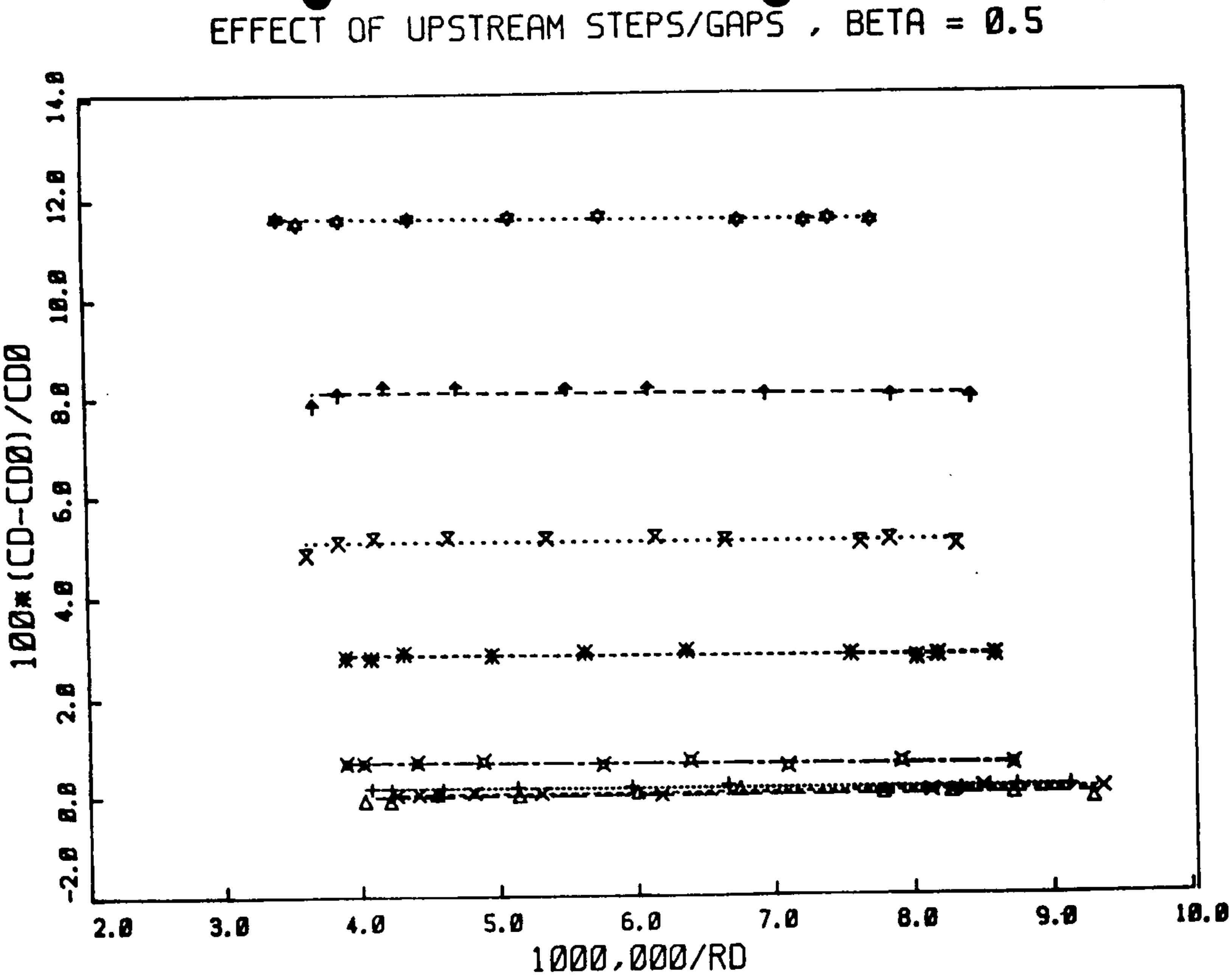

Figure 4b: Effect of Upstream Steps/Recesses at the Orifice for β = 0.5

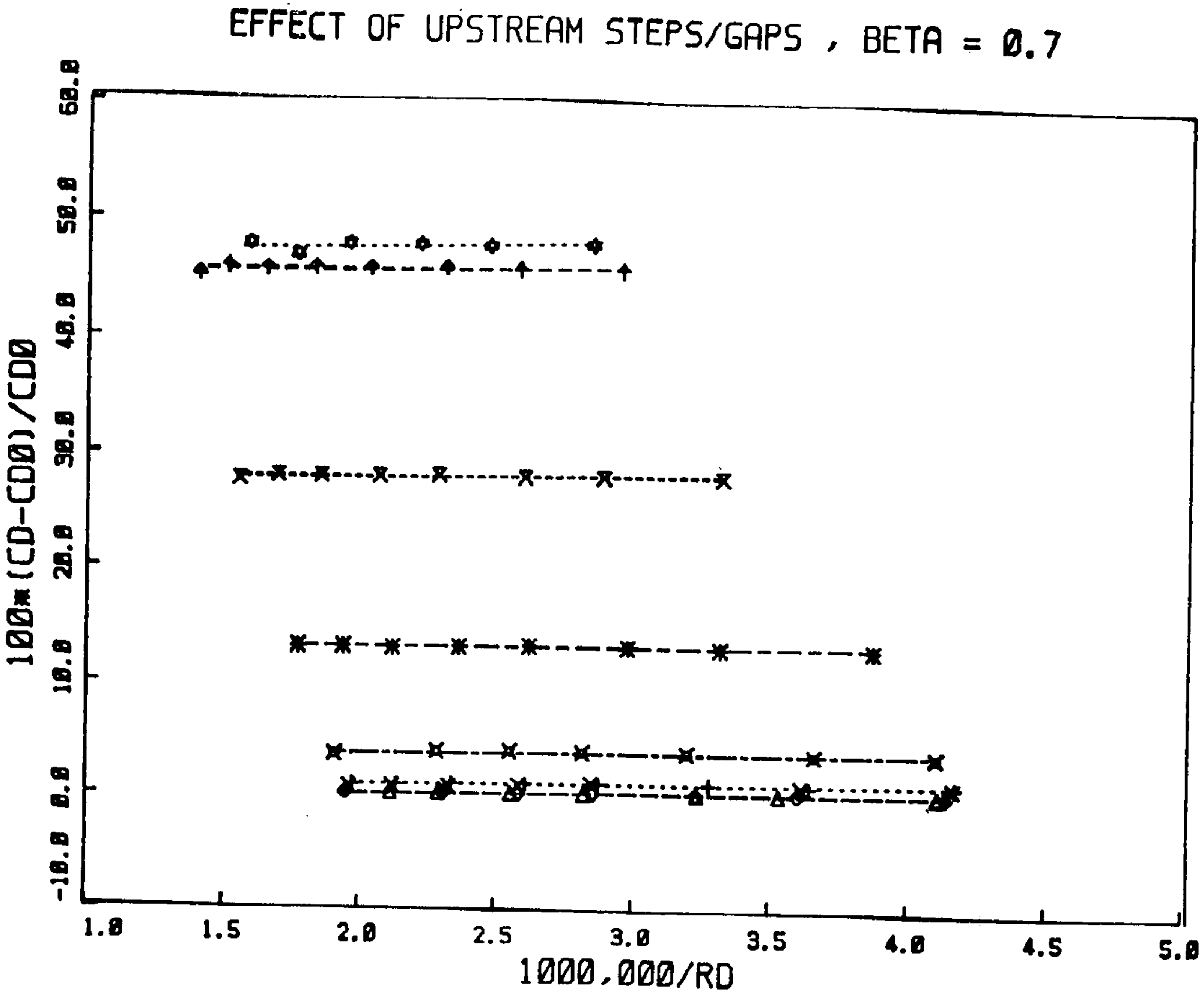

Figure 4c: Effect of Upstream Steps/Recesses at the Orifice for β = 0.7

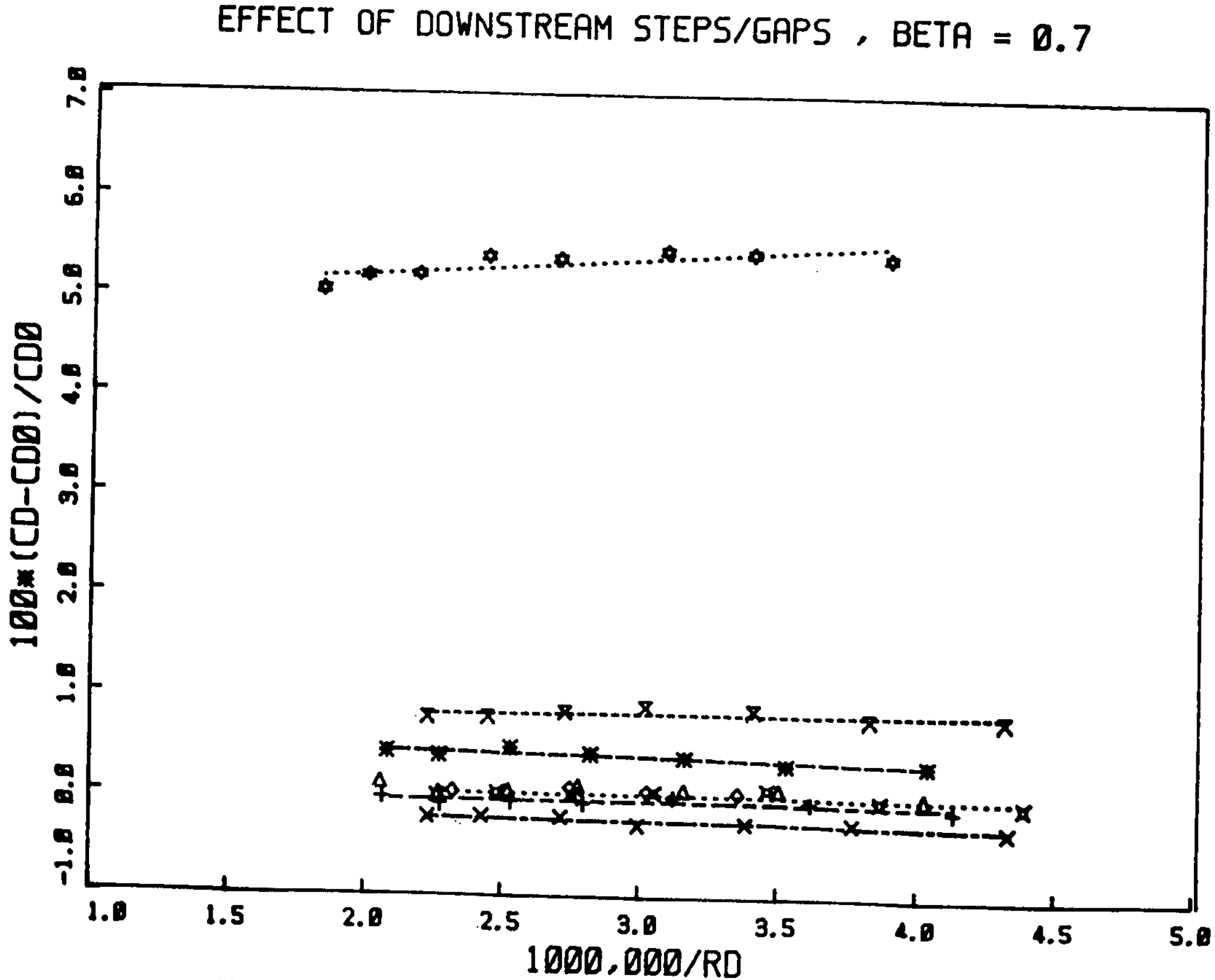

Figure 5: Effect of Downstream Steps/Recesses at the Orifice for β = 0.7

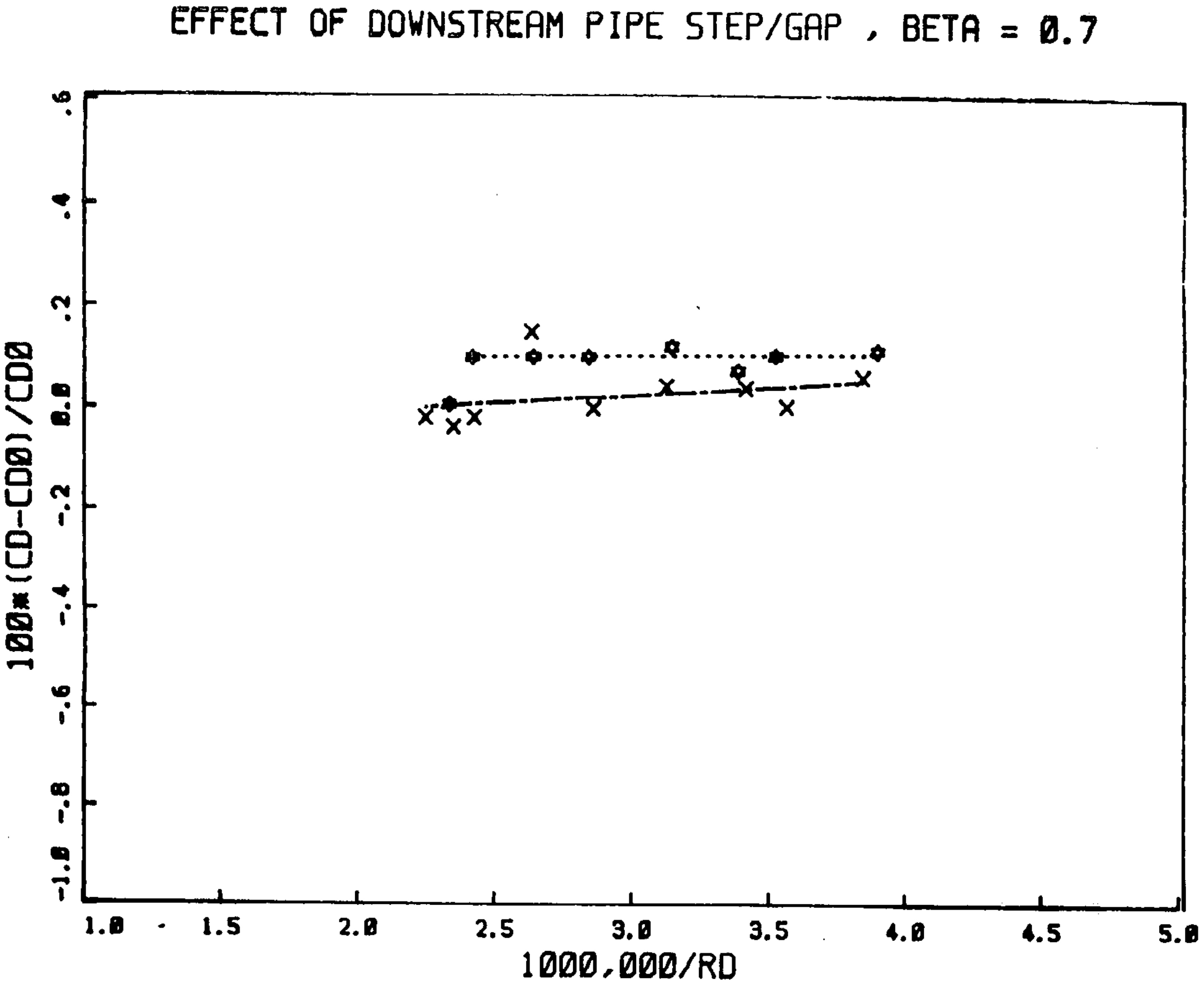

Figure 6: Effect of Steps/Recesses at 2D Downstream of the Plate for:
β = 0.7; ✡, step = 0.25 in.; X, Step = -0.25 in.

References

[1] Paper presented at the North Sea Flow Measurement Workshop, a workshop arranged by NFOGM & TUV-NEL

Note that this reference was not part of the original paper, but has been added subsequently to make the paper searchable in Google Scholar.