Flowmeter Installation Effects Due to Several Elbow Configurations

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ABSTRACT

This paper presents experimental results for the decay of pipe elbow - produced swirl in pipeflows and its effects on flowmeter measurement accuracy. Experiments include the decay of swirl produced by single and double elbow configurations for pipe diameter Reynolds numbers of 10^4 to 10^5 using water in a 2 in. diameter facility at NIST in Gaithersburg, MD. Results show that different types of swirl are produced by the different piping configurations. The swirl decay is found to be dependent on the type of swirl and the pipe Reynolds number. At high Reynolds number very long lengths of straight, constant diameter pipe are required to dissipate the single eddy type swirl that is produced by the two elbows-out-of-plane configuration. Without flow conditioning, it is concluded that the specifications of upstream pipe lengths in the current flowmetering standards may not be sufficient to achieve the desired flow metering accuracy.

INTRODUCTION

The effects of swirl on orifice meter performance were initially observed in the U.S. in the early 1900's [1-2]. Consequently, early testing programs, sponsored by the American Gas Association (A.G.A.), were devised to describe and quantify these effects, see Appendix No. 3 [1]. These early U.S. programs were followed by others that were supported by the gas industry and other sources such as the American Society of Mechanical Engineers (ASME), the National Institute of Standards and Technology (NIST), and the American Petroleum Institute (API).

A better understanding of the effects of pipeflow swirl on practical flow measurements and related fluid mechanics phenomena can be obtained through experimental fluid metering research programs that use the currently available flow research tools, [2]. The results produced herein are considered to be the type of data that will be needed to improve current flow measurement standards and associated metering practice.

The upstream pipe length requirements in two international orifice metering standards - ISO-5167 and ANSI/API-2530 - are quite different [1,3]. ISO-5167 specifies, for a 0.75 beta ratio (orifice hole to pipe diameter) orifice plate, minimum straight lengths of 36 and 70 diameters downstream of a single elbow and two elbows out-of-plane, respectively, [3]. ANSI/API-2530 [1] specifies 13.5 and 35 diameters for these installations. The ISO standard also specifies that, anywhere in the pipe cross-sectional area, swirl angles should be less than $\pm 2°$ at the location where the meter is to be installed. In both of these standards, no dependence is given for the effects of the type of swirl, the Reynolds number, the pipe roughness, etc. This paper presents experimental data on the decay of two different types of swirl generated by conventional pipe elbow configurations, the dependence of these swirls on Reynolds number, and the resulting swirl effects on the performance of specific types of flowmeters.

EXPERIMENTAL PROCEDURE

Experiments in an NIST water flow facility has been used to characterize swirl decay in a 2-inch pipe at Reynolds numbers of 10^4 and 10^5. Two different types of swirl were generated using two pipe arrangements: (1) a single long radius elbow and (2) two, long-radius elbows in an out-of-plane configuration. These configurations and the coordinate systems used are shown in figure 1. Velocity profiles were measured with a laser Doppler velocimeter (LDV) [4]. These results have been produced in piping with surface roughness of $3\mu m$ (relative roughness of $6 \times 10^{-3}\%$ based on pipe diameter) as measured with a calibrated profilometer [5-8]. For each of these piping configurations, the entering pipeflow was that from the same, very long (80 D) pipe which was preceded by several flow conditioners. When the flow from this unit of pipe work was measured using LDV, it was found that the mean velocity profile conformed to the power law distribution with the appropriate exponent [5-8].

RESULTS

All of the pipeflow profile results shown below are for Reynolds number of 10^5.

1. Single Elbow Velocity profile measurements for the standard long-radius elbow are shown in fig. 2(a). These results pertain to different downstream diameteral distances from the elbow for a pipe Reynolds number of 10^5. Only two velocity components were measured: the streamwise component labelled W in the Z difection and the vertical component V in the Y direction see figure 1(a). Velocities and lengths are normalized using, respectively, the cross-sectional average of the axial velocity and the inner pipe diameter. The profiles for the ideal flows are denoted by the dashed lines. For an ideal flow, the vertical velocity is zero everywhere and the streamwise velocity profile is the pertinent power law distribution. The exponent for these conditions is taken to be 7. The centerline slope discontinuity associated with the power law distribution has been smoothed. The profile between ± 0.1 is smoothed using a 3rd order polynomial based on the values at ± 0.1 and ± 0.15. The data indicates that the standard long radius elbow produces a dual-eddy (defined here as type II) swirl pattern that has two counter-rotating vortices on either side of the center plane of the elbow [7,8]. These vortices produce a strong transverse flow directed toward the outside of the elbow. The center core of this flow is found to have axial velocities that are much slower than the corresponding ideal flow. A time-averaged swirl angle can be defined as the arc tangent of the mean vertical velocity component divided by the mean streamwise component and results are shown in figure 3(a). The results close to the elbow show that the transverse flow produced by the counter rotating vortices gives swirl angles of -14° near the center of the pipe while the flows near either pipe wall give angles of +8°. The corresponding turbulent velocity distributions are presented in fig. 4(a). The dashed lines in these figures are the distributions measured by Laufer [9] in straight pipe in an airflow at Reynolds number 4×10^5. The turbulence measured in the present experiments is greater than that found by Laufer. However, Laufer's experimental arrangement had different inlet conditions which

are interpreted here as the explanation for the increased levels of turbulence found in the present experiments. With downstream distance, the present experimental results show that the distributions of mean and turbulent velocities decay in different ways according to the type of swirl and the pertinent Reynolds number and roughness conditions.

2. Double Elbows-Out-of-Plane For this configuration where the two elbows are closely-coupled, (s = 0 in figure 1(b) i.e., no straight pipe separates them) intense, single-eddy (defined here as type I) swirl is created. Velocity profiles are shown in fig. 2(b) for Reynolds number 10^5. Details can be found in [5,6]. Swirl angle distributions are presented in figure 3(b) for a pipe Reynolds number of 10^5. These distributions show that in the downstream piping near these elbows: (1) swirl angles are about $\pm 20°$ near the pipe walls, and (2) in a core region about the center of the pipe, the swirl angle is essentially zero indicating that little or no swirl is present. This suggests that a flow conditioning element placed near pipe wall could be very effective to reduce this swirl. This type of swirl is found to decay very slowly with downstream distance as compared to the single elbow swirl patterns described above. The corresponding turbulent velocity distributions are presented in fig. 4(b). As noted above these distributions are different for those for the single and from those measured by Laufer.

3. Decay of Swirl The decay of both types of swirl are shown in figure 5 by the maximum swirl angles. These maximum swirl angle distributions are defined as half of the difference between the maximum and minimum swirl angles shown in figure 3. In 20 diameters, the type II swirl has dissipated more than 90 percent (as quantified via the maximum value of the swirl angle) for a Reynolds number of 10^5. Single-eddy type swirl (type I) that is produced by two close-coupled elbows decays much more slowly. The swirl produced by spaced double elbows is much more complicated [6,7]. It is a composite of type I and type II swirl depending on the length of the spacer, s. For a long spacer, the swirl should approach to that of single elbow case. The data for s = 2.4 and 5.3 diameters show that the type I swirl flow pattern still dominates the swirl interactions although the initial swirl is much smaller than that for the close-coupled elbows. The decay of this swirl is also slow. The Reynolds number dependence of type I swirl shows that the decay rate decreases markedly as the Reynolds number increases, [7]. Very long lengths of pipe are required to dissipate this single-eddy type swirl, [8].

Other researchers [10-14] have described the decay of swirl as an exponential decay function of the following form:

$$S/S_o = e^{(-\alpha Z)} \qquad (1)$$

where:

- S is some selected measure of the swirl (angular momentum, angular momentum flux, mean swirl angle, etc.),
- S_o is the value of S where Z = 0,
- α is the swirl decay parameter, and
- Z is the number of diameters of straight, constant diameter piping downstream of the initial position where $S = S_o$.

This function can be used for predicting the percent of initial swirl as a function of the dimensionless axial distance Z.

The decay parameter, α, depends on the type of swirl, the selected measure of the swirl, and the pipe diametral Reynolds number, Re_D. To estimate the values of the various swirl decay parameters, a least squares fit of the experimental data was made for each swirl quantity, S for each Reynolds number. This fit was produced using an iteration technique until the change in the squared error was less than 0.1%. If S is taken to be the maximum swirl angle, then at a Reynolds number of 10^5, α will be 0.026 and 0.186 for the single-eddy and double-eddy type swirls, respectively; at a Reynolds number of 10^4 α will be 0.029 and 0.201 for single-eddy and double-eddy type swirls, respectively. These equations show that swirl decays more slowly at higher Reynolds numbers. Therefore, the double-eddy swirl decays much faster than the single-eddy swirl at the same Reynolds number. Using these values we obtain the following Reynolds number dependencies. For the maximum swirl angle, we have:

For a single-eddy (type I) swirl:

$$\alpha = 0.045\ Re_D^{-0.047} \tag{2}$$

For a double-eddy (type II) swirl:

$$\alpha = 0.275\ Re_D^{-0.034} \tag{3}$$

These experimental results can also be used to evaluate the installation specifications in current flow measurement standards [1,3]. For the case of a single elbow producing (type II) swirl angles of up to 19°, to reduce that swirl to less than 2° at a pipe Reynolds number of 10^5, about 12 pipe diameters would be required. The ISO-5167 specification of 36 diameters for a 0.75 beta orifice meter for this situation would be very conservative, whereas the ANSI/API-2530 specification of 13.5 seems to be barely sufficient. For the case of a double elbow producing a single-eddy (type I) swirl of 20°, to reduce the swirl to less than 2° at a pipe Reynolds number of 10^5, about 89 diameters would be necessary. Neither ISO nor ANSI specifications would provide sufficient upstream length to reduce this swirl to the acceptable levels quoted. When Reynolds numbers are very high - i.e. 10^6 or 10^7 - which can frequently occur in metering practice, the current specifications would appear to grossly underpredict the necessary upstream lengths for orifice meters installed downstream of this double elbow configuration.

While the decay analysis presented above is applied to the maximum value of the swirl angle found along the horizontal diameter, other swirl parameters can be generated as based upon angular momentum parameters and analyzed to describe swirl decay phenomena. Several of these have been found to be very effective for accurately predicting the performance of different types of flowmeters when installation conditions are not ideal [5-8]. Because of differences in the mean and turbulent velocity distributions the performance of some flow meters installed in these pipeflows can be expected to be different from the performance expected in ideal pipeflow.

4. <u>Effects on Meters</u> Both orifice and turbine-type flowmeters of differing designs were calibrated in installations affected by the types of swirl described

above.

a. Orifice Tests A range of orifice beta ratios were tested in the 50 mm (2 in) diameter water flow facility [5-8]. The orifice taps were the flange-type and oriented in the X-Z plane and on the positive X-axis side, see figures 1(a) and (b). The meter calibration results are considered in terms of shifts relative to the average discharge coefficient from ideal installation conditions. By ideal installation conditions is meant that the meter is located 210 pipe diameters of straight constant diameter piping upstream of the meter; about 25 diameters of piping were installed downstream. The results were taken over the range of Reynolds number tested; these are (1) $\beta = 0.363$, $15000 \le Re \le 45000$, (2) $\beta = 0.50$, $3000 \le Re \le 75000$, (3) $\beta = 0.75$, $45000 \le Re \le 100,000$. Figure 6(a) presents the effects of single elbow swirl on these meters. These results show that the single elbow flow reduces the discharge coefficients for these conditions. Relative to the ideal situation, these reductions range between -0.1% and -5.0%, when these meters are installed between 20 and 2.5 diameters, respectively, from the elbow. The reduction of the discharge coefficient is largest for the installation nearest the elbow and this reduction increases with beta ratio.

Figure 6(b) presents the effect of the double-elbows-out-of-plane (type I) swirl on these meters. These results show that the double-elbows-out-of-plane flow can either increase or decrease discharge coefficients. Increased discharge coefficients are speculated to be the result of type I swirl effects that reduce the differential pressure. Decreased discharge coefficients can be explained by the flatness of the axial velocity distribution as compared to the ideal profile. Increased discharge coefficients can be explained by swirl effects propagating throught the orifice and elevating the pressure at the downstream tap via conservation of angular momentum principles. The relative significance of these effects is different for different beta ratios. It is shown elsewhere that these elbow flows influence orifice meters differently for different Reynolds number conditions, [5-8,13]. The erratic results found in figure 6(b) for the largest beta ratio are interpreted to be the result of the complicated nature of this pipeflow very near the exit from this elbow configuration, see figures 2-4.

Based on these orifice test results, it appears that the 2° limit on swirl angle is not a sufficient criterion to guarantee that orifice meter performance will be within ±0.5% of the ideal installation value. Specifically, for the 0.75 beta orifice meter the 2° swirl angle criterion indicates the meter should be installed 12 diameters downstream of the single elbow configuration, but the shift in discharge coefficient at this location is found from figure 6(a) to be -2%. Conversely, for the 0.363 beta orifice meter, the 2° swirl angle criterion is quite conservative since the discharge coefficient shift is only -0.25% at this location. If a ±0.5% tolerance on the discharge coefficient is allowed for the 0.363 beta meter downstream of the single elbow, this can be achieved with $Z = 8$ (where the swirl angle is 4°). Furthermore, for the closely coupled double elbow configuration, the 2° swirl angle criterion produces discharge coefficient shifts less than ±0.5% for all beta ratios. For an installation criterion based upon ±0.5% shift in the discharge coefficient, our results show that: (1) a 0.75 beta orifice meter requires $Z = 50$ (where the swirl angle is greater than 4°), and (2) a 0.363 beta meter requires only $Z = 20$ (where the swirl angle is 8°).

b. Turbine Tests In water flow tests, both types of swirl were found to shift the performance of a turbine-type meter, as shown in figure 7. This meter is constructed to spin counterclockwise looking downstream which is in the same direction as the type I swirl generated by the double elbow configuration tested. This meter has straight, flat blades approximately one pipe radius in length. These results show that this turbine meter is shifted upward from 0.3 to 2% when it is installed within 90 diameters from the double elbow out-of-plane configuration. When this meter is installed near the single elbow, the shift is downward and smaller than 0.3% in locations within 20 diameters of the elbow [5].

To improve the performance of the types of meters described above, a number of strategies can be used. Firstly, the conventional strategy has been to perform a calibration using the identical conditions of fluid piping, meter, flowrate range, etc. Secondly, the use of flow conditioning elements installed in the piping between the elbow configuration and the meter can possibly produce improved metering performance. These flow conditioning elements vary widely in their geometrical arrangements; their conditioning capabilities can be dependent on the type of pipeflow and their geometry; they can cause significant pressure losses in the pipeflow [15]. Thirdly, it has recently been demonstrated that satisfactory metering performance can be successfully predicted and achieved without resorting to flow conditioners if sufficient data is available on the non-ideal pipeflow and data on how the respective meter is shifted with respect to the non-ideal pipeflow, see [5-8]. By correlating the pipeflow data with the meter-shifts, it has been demonstrated that it is feasible to adjust the ideal meter performance so that accurate flow measurements can be obtained in the non-ideal meter installations [16].

Although not investigated here, the role of pipe roughness on swirl decay has been studied elsewhere. Mottram and Rawat [17] have shown that increased pipe roughness can reduce the lengths of piping required to dissipate pipeflow swirl.

CONCLUSIONS

The decay of swirl is dependent on the Reynolds number and the type of swirl. Installation specifications in the current flow measurement standards are concluded to be insufficient if strong single-eddy type swirl is present. Extremely long lengths of pipe are required to dissipate this type of swirl at high Reynolds numbers. In many meter installations, the necessary length requirements may be understated as judged from the present results. Meter installations where measurement accuracy is important should be re-evaluated to ensure swirl phenomena does not detrimentally affect the particular meter in the specific location.

The effects of single and double eddy types of swirl are found to significantly change the performance of orifice and turbine type flowmeters. These shifts in performance vary both in direction and in magnitude depending on the type and strength of swirl, Reynolds number, and the specific type and design of the flowmeter.

ACKNOWLEDGEMENT

This research is supported by an industry-government consortium formed by NIST to conduct critical research on generic fluid measurement topics. The members of this consortium as of June 1990 are: Ametek-McCrometer, Chevron Oil, Controlotron, Dow Chemical, E.I. DuPont de Nemours, Ford Motor, Co., Gas Research Institute, Gas Unie, ITT Barton, Kimmon Mfg. Ltd., Rockwell International, and Rosemount, Inc. Special acknowledgement is given to Dr. K.M. Kothari of the Gas

Research Institute for his technical input and support for this program.

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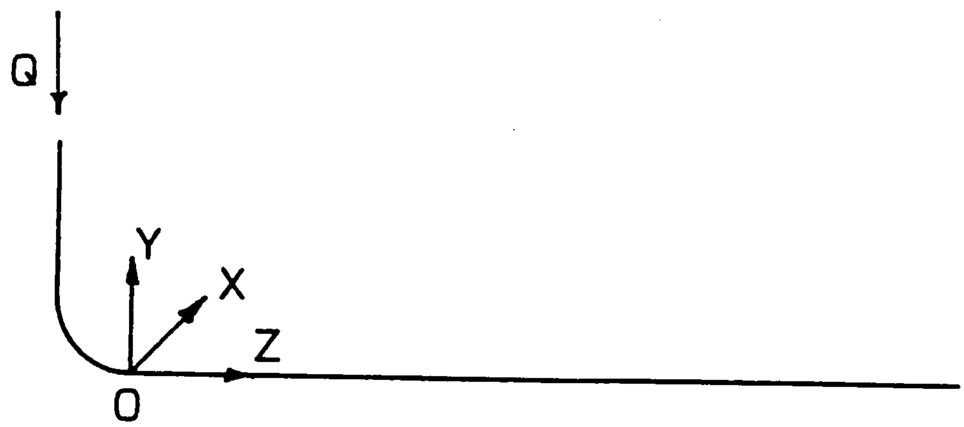
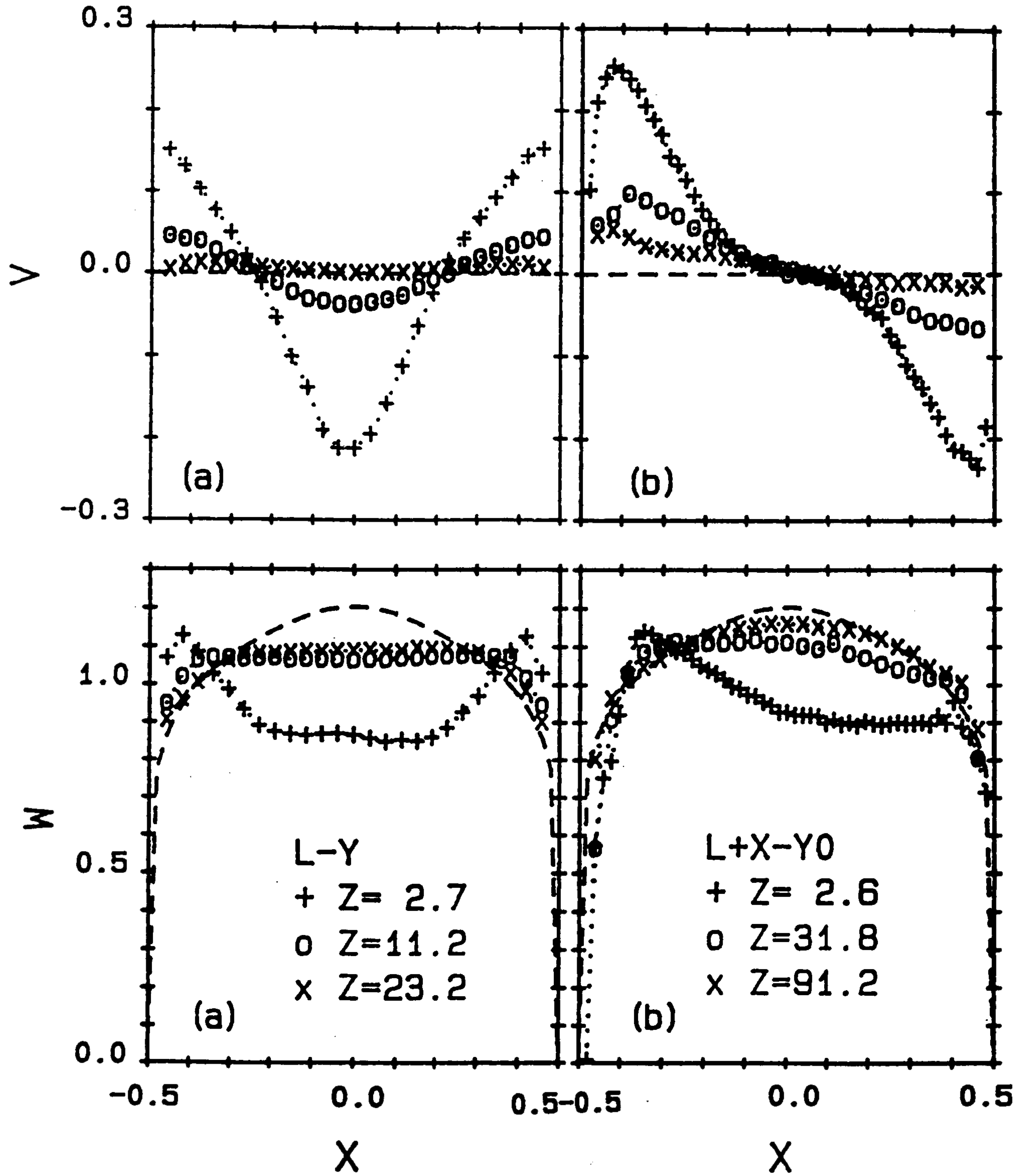
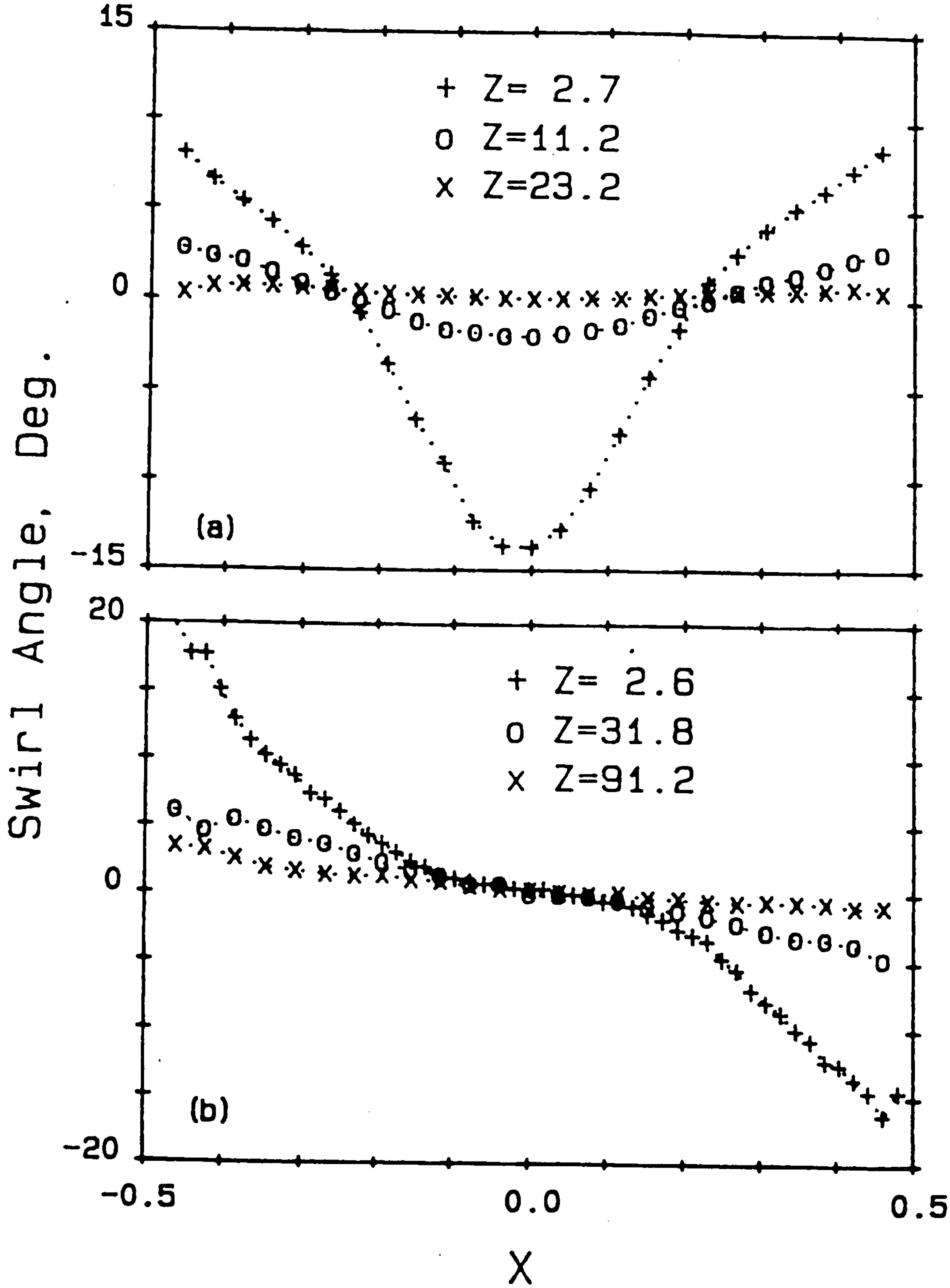


Figure 1(a) Single Elbow Configuration

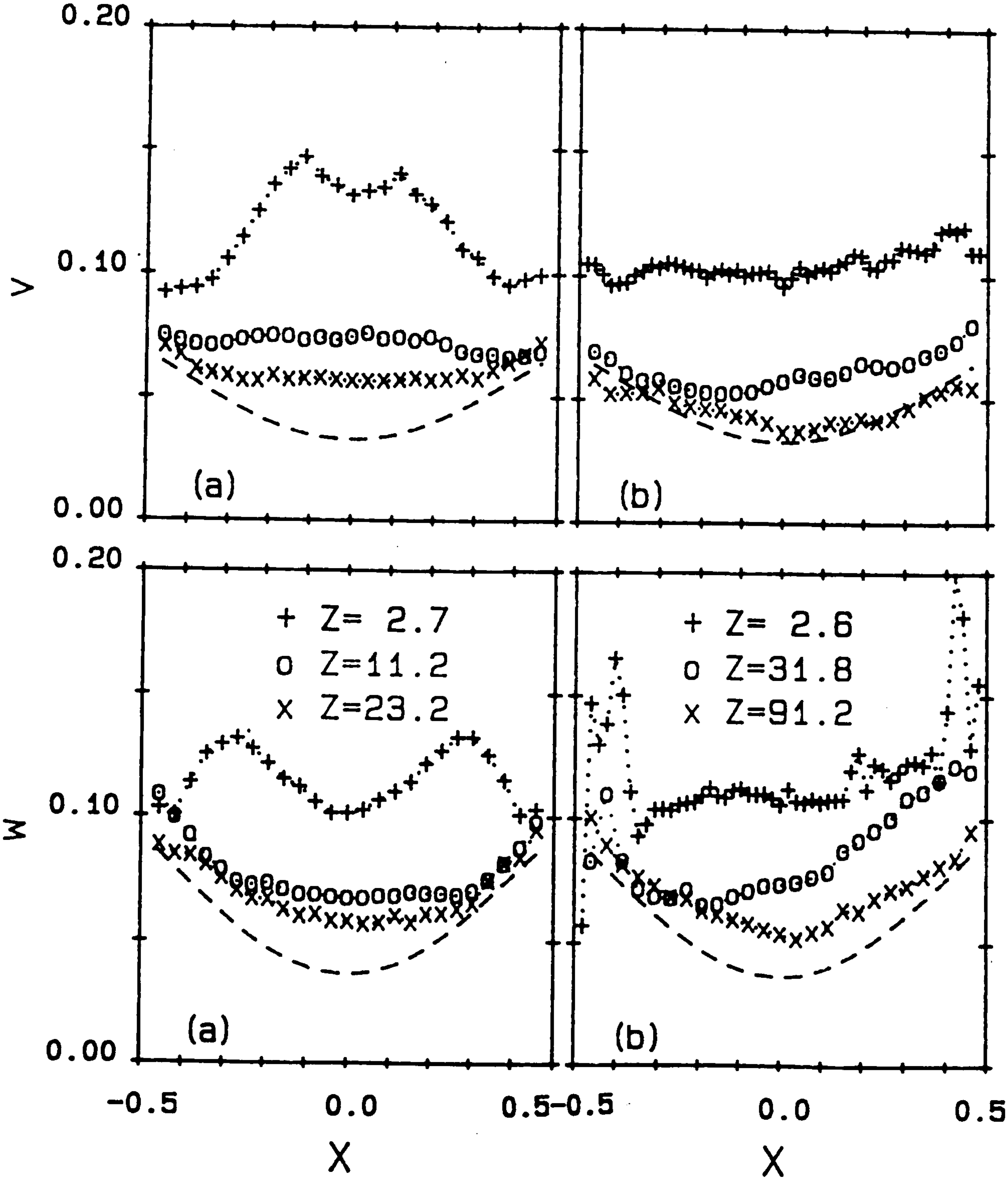
Figure 1(b) Double Elbow-out-of-Plane Configuration with Spacing, s.



<u>Figure 2</u> **Vertical V, and Streamwise, W Velocity Profiles Along the Horizontal Diameter for (a) The Single Elbow Configuration, and (b) The Close Coupled Double Elbows-out-of-Plane Configuration. Downstream distances are labelled in Diameters. Ideal Profiles are shown via the dashed lines.**



<u>Figure 3</u> Swirl Angle Distributions Produced by: (a) the Single Elbow Configuration, and (b) the Closely Coupled Double Elbows-out-of-Plane Configuration. Downstream Distances are in Diameters.



<u>Figure 4</u> Cross-stream Profiles of the Root-Mean-Square Values of the Vertical, v' and Streamwise, w' Turbulent Velocity Components: (a) Single Elbow, and (b) Close Coupled Double-Elbows-out-of-Plane. Downstream distances are labelled in diameters. The dashed lines refer to Laufer's data.

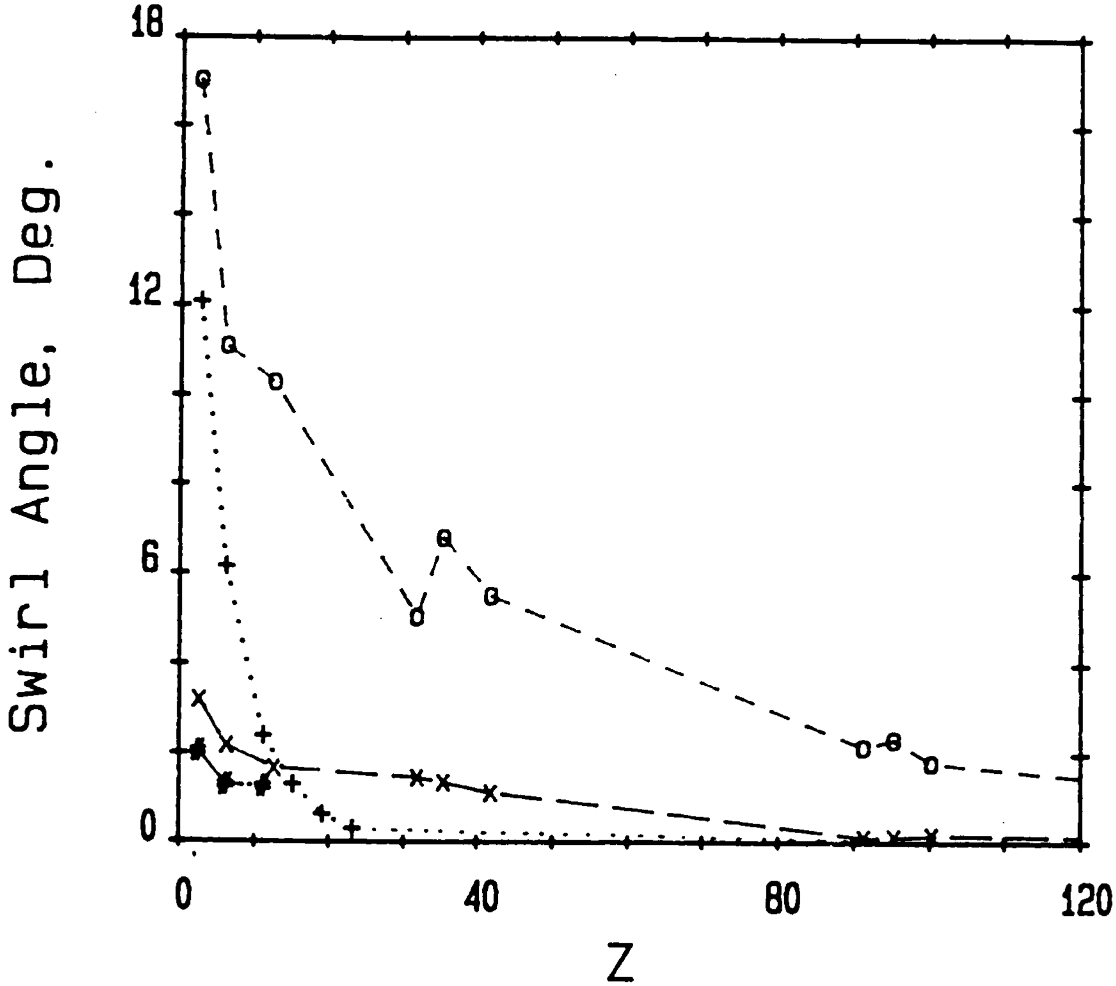


Figure 5 Streamwise Distributions of the Mean Maximum Swirl Angles for the Single Elbow Configuration, (+) and for the Double Elbows-out-of-Plane Configurations ((0) closely coupled; (x) spaced 2.4 diameters; and (#) spaced 5.3 diameters)).

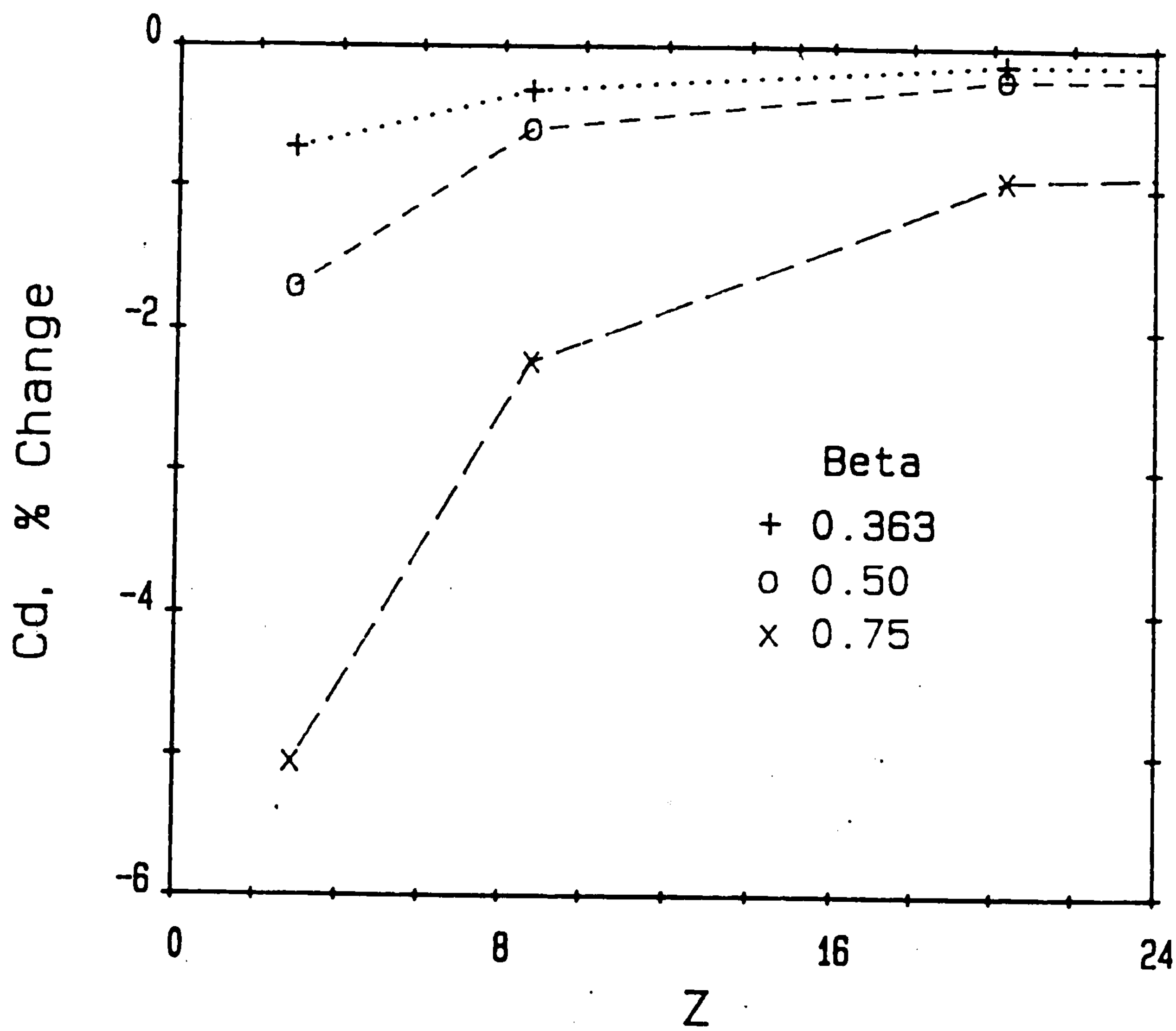


Figure 6(a) Calibration Results for Orifice-Type Meters Installed in Non-Ideal Conditions Downstream of a Single Elbow.

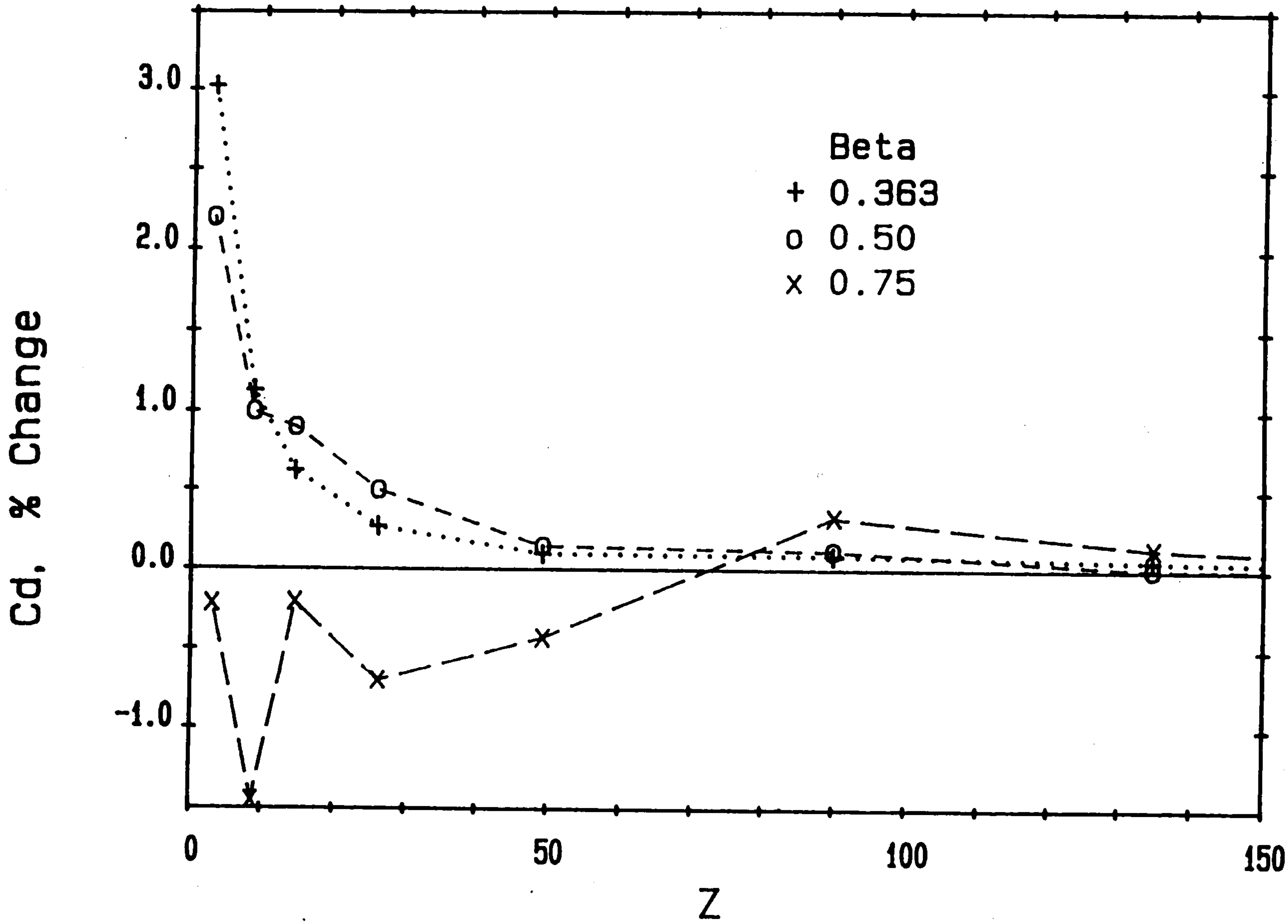
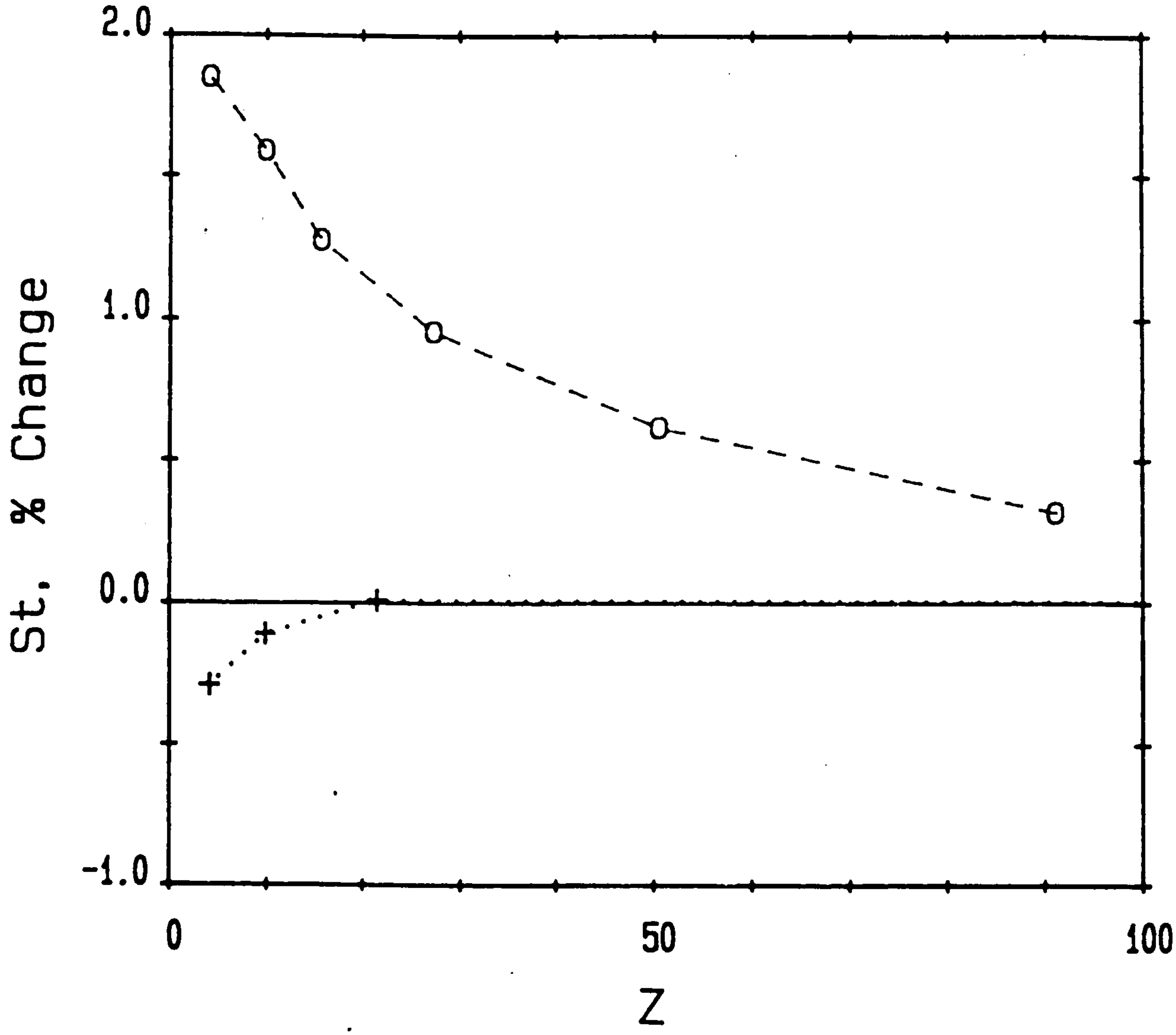


Figure 6(b) Calibration Results for Orifice-Type Meters Installed in Non-Ideal Conditions Downstream of a Closely-Coupled Double Elbows-out-of-Plane Configuration.



<u>Figure 7</u> Calibration Results for a Turbine-Type Meter Installed in Non-Ideal Conditions Downstream of a Single Elbow, (+) and Downstream of a Closely Coupled Double Elbows-Out-of-Plane Configuration, (0).