NISTIR 4753

Summary Report of NIST's Industry-Government Consortium Research Program on Flowmeter Installation Effects With Emphasis on the Research Period February - December 1990: TEE, Used As An Elbow Configuration

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Issued January 1992

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PREFACE

The research results reported in this document were produced with the support of a National Institute of Standards and Technology (NIST) initiated industry-government consortium. In this mode of operation, there is a high degree of interaction between the representatives of the consortium member companies and the NIST researchers. Their interactions include: (1) the planning of the specific focus of the NIST research efforts, (2) the analyses of the results obtained, and (3) the conclusions drawn for the particular phase of the work. For this reason, it is pertinent to acknowledge both the support given to this phase of the research program and the technical contributions made by the representative of the consortium members.

The current consortium as of December 1990 is, alphabetically:

1. Ametek-McCrometer
2. Chevron Oil
3. Controlotron
4. Dow Chemical Co.
5. E.I. Dupont de Nemours
6. Ford Motor Co.
7. Gas Research Institute*
8. Gas Unie (The Netherlands)
9. Instrument Testing Service
10. ITT Barton
11. Kimmon Mfg. Ltd. (Japan)
12. NIST-Boulder
13. Rockwell International
14. Rosemount

*Specific acknowledgment is due to Dr. Kiran M. Kothari of the Gas Research Institute (GRI). Both his support of this program and his technical inputs in the analyses of results and in the conclusions drawn are gratefully acknowledged.

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ABSTRACT

This report presents results obtained in a consortium-sponsored research program on flowmeter installation effects being conducted at NIST-Gaithersburg. This project is a collaborative one that has been underway for six years; it is supported by an industry-government consortium that meets twice yearly to review and discuss recently obtained results and to plan subsequent phases of the work.

The objective of this research program is to produce improved flowmeter performance when meters are installed in non-ideal conditions. This objective is being attained via our proposed strategy to:

(a) measure, understand, and quantify the salient features of non-ideal pipe flows from such pipeline elements as elbows, reducers, valves, flow conditioners, etc. or combinations of these,

(b) correlate meter-factor shifts for selected types of flowmeters installed downstream from these pipeline elements with quantified flow features so as to be able to predict meter performance accurately in non-ideal installations, and,

(c) disseminate the resulting technology through appropriate channels such as publishing our results in pertinent journals and upgrading paper standards for flow measurements.

As well, this research effort has included experimental studies of the flow into and out of tube bundle flow conditioners. These results have produced detailed descriptions of the effects these devices have on swirling pipe flows. The performances of both orifice and turbine meters have also been determined for different installation locations downstream of arrangements of these pipeline elements followed by tube bundles.

This report contains the results and conclusions of the meeting of this consortium at NIST-Gaithersburg, MD in December 1990. Specific results included in this report are the effects produced by the conventional piping tee which is used as an elbow. This is a prevalently used configuration to enable easy access to the downstream piping through the blind flange. Orifice and turbine meter calibration results are given without and with conventional, concentric tube bundles - both 19 and 7 tube geometries. Meter performances are compared and contrasted in several ways.

INTRODUCTION

The increasing scarcity of fluid resources and the rising value of fluid products are placing new emphases on improved flow measurements. Improvements are sought from many starting points. Meters are being retrofitted into fluid systems that were not designed for them. This invariably means the flowmeters are being inserted into "non-ideal" installation conditions. By "non-ideal" is meant any of the infinitude of conditions where the upstream piping conditions produce pipeflow distributions that differ from that associated with fully developed flow that occurs in ideal installation conditions. Ideal conditions are where the meter location is preceded by long, straight lengths of constant diameter piping.

The prevalent concern in today's flow measurement community is for increased accuracy levels. These are desired for installed meter systems - either by upgrading the flow conditions that enter the meter or by replacing the device itself or its auxiliary components.

Flow conditioning devices of one geometry or another are frequently recommended in metering standards for improving flowmeter performance when installation conditions are not ideal. However, the pipeflows generated by these devices have to be considered with respect to the flowmeter installed downstream and the pertinent parameters that control pipeflow phenomena and the factors that influence the performance of the particular meter. It will be shown in what follows that certain flow conditioner installations can produce serious deviations from the performance of specific meters in ideal installation conditions.

When flow conditioners cannot be used to remedy a "non-ideal" installation condition, it has been conventional practice to calibrate the actual piping and meter configuration. When this is not possible or unreasonable, an alternative procedure may be used which has been put forth for the first time in this research program.

The industry-government consortium research program on flowmeter installation effects that is currently underway at NIST is designed to help improve fluid metering performance when installation conditions are not ideal. The design of the program is to produce a basic understanding of the flow phenomena that are produced in non-ideal pipe flows and to quantify these phenomena. When these phenomena and their quantified characteristics are correlated with the performance of specific types of meters, it should be feasible to predict and achieve satisfactory measurements in non-ideal meter installations. The success of this approach has been demonstrated using several different types of flowmeters installed downstream of several different pipe elbow configurations.[1-4]

The experimental research program is based upon the measurements of pipe flows from selected piping configurations using laser Doppler velocimetry (LDV).[1-4] The program is intended to use the basic experimental research tools available to the fluid dynamicist to measure, understand, and parameterize the salient features of the pipeflow phenomena produced by pipeline configurations. The successive phase of the program is to evaluate quantitatively how these phenomena influence fluid meters and how to handle these effects. Selections of piping configurations and pipeline elements such as flow conditioners are done by vote of the consortium membership; one or two such configurations can be done in one year.

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*Square bracketed integers refer to references given below.

The LDV techniques that have been and are being applied to measure the basic pipe flows can also be used to measure the effects of other pipeline elements - valves, flow conditioning elements (for fluid velocity or pulsations, etc.), mixing devices, generic flowmeter geometries - or combinations of these. The resulting understanding provides the basis for improving the effectiveness of these devices and, in turn, the performances of flowmeters installed downstream of such piping configurations. It is expected that improved flowmeter performance will enhance fluid custody transfers and the optimization of industrial processes through better control produced by better flow measurement.

In the present study, the fluid is water and the piping is 52.5 mm diameter (2 in.), smooth, stainless steel. Water temperature is controlled using a heat exchanger to maintain 20°C. The relative roughness of this pipe has been measured with a profilometer to indicate a value of 0.006%. Diametral Reynolds numbers range from 10^4 to 10^5. According to the concepts of dynamic similitude, the results of the present research program should predict a range of other flows - both liquids and gases in geometrically scaled piping configurations when pertinent parameters match those in our experiments. The pertinent parameters considered important in the current experiments are Reynolds numbers and relative roughness; it is assumed the fluid compressibility and gravitational effects are negligible. When these conditions occur in other, geometrically scaled pipe systems, the fluid flows should be scaled versions of our results. These results are shown in reference [5].

It is expected that the results from this program will enable satisfactory flow measurements to be made in many situations where installation conditions are not ideal. For situations where it is not possible or desirable to install flow conditioning elements to remedy pipeflow anomalies, it is suggested here that - where specific calibration of the whole meter installation cannot be done - the proposed prediction technique be used.

When the performance of flowmeters - similar to or different from those selected - is determined by calibration tests in conditions that match exactly or are scaled correctly to those in these experiments, meter performance can be correlated to pipe flow parameters. Such correlations, when done for the pertinent range of "non-ideal" installations and for the appropriate flow meters, should produce the desired specifications for installing these meters. When this is achieved - by flowmeter manufacturers or users alike - it should then be possible to predict and achieve satisfactory metering performance for these meters in similar non-ideal installations.

PREVIOUS RESULTS

Previous phases of this research program have produced LDV measurements of the pipeflows in the downstream piping from single and double elbow configurations. Conventional, long-radius elbows are used in all of these studies; the radius of the centerline through these elbows is 1.5 pipe diameters. The results of these studies are given in references [1-5].

Previous phases of this research program have also produced data for the performance of orifice and turbine meters installed downstream of selected single and double elbow piping configurations, see [6-7]. Additionally, the demonstration of the success of the above-described prediction scheme for attaining accurate flowmeter performance for these types of meters installed downstream of these elbow configurations is given in reference [7]. Figure 1 shows the arrangements of the piping configurations studied and the coordinate systems selected. In all of the results that follow, non-dimensionalized quantities will be used. Lengths and velocities are normalized using the pipe diameter and bulk-averaged velocity, respectively. Meter performances are given via discharge coefficients and Strouhal numbers, respectively, for the selected orifice and turbine meters.

The previous phase of this research program determined the effects on orifice and turbine meters of the conventional 19-tube tube bundle installed downstream of the single and closely-coupled double elbow out-of-plane configurations, see figure 2(a) and reference [1]. Also tested in the recent phase of this program was the 7-tube tube bundle shown in figure 2(b).

The results obtained for these conditions show that while the 19-tube tube bundle successfully removes swirl from these pipeflows it apparently produces other effects in the streamwise velocity profiles that cause several different perturbations on orifice meter performance. The effects on this specific design of turbine meter were less varied than those for orifice meters, see references [4 and 7].

Specific results included in this report are the effects produced by the conventional piping tee which is used as an elbow. This is a prevalently used configuration to enable easy access to the downstream piping through the blind flange. Orifice and turbine meter calibration results are given without and with conventional, concentric tube bundles - both 19 and 7 tube geometries. Meter performances are compared and contrasted in several ways. The tube bundle designs tested in the recent phase of this program are installed downstream of the piping configurations as shown in figure 3(a) and (b). The coordinate Z has its origin in the exit plane of the elbow as shown in figures 1 and 3. The 19-tube tube bundle shown in figure 3(a) is the concentric arrangement. The 7-tube tube bundle, installed as shown in figure 3(b) has its entrance plane at the same Z location as that used for the 19 tube.

ORIFICE METER CALIBRATION RESULTS

1. Downstream Of A Single Elbow. The test results for three orifice meter geometries installed at varying distances downstream of the single elbow have been reported previously, see reference [3]; these characteristics are summarized for installations within 25 diameters of the elbow as shown in figure 4. These results plot the percentage change in the mean value of the discharge coefficient determined over the flow rate range tested, relative to the mean value for the ideal installation condition for the respective beta ratio. Beta ratio is the orifice hole diameter divided by the inside pipe diameter. The ideal installation condition refers to meter positions preceded by more than 200 diameters of straight constant diameter piping. These ranges, in terms of diametral Reynolds number, are nominally:

Beta Ratio	Reynolds Number
0.363	14,000 - 45,000
0.500	25,000 - 80,000
0.750	40,000 - 100,000

These results show that for these conditions the mean discharge coefficients are shifted negatively relative to the ideal values due to the effects of the single elbow on the downstream pipe flow. These negative shifts range from about 1% to 5% for beta ratios from 0.363 to 0.750, respectively, for meter installation 2.5 diameters from the exit plane of the elbow. With increased downstream installation distance these shifts decay toward zero non-linearly with diametral displacement distance from the elbow. Details for individual meters are found in the respective calibration results.

The calibration results for the beta = 0.363 orifice meter installed in different locations downstream of the single elbow are shown in figure 5. The ordinate in figure 5 is the percentage change found at the pertinent flowrate relative to the value obtained when installation conditions are ideal. The results shown in figure 5 include those shown in figure 4 and similar results obtained for meter installations beyond the 30 diameter downstream position. These downstream results show that the orifice discharge coefficients attain shifted values in the range between 0.1 to 0.2%. If tolerances in the amount of ±0.25% are placed on this orifice meter's ideal performance, this meter can be installed at or beyond 8 diameters from the elbow to achieve this level of performance.

Figure 6 presents calibration results for the beta = 0.50 orifice. These results show that for the previously specified tolerance of ±0.25% this orifice meter should be installed at or beyond 14 diameters from the elbow in order to attain this level of performance.

Figure 7 presents orifice performance characteristics for a beta = 0.75 meter. These results show that for this meter and these conditions, installations should be at or beyond the 30 diameter location downstream from the elbow to attain performance within ±0.25% of the ideal.

The precision of the above described orifice performance characteristics is typified by the data shown in figure 8. Here, the individual discharge coefficient determinations are plotted for the respective flow rates for the beta = 0.50 meter. These results indicate that the imprecision at each installation position is greatest at the lowest flow rate of the range. The imprecision is greatest when the meter is closest to the single elbow and least for the ideal installation condition. It is noted that the imprecision for the two installations near the elbow is bounded by about ±0.13% while in the ideal installation the imprecision is about ±0.05%.

2. Downstream Of A Tee Used As An Elbow. For the tee used as an elbow configuration shown in figure 1(c), the orifice meter performance data obtained for different installation distances for a beta = 0.363 meter is shown in figure 9. The data pattern is similar to that described above for the single elbow. However, if the ±0.25% tolerance value is used as described above, the beta = 0.363 meter should be installed at or beyond the 8 diameter distance from the exit of the tee.

Figure 10 presents calibration results for the beta = 0.50 orifice meter. Again, the pattern of performance duplicates that shown for the elbow in figure 6. The results in figure 10 show that for this meter and these conditions installations should be at or beyond about the 14 diameter distance downstream from the discharge coefficient within ±0.25% of the ideal value.

Figure 11 presents orifice meter performance for beta = 0.75 for installations downstream from the tee used as an elbow. For these conditions and for the ±0.25% tolerance, this meter should be installed at or beyond the 32 diameter location downstream from the exit of the tee.

TURBINE METER CALIBRATION RESULTS

1. Downstream Of A Single Elbow. The performance for the selected turbine meter installed at varying distances downstream of the single elbow are shown in figure 12. These results plot the percentage change in the meter's Strouhal number relative to the corresponding value for the ideal installation and for the same flow rate. The Strouhal number is the meter frequency non-dimensionalized using the pipe diameter and bulk-averaged velocity. The results shown in figure 12 indicate that the elbow effects produce negative shifts in Strouhal number for all installation positions between about 3 and 84 diameters downstream from the exit of the elbow. If a tolerance of ±0.1% within the ideal Strouhal value is selected as the performance objective, this meter in these conditions should be installed at or beyond the 25 diameter location downstream from the exit plane of the tee.

2. Downstream Of A Tee Used As An Elbow. Figure 13 presents the performance results for the selected turbine meter installed downstream from the tee. Again, the shifts in Strouhal number are negative relative to the ideal values. Although the largest negative shift observed downstream of and nearest to the tee is less than that for the elbow, the tee effects on this meter seem to produce larger shifts at the other positions tested. Therefore, it appears that the pipeflow perturbations that affect this meter are larger, initially, for the elbow, but diminish more rapidly as compared to those from the tee.

It should be emphasized that these turbine meter effects should be considered as specific to the selected meter. Undoubtedly, similar meters can be expected to behave similarly, but different designs may produce different results.

TUBE BUNDLE EFFECTS ON METER CALIBRATIONS

1. 19-Tube Tube Bundle. The 19-tube tube bundle shown in figure 2(a) is the concentric arrangement that is prevalently used in U.S. orifice metering practice. This unit is a geometrically scaled version of the shape used in large pipe sizes in U.S. industries such as gas, oil, petrochemical, etc. It is concluded, therefore, that when the pertinent, non-dimensional flow parameters used in the results described below match those in larger or smaller industrial pipelines the fluid flow phenomena will be predicted by our research results according to the scaling laws of dynamic similitude.[8]

The 19-tube tube bundle was installed downstream of the single elbow as shown in figure 3(a) and flowmeter performance was determined in numerous installation positions downstream. The distance downstream in pipe diameters from the tube bundle exit is denoted by C; the distance downstream from the exit plane of the elbow or tee is denoted by Z where

$$C = Z - 5.7 \tag{1}$$

a. Orifice Meter Results. Figure 14 presents beta = 0.363 orifice meter results for various installation locations downstream from the tee used as an elbow and the 19-tube tube bundle. The ordinate is the percentage change in discharge coefficient relative to the ideal value at the respective flow rate which is quantified using Reynolds number. These results show that both negative and positive shifts are produced in the discharge coefficient depending upon installation location. As noted before in the results obtained downstream of the single elbow and this tube bundle, when the orifice meter is near the exit of the tube bundle, the coefficient is about -0.3%. For installations at or beyond about 7 diameters downstream from the tube bundle exit, the discharge coefficient varies less than ±0.25% from the ideal value.

Figure 15 presents results similar to those described above but for the case beta = 0.5. Again a trend similar to that obtained for the single elbow is observed. It is noted here that to attain orifice meter performance in these conditions within the ±0.25% of the ideal value, installations should be at or beyond the 13 diameter location downstream of the tube bundle. However, at and near the 25 diameter location, discharge coefficients can exceed the ±0.25% tolerance level from the ideal value.

Figure 16 presents results similar to those described above but where beta = 0.75. Again trends similar to those obtained for the single elbow are shown. For the selected ±0.25% tolerance about the ideal values, this meter in these conditions should be located at or beyond the 13 diameter distance downstream of the tube bundle. However, again as noted above, the shift in discharge coefficient exceeds ±0.25% for installations between about 20 to 40 diameters downstream of the tube bundle.

b. Turbine Meter Results. Figure 17 presents results for the selected turbine meter installed downstream from the tee used as an elbow and the 19-tube tube bundle installed as shown in figure 3(a). These results show that this meter has Strouhal numbers lower than the ideal for all installation positions tested. These shifts decay in an essentially monotonic fashion with increased distance from the tube bundle. For this meter in these conditions to be within ±0.1% of its ideal performance values, it should be installed at or beyond the 13 diameter location downstream from this tube bundle.

2. 7-Tube Tube Bundle. A 7-tube tube bundle having the configuration shown in figure 2(b) was installed downstream of a tee as shown in figure 3(b) and a series of tests were made using orifice meters and a specific turbine meter geometry.

a. Orifice Meter Results. Figure 18 presents results for the percentage shifts in discharge coefficient for the beta = 0.363 orifice meter relative to the ideal values. These results contrast markedly with those obtained for the 19-tube tube bundle shown in figure 14. These 7-tube tube bundle results for this orifice meter and for these conditions show that discharge coefficients are shifted positively with respect to the ideal values. If the ±0.25% tolerance is used as above, these results indicate that this meter can be installed at or beyond the 9 diameter location downstream of this 7 tub tube bundle. This is judged to be a significant improvement over the corresponding results for the 19 tube tube bundle. This orifice meter shows no such "over-shoot" characteristics as observed previously, and this orifice meter asymptotically approaches the ideal values with downstream orifice installation distance, C.

Figure 19 presents results analogous to the above for the case beta = 0.50. Again, it is noted that, for these conditions, this orifice performance is greatly improved over that noted for the installations downstream from the 19-tube tube bundle. These results show that this meter can be installed at or beyond the 10 diameter location downstream of this tube bundle and tee configuration and the discharge coefficient will be within the ±0.25% tolerance of the ideal values.

Figure 20 presents results analogous to the above for the case beta = 0.75. Again it is shown that, for these conditions, this meter can be installed at or beyond the 14 diameter location and the discharge coefficient will be within the selected ±0.25% tolerance of the ideal values.

b. Turbine Meter Results. Figure 21 presents results obtained for the performance of the specific turbine meter tested downstream of the 7-tube tube bundle shown in figure 2(b) and installed as sketched in figure 3(b). These results show that the Strouhal number is shifted negatively relative to the ideal values at all positions downstream of this configuration. The performance of this meter shows that the largest shift in Strouhal number occurs for the installation closest to this tube bundle. From this extreme value the shift diminishes with downstream distance monotonically. If the ±0.1% tolerance is selected about the ideal values as the installation criteria, this meter should be installed at or beyond the 25 diameter location downstream of the tube bundle exit.

INTERCOMPARISONS OF METER EFFECTS WITHOUT TUBE BUNDLES

1. Orifice Meter. The above-described orifice meter results can be intercompared in several ways to illustrate the effects of Reynolds number, beta ratio, upstream piping arrangements, the different tube bundle geometries, etc. for the conditions tested. From these intercomparisons, orifice meter performance can be characterized and interpreted so that improved understanding and evaluation of orifice meter phenomena can be established and disseminated. In these ways, better installation specifications can thereby be achieved and these in turn should lead to better paper standards and to better orifice metering measurements.

Figures 22 and 23 present, respectively, the performances of a 0.75 beta ratio orifice meter installed at different locations as far as 84 diameters downstream from a single elbow and the tee used as an elbow. The three lines on each plot show different Reynolds numbers as indicated by the legends on the graphs. The central conclusion to be drawn from these intercomparisons is that the single elbow produces the greater shifts in discharge coefficient when this meter is installed very close to these pipeline elements. With the single exception of the results obtained for the meter installed very close to the tee, no significant differences are noted for Reynolds numbers of 45,000, 100,000, or the mean discharge coefficient taken over this flow rate range. For installation positions in the range of 10-20 diameters downstream from these configurations, the single elbow produces slightly larger negative shifts in discharge coefficient than the tee. The change of this orifice meter performance downstream of the tee is considered to be a more gradual, monotonic one, in that no significant "overshoot" region is found where the discharge coefficient changes shift from negative to positive. Perhaps these results are due to the fact that the smooth, long-radius turn of the elbow generates more organized and more energetic secondary vortices with reduced turbulence. This can be considered fortuitous for orifice meter users in that this tee used as an elbow configuration also affords convenient access to the pipeline between the tee and the meter. This access can be very handy for meter inspection or for changing or installing flow conditioners.

Figures 24-26 present, respectively, the orifice meter performances of all three beta ratios at the single flow condition of Re = 45,000 for downstream installation positions from the single elbow, the tee, and the closely coupled double elbows out of plane. If the ±0.25% tolerance is used about the ideal values, a set of installation specifications for these conditions can be given for the different beta ratios for this test condition; these are given in table 1. These pipe lengths are minimal upstream lengths, in diameters, between the exit plane of the fitting and the orifice plate, and ample pipe lengths (i.e. greater than ten diameters) are used between the orifice plate and the closest downstream fitting which is an elbow.

TABLE 1. MINIMAL INSTALLATION LENGTHS (IN DIAMETERS) WITHOUT THE 19-TUBE BUNDLE FOR THE RESPECTIVE TEST CONDITIONS (RE = 45,000). CRITERIA IS ±0.25% OF IDEAL VALUES.

Configuration	Beta Ratio		
	0.363	0.50	0.75
Single Elbow	7	14	22
Tee used as an elbow	7	15	30
Closely Coupled Double Elbows Out Of Plane	35	45	58

The results presented in figures 24 and 25 indicate that the largest beta ratio meter has the largest negative shift when installed about 2.5 diameters downstream from the elbow. The other meter geometries are affected about the same in this installation position. It is noted from the above tabulation that the tee and the single elbow produce essentially the same effects on the two smaller beta meters. However, the largest beta meter requires additional separation distance from the tee to attain discharge coefficients with the ±0.25% tolerance of the ideal value. It is also noted that the closely coupled double elbows out of plane configuration requires very long lengths of piping for all three beta ratios to dissipate the effects of this configuration on orifice meters. It is also noted from figure 26 that the effects produced on the largest beta meter by the flow from this configuration shift this meter differently from the shifts recorded for the smaller beta meters. This can be interpreted using previous LDV results for the time-averaged velocity and swirl profiles produced downstream of this piping configuration[7].

The definition of the orifice discharge coefficient for an incompressible fluid is:

$$C_d = \frac{Q_{actual}}{Q_{theoretical}} \propto \frac{1}{(\Delta P)^{1/2}} \tag{2}$$

where ΔP is the upstream to downstream pressure difference measured at the respective tap locations. This pressure difference can be considered to be the sum of three contributions.

1. that due to the ideal, pipe flow as produced by long straight lengths of constant diameter piping,
2. that due to the effects of single eddy swirl, and
3. that due to the streamwise velocity profile effects on the respective meter.

By considering the signs of these perturbations on C_d for the particular swirl and velocity, one can explain the orifice performance shown in figure 26. The effect of the streamwise velocity profile on ΔP can be interpreted in terms of the uniformity of the profile. If a pipeflow profile is more uniform than the ideal distribution, then ΔP is increased, i.e., $\Delta P_{\text{velocity profile}} > 0$. This would tend to shift C_d negatively, as noted in (2). The effect of single eddy swirl can be assessed using angular momentum considerations and the associated radial distributions of pressure. Angular momentum, S about the pipe centerline can be defined as

$$S = \rho R V \tag{3}$$

where, in compatible units, ρ is the fluid density, R is the radial position from the centerline, and V is the velocity component perpendicular to the radial position. The radial pressure distribution associated with rotational motion is

$$P \sim \frac{V^2}{R} = \frac{S^2}{\rho^2 R^3} \tag{4}$$

from equation (3). Therefore, for single eddy swirl passing through the orifice meter, the swirl-produced pressure difference transmitted through the fluid to the taps will be

$$\Delta P_{swirl} \sim \frac{S^2}{\rho^2}\left[\frac{1}{R^3_{upstream}} - \frac{1}{R^3_{downstream}}\right] \tag{5}$$

where the R's refer to the sizes of the single eddy upstream and downstream of the orifice plate. Since the size of the single eddy swirl pattern upstream of the orifice plate is approximately the radius of the pipe and the size downstream approximates the radius of the hole in the plate, ΔP_{swirl} is a sensitive function of beta ratio and

$$\Delta P_{swirl} < 0 \tag{6}$$

This would tend to produce positive shifts in C_d thus explaining the very large ordinates for the smallest beta ratio and for positions closest to the double elbows out of plane configuration.

The negative shifts in C_d shown in figure 26 for the largest beta are interpreted to be due to velocity profile effects being dominant over swirl effects for these conditions. These negative shifts for the largest beta meter diminish with downstream distance and become positive. This could be interpreted to be due to swirl effects becoming dominant over the effects of velocity profile at these downstream distances. This could occur where the dissipation of single eddy swirl is slower than the dissipation of the uniformity of the streamwise velocity profile.

Figures 27-29, respectively, present orifice meter performance for specific beta ratio and flowrate at different downstream positions from the single elbow, the tee, and the double elbows out of plane. Error bars are placed on the points to show the standard deviations of the five (5) repeat determinations about the mean values. In figure 27, the scatter shown by these error bars is largest for the smallest beta ratio when this meter is installed closest to the double elbows out of plane configuration for the flowrate of Re = 45,000. This undoubtedly is the result of the complicated nature of the helical, single eddy swirl pattern, the high levels of turbulence, and the geometry of this meter in these conditions and positions.

Figure 28 shows that for the 0.5 beta ratio meter, the single elbow produces larger negative shifts in discharge coefficient than found downstream of the tee at the flowrate of Re = 74,000.

Figure 29 shows that for the 0.75 beta ratio meter at Re = 100,000, the shifts in discharge coefficient downstream from the single elbow are negative and greater in magnitude than those for the tee when this meter is installed very close to these fittings. Further downstream, larger negative shifts in discharge coefficient occur for the tee. The effects of the double elbow configuration are found to be less severe than from the single elbow or tee for installations close to these fittings. However, for installation positions between 25 and 50 diameters from the double elbow configuration, this meter has slightly larger negative shifts than the other two configurations.

Figures 27 and 28 both show clearly the large positive shifts in discharge coefficient for the two smaller beta ratio meters for installation positions close to the double elbows out of plane configuration. These are largest for the smallest beta meter thus confirming the interpretation given above via eqns. (6) and (2). The explanation for these shifts is the dominant effect of the single eddy swirl effects which tend to reduce the differential pressure between these taps.

2. Turbine Meter. Figure 30 shows that the different types of swirl produce very different effects on this turbine meter, see references [1-4]. These data are presented with error bars denoting the standard deviations of the repeated results about the respective mean values. The single eddy swirl produced by the closely coupled double elbows out of plane configuration is the cause of the significant positive shifts in Strouhal number. These shifts reach almost 2% for installation close to the double elbow configuration. These elevated values of Strouhal number persist with successive downstream installation positions so that shifts of 0.1% are present as far downstream as 125 diameters for these conditions. Accordingly, for turbine meters having this or similar designs operating at higher Reynolds numbers, it can be expected that such effects would persist even farther for pipe smoothness to match or exceed that for the pipes tested. Conversely, it can be expected that for Reynolds numbers less than 10^5 or for larger relative roughness pipe conditions, the 125 diameter separation could be reduced.

It is concluded from figure 30 that this turbine meter tends to average the effects of the dual eddy swirl patterns produced by the single elbow and tee configurations. Figure 30 also shows that larger negative shifts in Strouhal number are found for this meter installed close to the elbow as compared to the tee used as an elbow. For successive downstream positions, these results show that similar shifts occur for both the elbow and the tee.

DOWNSTREAM VARIATIONS OF TUBE BUNDLE EFFECTS ON ORIFICE METERS

1. 19-Tube Tube Bundle. The 19-tube tube bundle was installed in the piping downstream from the exit plane of the single elbow, the tee used as an elbow, and the closely coupled double elbows out of plane as shown in figure 2. Figures 31-33, respectively, present results obtained, for the single flow rate Re = 45,000, for the three beta ratio orifice meters installed downstream from these three configurations. The abscissa "C" is the separation in diameters between the exit plane of the tube bundle and the orifice meter. These results can be compared with figures 24-26 which are similar orifice test results without the tube bundle and where equation (1) interrelates C and Z. The results in figures 31-33 show that the 19-tube tube bundle installed in these conditions produces qualitatively similar effects on these orifice meters. The flow from this tube bundle has essentially removed the swirl produced by these configurations [1,7]. This flow also exhibits the expected effects of the tube bundle both in the time-averaged streamwise velocity profiles and also in the turbulence profiles. The time-averaged streamwise velocity profiles measured close to the tube bundle exit show the jetting flows from individual tubes. The turbulence profiles in these locations show the intense mixing produced both by the blockage effects of the tube bundle geometry and by the interactions between these jetting flows. The combination of these effects produces increased uniformity of the streamwise velocity profiles. These produce negative shifts in the discharge coefficients which are largest for the largest beta ratio. These negative shifts diminish as greater separation distances are arranged between this tube bundle and the orifice meter.

For each of the conditions shown in figures 31-33, the orifice discharge coefficients increase from the maximum negative shifts measured nearest the tube bundle to attain a zero shift condition that can be termed a "cross-over" point. This cross-over point occurs, for our conditions, between C = 9 to C = 18 for this range of meters. At this point the performance of the largest beta ratio meter changes radically with the variable, C. Following the cross-over point the orifice discharge coefficients attain positive shifts with maximum values for the largest beta ratio meter. It is noted that for the smallest beta ratio, the positive overshoot condition is within the ±0.25% tolerance of the ideal values.

It is recalled from figures 24-26 that the ±0.25% tolerance of the ideal discharge coefficients could be selected to define minimal installation lengths from these piping configurations as given in table 1. When the 19-tube tube bundle is installed as shown in figure 2(b), the minimal installation lengths downstream from the tube bundle for the ±0.25% tolerance are given in table 2. This shows that the overshoot conditions produced by the effects of the tube bundle can produce complicated installation specifications for medium or large beta orifice meters. In table 2 for the 0.5 or 0.75 beta ratio meters installed downstream of the tube bundle and the single elbow or the tee, a minimum length of 40 diameters is required to insure that any further installation position conforms to the ±0.25% tolerance. These lengths are considerably longer than the counterparts given in table 1. On this basis, it is concluded that this tube bundle in these test conditions appears to produce more installation problems i.e., discharge coefficients in excess of the ±0.25% tolerance, than it solves. It is only for the small beta meter installed downstream of these configurations with this tube bundle that it has the desired effect of shortening the minimal lengths. It is also noted that for installations of the largest beta meter downstream of the double elbow configuration this tube bundle can save some 10 diameters of upstream pipe length.

TABLE 2. INSTALLATION LENGTHS (IN DIAMETERS) WITH THE 19-TUBE TUBE BUNDLE FOR THE RESPECTIVE TEST CONDITIONS (RE = 45,000). CRITERIA IS ±0.25% OF IDEAL VALUES.

Configuration	Beta Ratio		
	0.363	0.50	0.75
Single Elbow and tube bundle	6 4	8-15 or >40	12-17 or >40
Tee used as an elbow and tube bundle	4	8	12-18 or >40
Closely Coupled Double Elbows Out Of Plane and tube bundle	5	12	10-13 or >48

2. 7-Tube Tube Bundle. Results for the 7-tube tube bundle, installed in the piping downstream from the tee used as an elbow as shown in figure 2(b), are shown in figure 34. These indicate marked differences in contrast to the 19 tube tube bundle results shown in figure 32. Judging from these results, the 7-tube tube bundle apparently produces, initially, time-averaged, streamwise velocity profiles

that are less uniform than those from the 19-tube tube bundle. This would tend to produce the positive shifts in discharge coefficient noted in figure 34 for installations near this tee and 7 tube tube bundle. While large positive shifts are found, especially for the largest beta ratio, these shifts quickly reduce to zero for the two smaller beta meters. The largest beta meter is found to overshoot the zero percent change line to give a shift of -0.5% when this meter is installed 8 diameters downstream from the 7-tube tube bundle. The smallest and medium beta meters show that this flow conditioner produces only small positive shifts in discharge coefficient for installations close to the 7-tube tube bundle and for installations further downstream these meters have essentially zero shift in discharge coefficient.

This orifice meter performance indicates very promising flow conditioning capabilities for this tube bundle in these conditions. It is expected that the pipeflow exiting this tube bundle rapidly recovers from the velocity distributions generated downstream to produce profiles which closely approximate those for fully developed, equilibrated pipe flow which occurs in ideal installation conditions.

INTERCOMPARISONS OF METER EFFECTS WITH TUBE BUNDLES

1. Orifice Meter. Figures 35-37 show, respectively, the three beta ratio orifice meter performances at specific flow rates downstream of the single elbow, the tee used as an elbow and the closely coupled double elbows out-of-plane configurations followed by the 19-tube tube bundle installed as shown in figure 2(b). Also shown is the tee followed by the 7-tube tube bundle installed as shown in figure 2(c).

Figure 35 shows that, for small beta orifice meters and flow conditions denoted by Re = 45,000, the 19-tube tube bundle initially shifts orifice meter discharge coefficients negatively when they are installed close downstream. Following these situations there is an extended range of installation positions where small but positive shifts in discharge coefficient occur. Following this region, at around 50 diameters downstream from these tube bundles, the orifice discharge coefficients have essentially the ideal values.

Figure 35 shows trends different from that described when the 7 tube tube bundle is used. Within ten diameters from this conditioner, this meter in these conditions has discharge coefficients within ±0.1% of ideal values.

Figure 36 shows that the above-described trends for the smallest beta ratio meter are duplicated for the 0.5 beta meter for Re = 74,000. Again, the 7-tube tube bundle achieves desired performance of ±0.25% from ideal values within ten diameters of separation distance between meter and this tube bundle.

Figure 37 shows the above-described trends for the 0.75 beta ratio meter and flow rate of Re = 100,000. Within about 12 diameters of separation between the exit plane of the 7-tube tube bundle, this meter attains the desired performance levels of ±0.25% of ideal values. This is not the case for the more conventional, 19-tube tube bundle.

2. Turbine Meter. Figure 38 presents results for the turbine meter for flowrate specified by Re = 100,000 installed downstream of the single elbow, the tee, and the closely coupled double elbows followed by the 19-tube tube bundle. Also shown for these conditions is the tee followed by the 7-tube tube bundle. These results show that, for the elbow and the tee with both tube bundles, negative shifts are

obtained for installation positions less than 30 diameters downstream. The small positive shifts in Strouhal number observed for this meter installed downstream of the double elbow configuration followed by the 19-tube tube bundle is interpreted to be due to the streamwise velocity profile or to low levels of swirl passing through or around this tube bundle or both.

CONCLUSIONS

The most important general conclusion to be drawn from the meter performance characteristics observed in this research program to date is that the fluid mechanical features of the pipe flows entering these meters and the sensitivities of the meter geometries to these flow features are the critical elements needed to interpret and to explain observed results. Furthermore, it is concluded that, before satisfactory paper standards are produced for flow meters, more detailed investigations of pipe flow phenomena and of meter sensitivity to such phenomena have to be done. It is apparent that in conducting such investigations, the efficiencies afforded by the concepts of dynamic similitude should be used. This could be done by using experimental results to validate that such parameters as Reynolds number and relative pipe roughness are the pertinent ones to predict the salient features of pipe flows. Following this, experimental programs should be arranged so that realistic ranges of these parameters are used to span the practical intervals of interest or that permitted by available funding. In this way, the technical results produced should cost-effectively substantiate the paper standards generated and the associated practical applications to actual meter installations.

The pipeflows produced downstream of the single, long radius elbow and the tee used as an elbow, for the conditions tested, shift the discharge coefficients of orifice meters negatively from ideal values. The magnitudes of these shifts depend on beta ratio. These negative shifts are interpreted to be due to the uniformity of the streamwise velocity profiles that exit these configurations. With increased installation position downstream of these configurations, the orifice discharge coefficients monotonically approach the ideal values. Specific installation conditions can be determined from these shift distributions after tolerances about the zero-shift levels are chosen.

The closely coupled, double elbows out of plane configuration produces complicated pipe flows which can shift orifice meters positively or negatively depending upon specific conditions. It is concluded that single eddy swirl effects i.e., axial vorticity, and the streamwise velocity profile effects can produce oppositely signed shifts in orifice discharge coefficients. The shifts observed indicate positive or negative shifts depending upon meter geometry and test conditions.

For the specific turbine meter design, and for the conditions tested, the long-radius single elbow and the tee used as an elbow produce pipe flows which shift the meter's Strouhal number negatively from ideal values. These shifts diminish monotonically with increased distance from these configurations. The single eddy flow from the double elbow configurations causes significant and very long lasting positive shifts in this turbine meter Strouhal number.

The effects of tube bundles installed upstream of this range of orifice meters and this specific turbine meter design are assessed via the performance characteristics of these meters. It is concluded that both the 19-tube and the 7-tube tube bundles reduce the swirl patterns from all of these piping configurations to very low levels. However, it is also concluded that the blockage effects by these different tube bundle arrangements can produce different flow profile development patterns.

It is concluded that the 19-tube tube bundle removes swirl and produces a very uniform profile of the streamwise velocity component. Additionally, it produces high levels of turbulence associated with both the mixing of the jetting flows out of the small tubes and also the blockage effects of the particular arrangement of tubes. Initially, this causes negative shifts in orifice discharge coefficients with magnitudes dependent upon beta ratio. With downstream distance, these uniform velocity profiles over-develop to produce core flows at and near the center of the pipe that flow faster than the velocities predicted by the fully developed pipe flow distribution. This results in positively shifted discharge coefficients with magnitudes again dependent upon beta ratios.

It is concluded that the 7-tube tube bundle produces a pipeflow pattern that is very different from that of the 19-tube arrangement. The orifice discharge coefficient pattern is very different in that only very short lengths of pipe are required between this tube bundle exit and the orifice meter to produce the ideal values. This pipeflow should be investigated using LDV to provide the explanation for this orifice performance.

These tube bundle geometries do not seem to significantly alter the negative Strouhal number shift patterns for this turbine meter design for installations downstream from the tee and the single elbow. Meter installations downstream of these configurations indicate negative shifts in Strouhal number. For installations downstream of the double elbow configuration followed by the 19-tube tube bundle the Strouhal shift is positive but much smaller than that observed without the tube bundle.

ACKNOWLEDGMENT

The authors acknowledge the technical assistance for these experiments provided by Mr. B. L. Shomaker and the secretarial efforts of Mrs. G. M. Kline in preparing this report.

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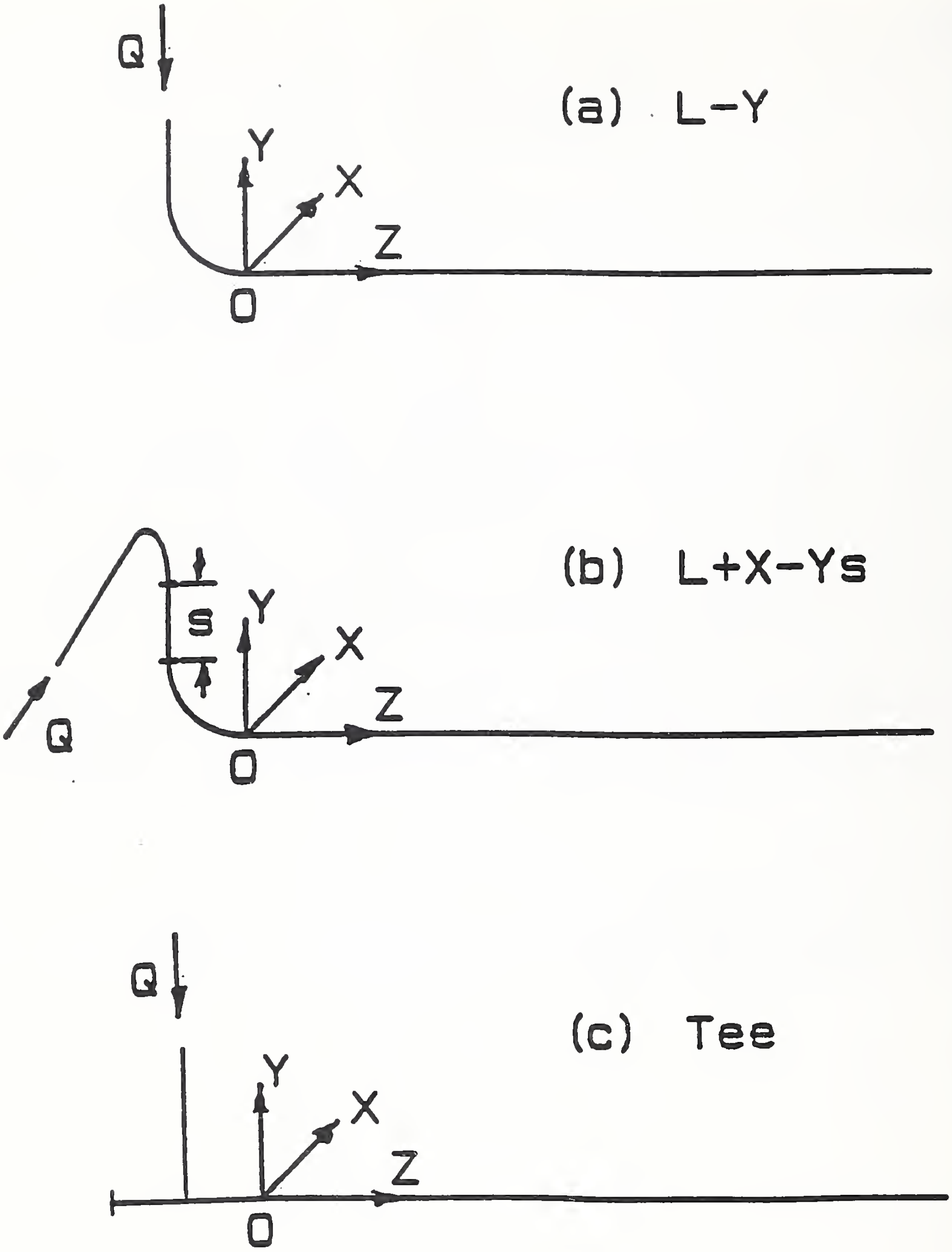
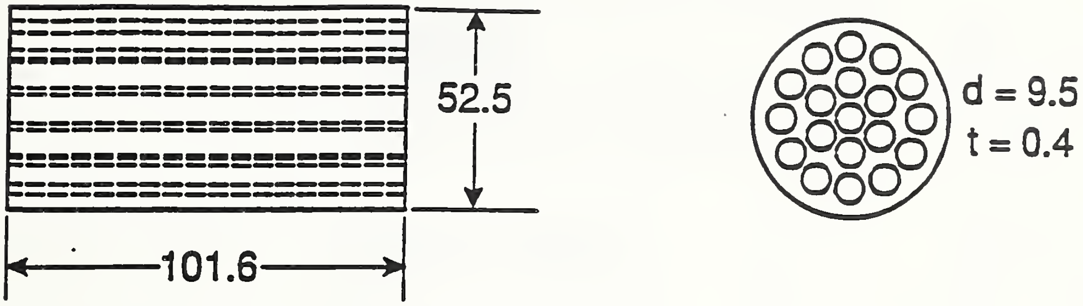
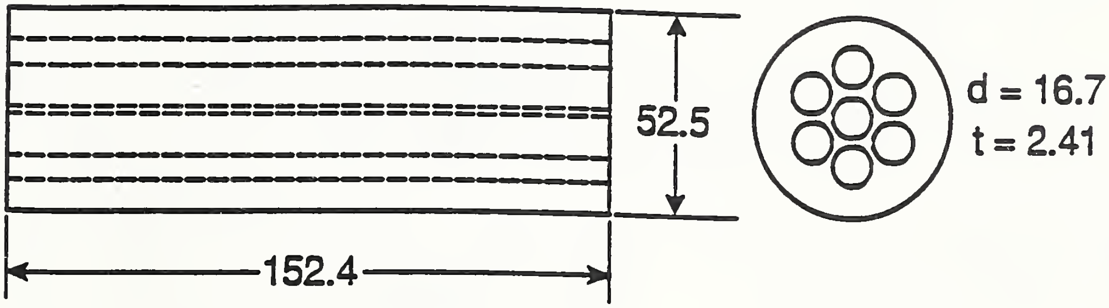


Figure 1 Sketches of Piping Configurations and the Coordinate Systems Selected. (a) Single Elbow, (b) Double Elbows Out-Of-Plane, and (c) Tee Used-As-An-Elbow.

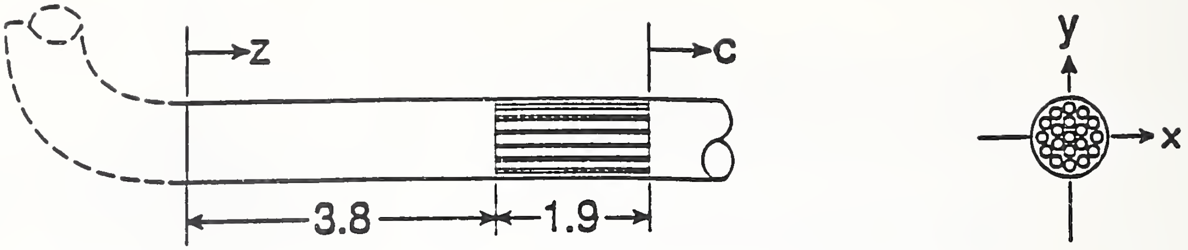


(a) 19 tubes

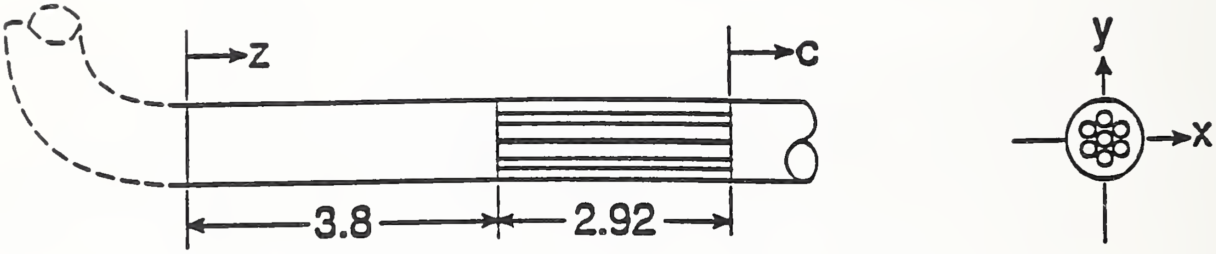


(b) 7 tubes

Figure 2 Sketches of Tube Bundle Geometries. Dimensions are given in millimeters. Tube Diameter is Denoted "d"; Tube Wall Thickness is Denoted "t". (a) 19 Tube, Concentric Pattern, and (b) 7 Tube.



(a) 19 tubes



(b) 7 tubes

Figure 3 Sketches of Tube Bundle Installations Downstream of Pipeline Elements. The Single Elbow, Shown Dashed, Exemplifies all of the Pipeline Elements Tested.

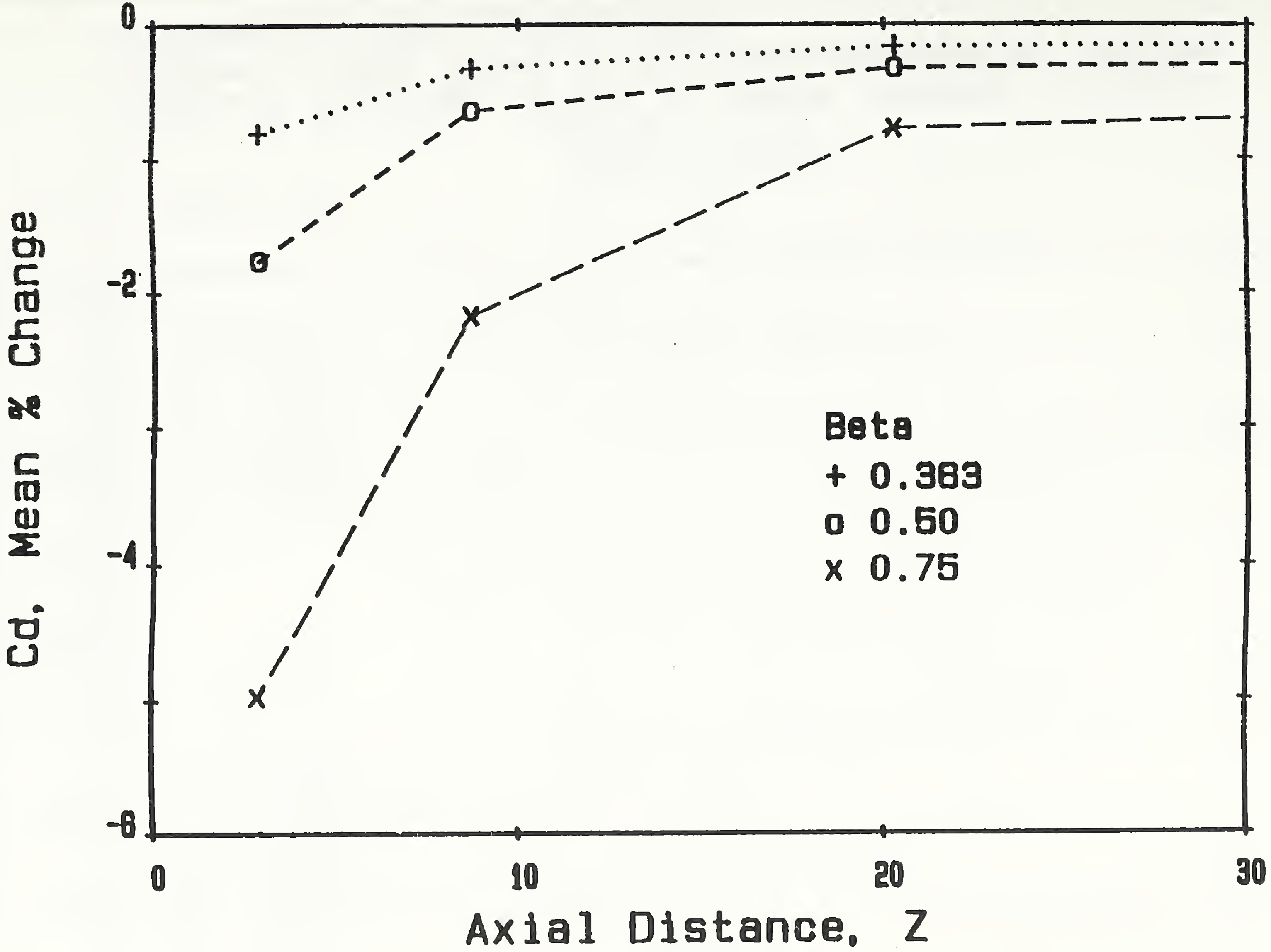
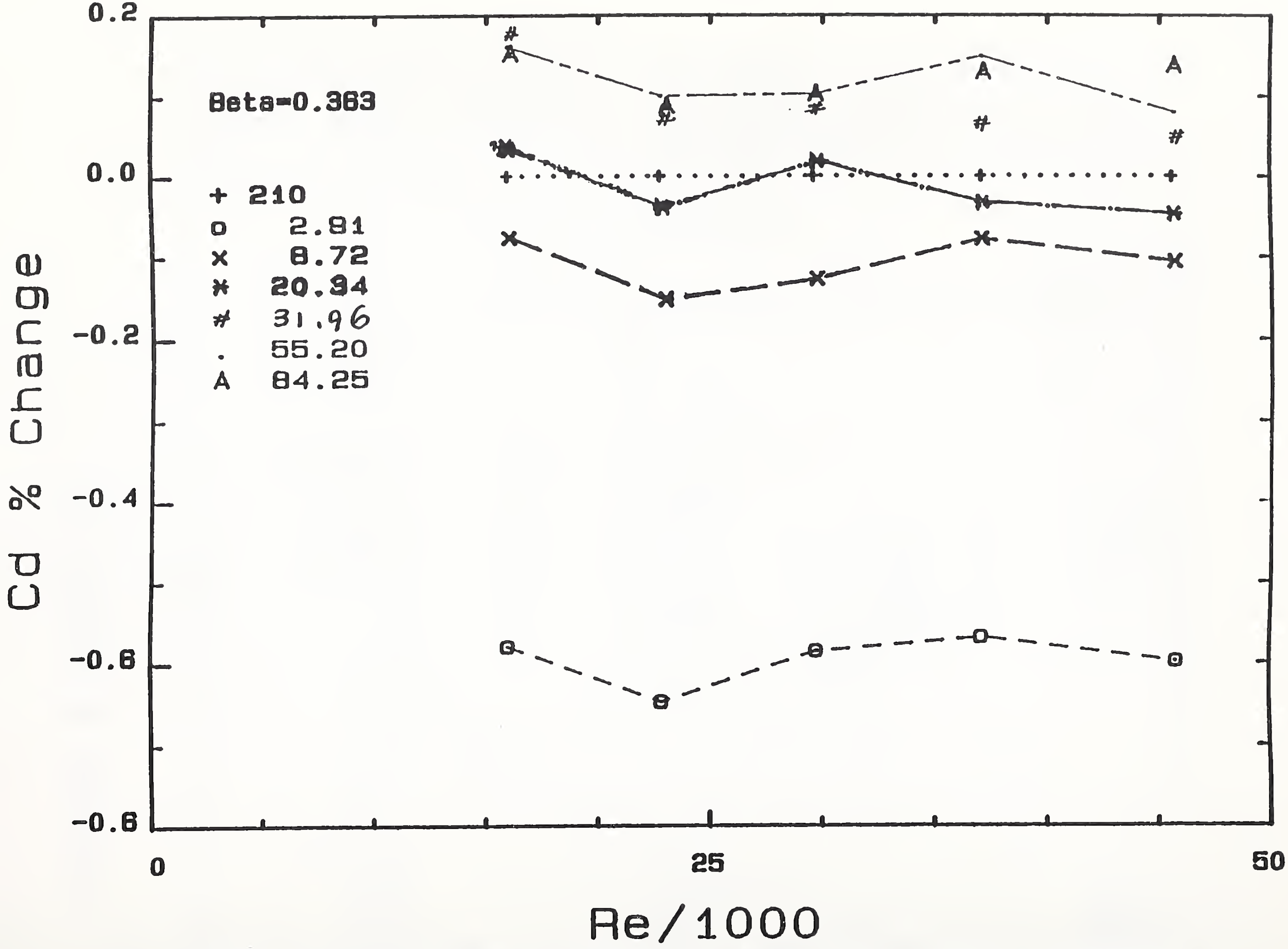


Figure 4 Averaged Orifice Meter Discharge Coefficient Changes Relative to Ideal Values For Different Positions Downstream Of A Single Elbow. Averages are for Flowrate Ranges: (+) β = 0.363, 14,000 $\leq$ Re $\leq$ 45,000; (0) β = 0.50, 25,000 $\leq$ Re $\leq$ 80,000; (X) β = 0.75, 40,000 $\leq$ Re $\leq$ 100,000.



<u>Figure 5</u> Percentage Change in Orifice Discharge Coefficient Relative to Ideal Values at Respective Flowrates for Different Locations (Z) from a Single Elbow.

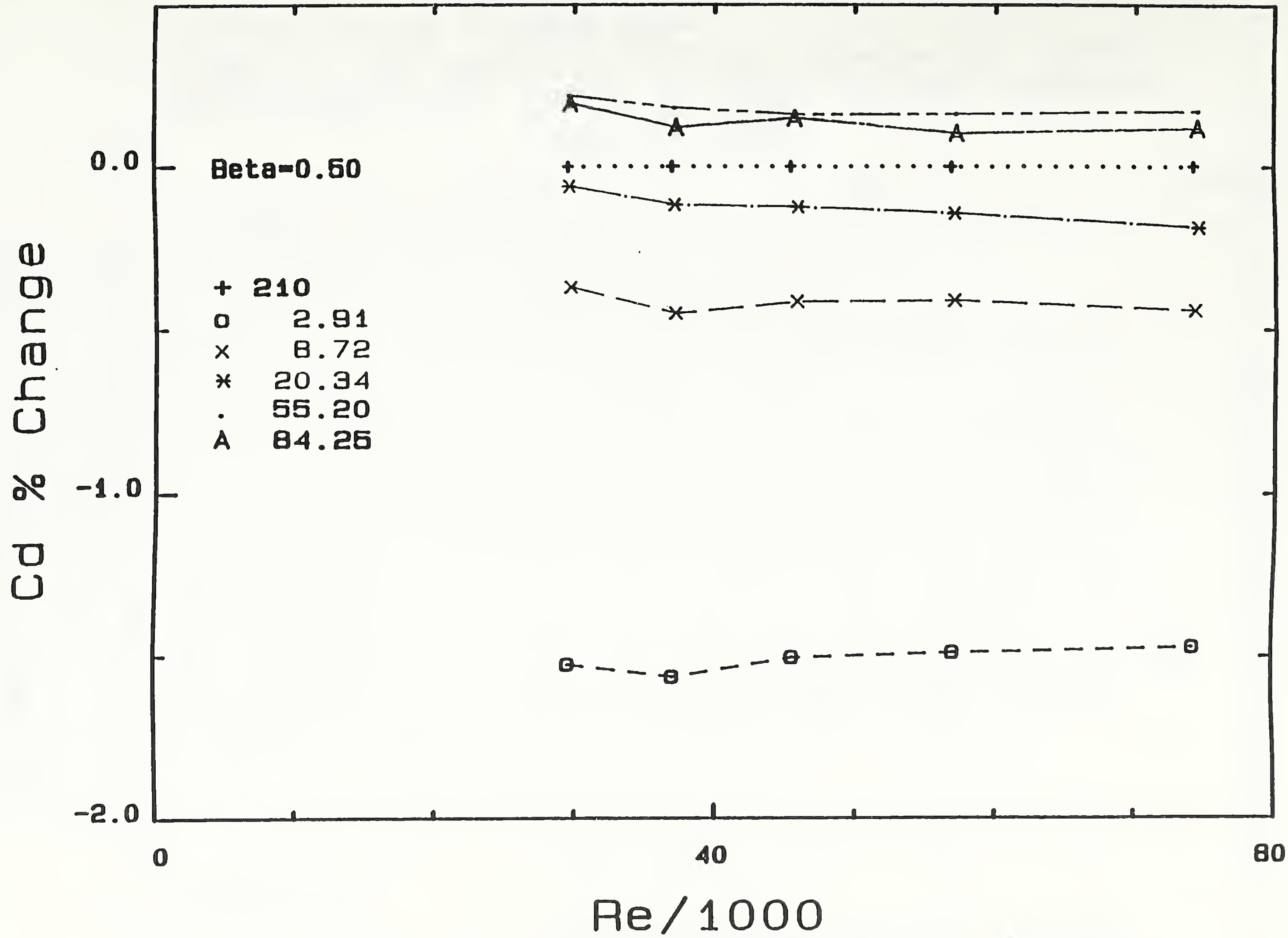


Figure 6 Percentage Change in Orifice Discharge Coefficient Relative to Ideal Values at Respective Flowrates for Different Locations (Z) from a Single Elbow.

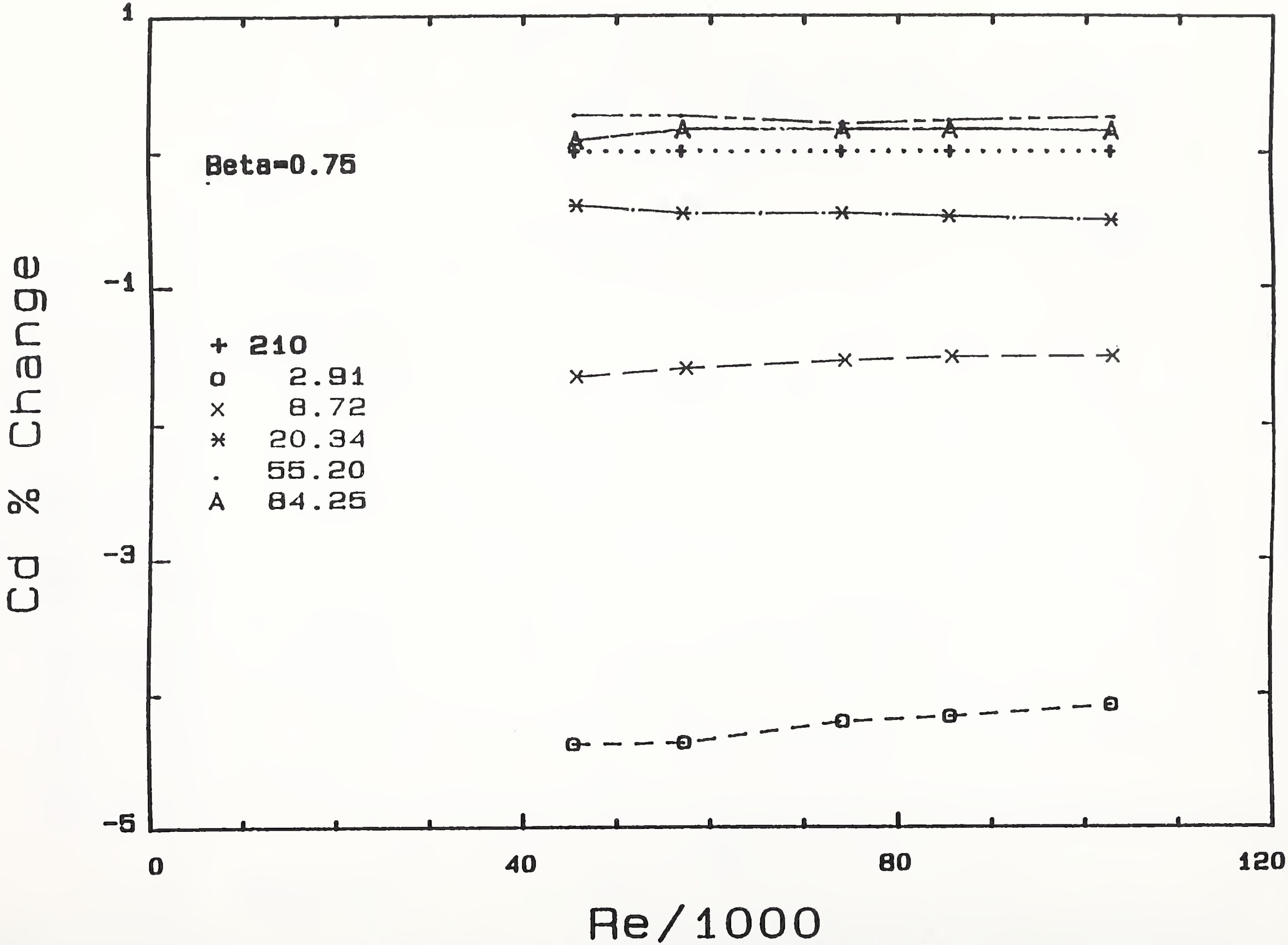


Figure 7 Percentage Change in Orifice Discharge Coefficient Relative to Ideal Values at Respective Flowrates for Different Locations (Z) from a Single Elbow.

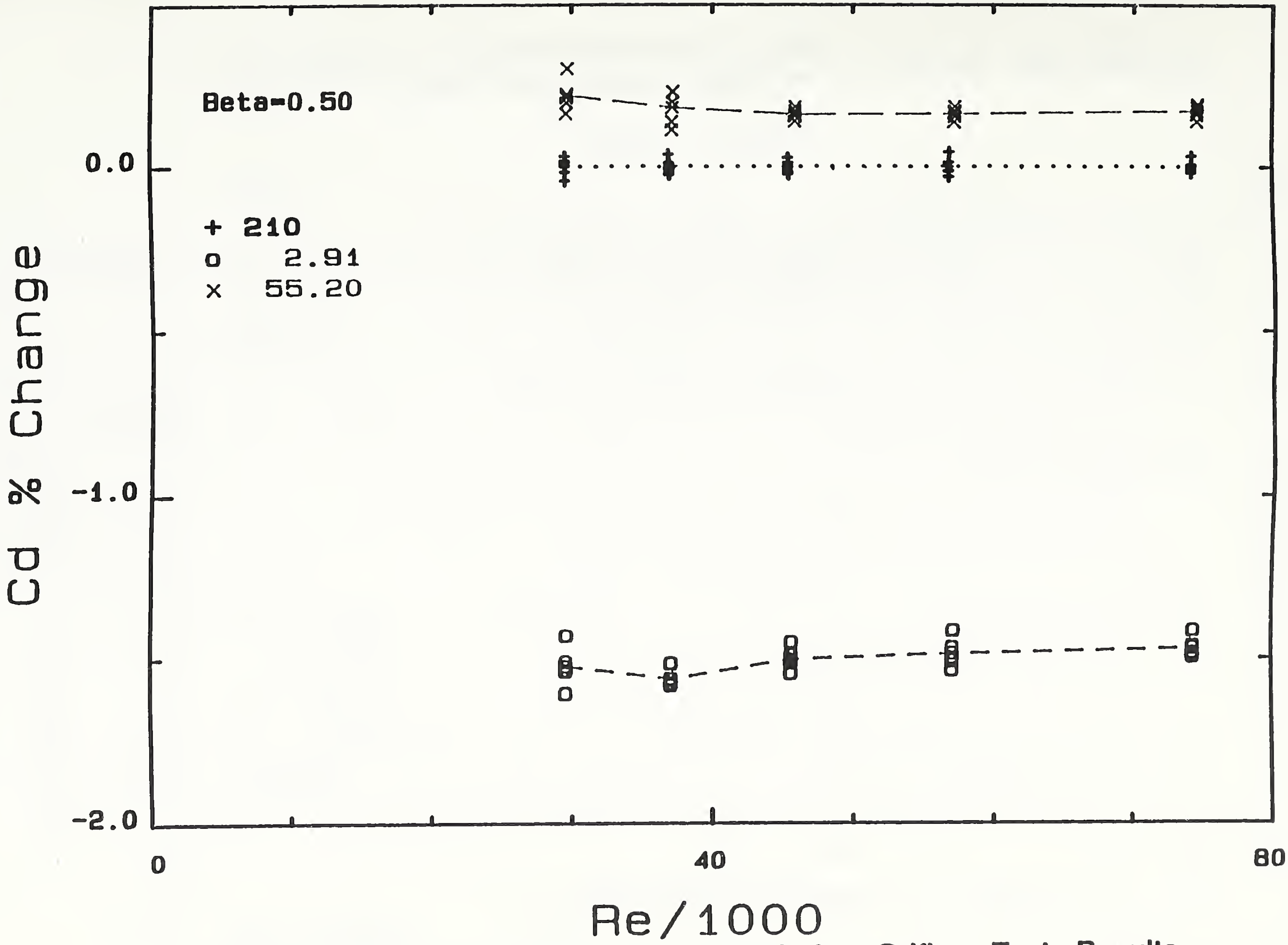
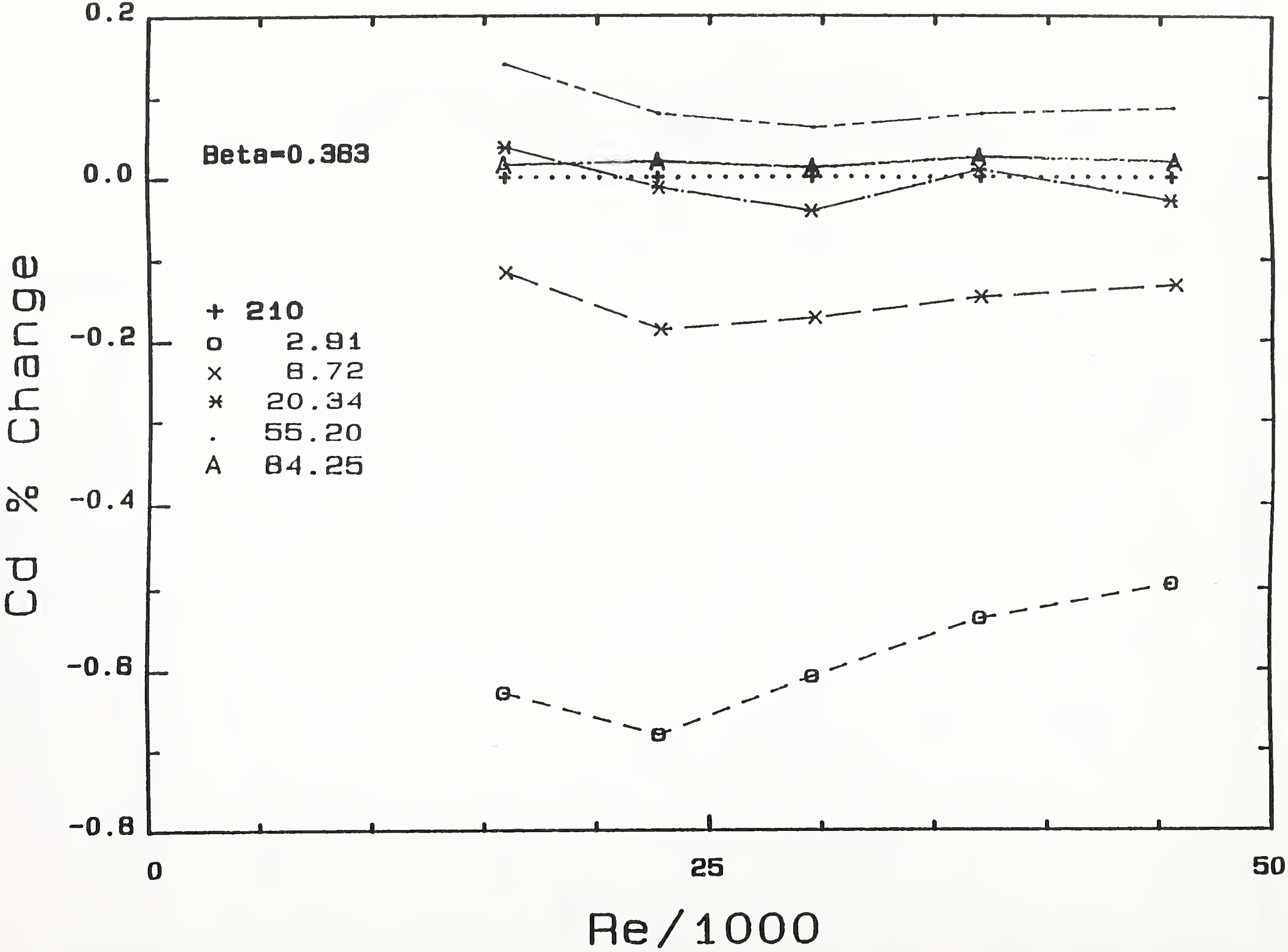
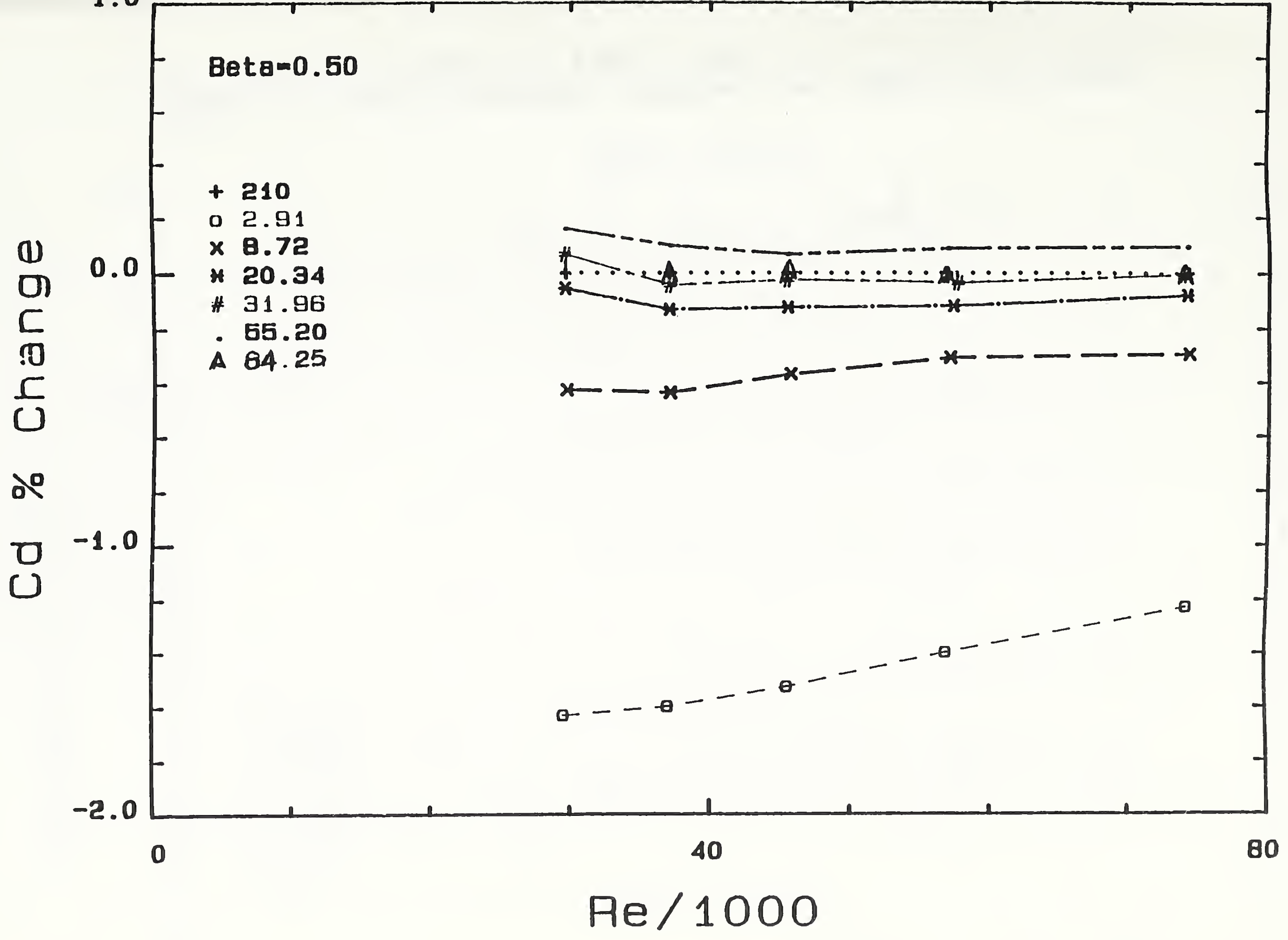


Figure 8 Typical Imprecision Obtained for Orifice Test Results for Different Locations (Z) from a Single Elbow.



<u>Figure 9</u> Typical Imprecision Obtained for Orifice Test Results for Different Locations (Z) from a Tee.



<u>Figure 10</u> Typical Imprecision Obtained for Orifice Test Results for Different Locations (Z) from a Tee.

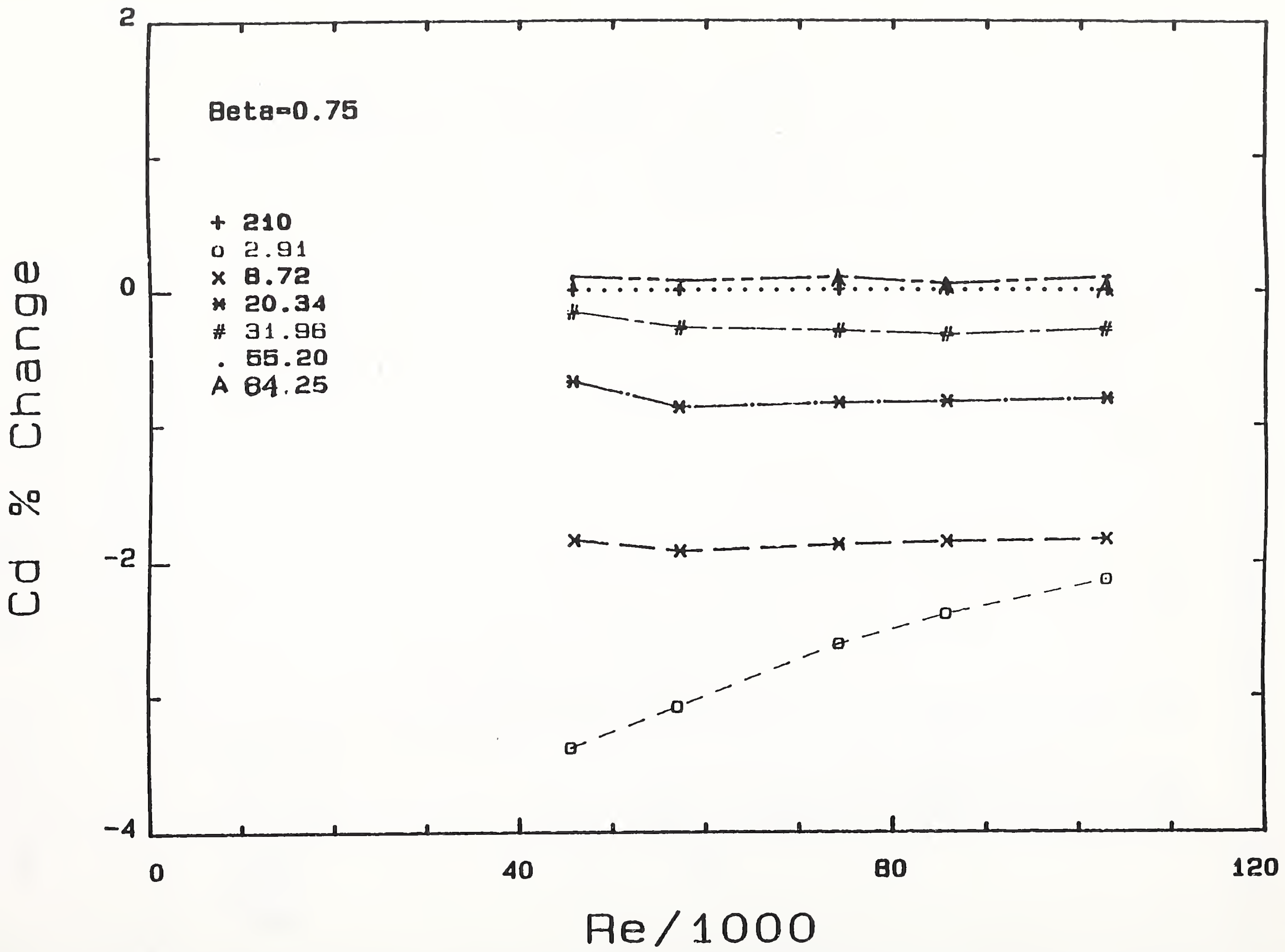
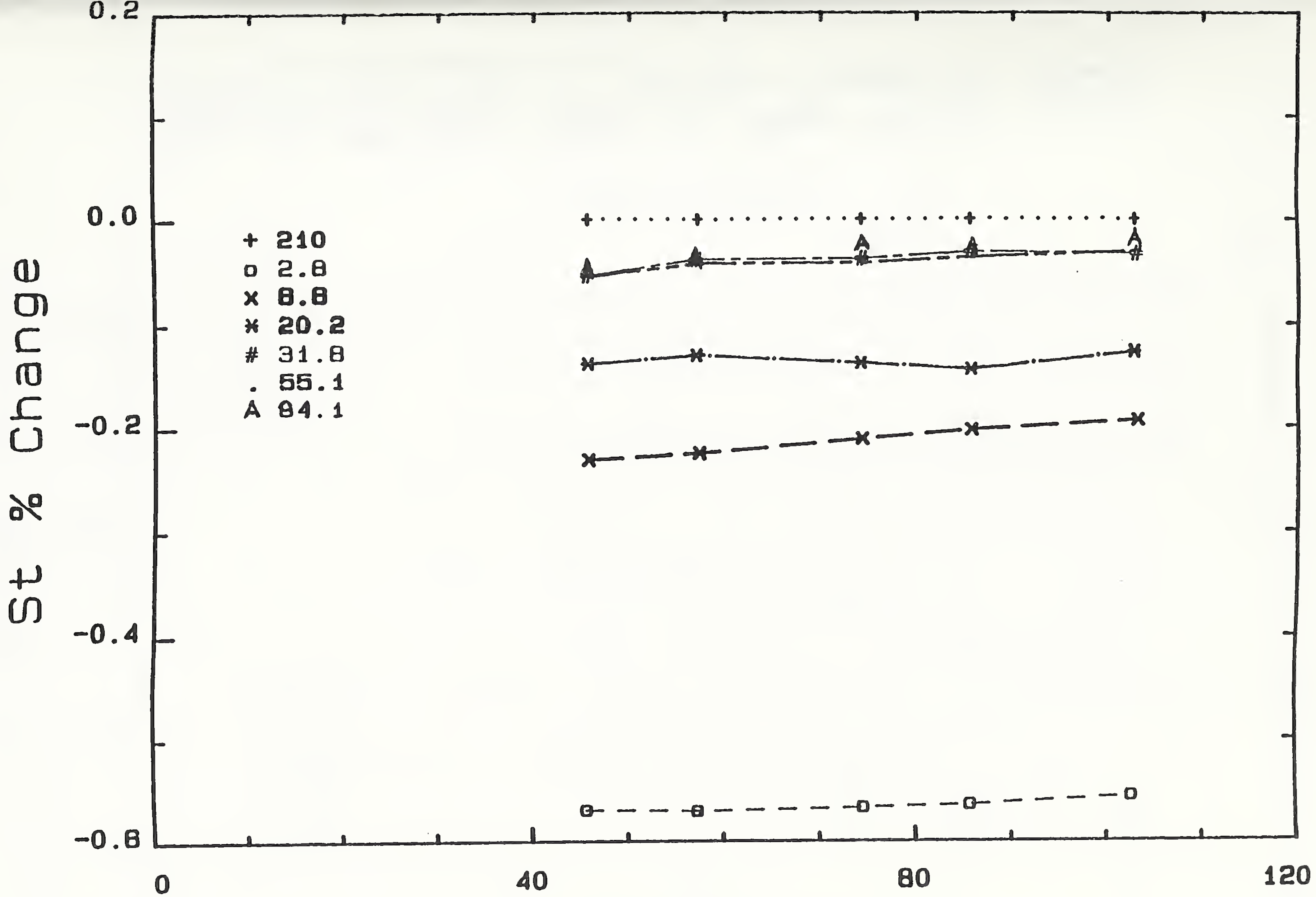


Figure 11 Typical Imprecision Obtained for Orifice Test Results for Different Locations (Z) from a Tee.



<u>Figure 12</u> Percentage Change In Turbine Strouhal Number Relative to Ideal Values at Respective Flowrates for Different Locations (Z) Downstream from a Single Elbow.

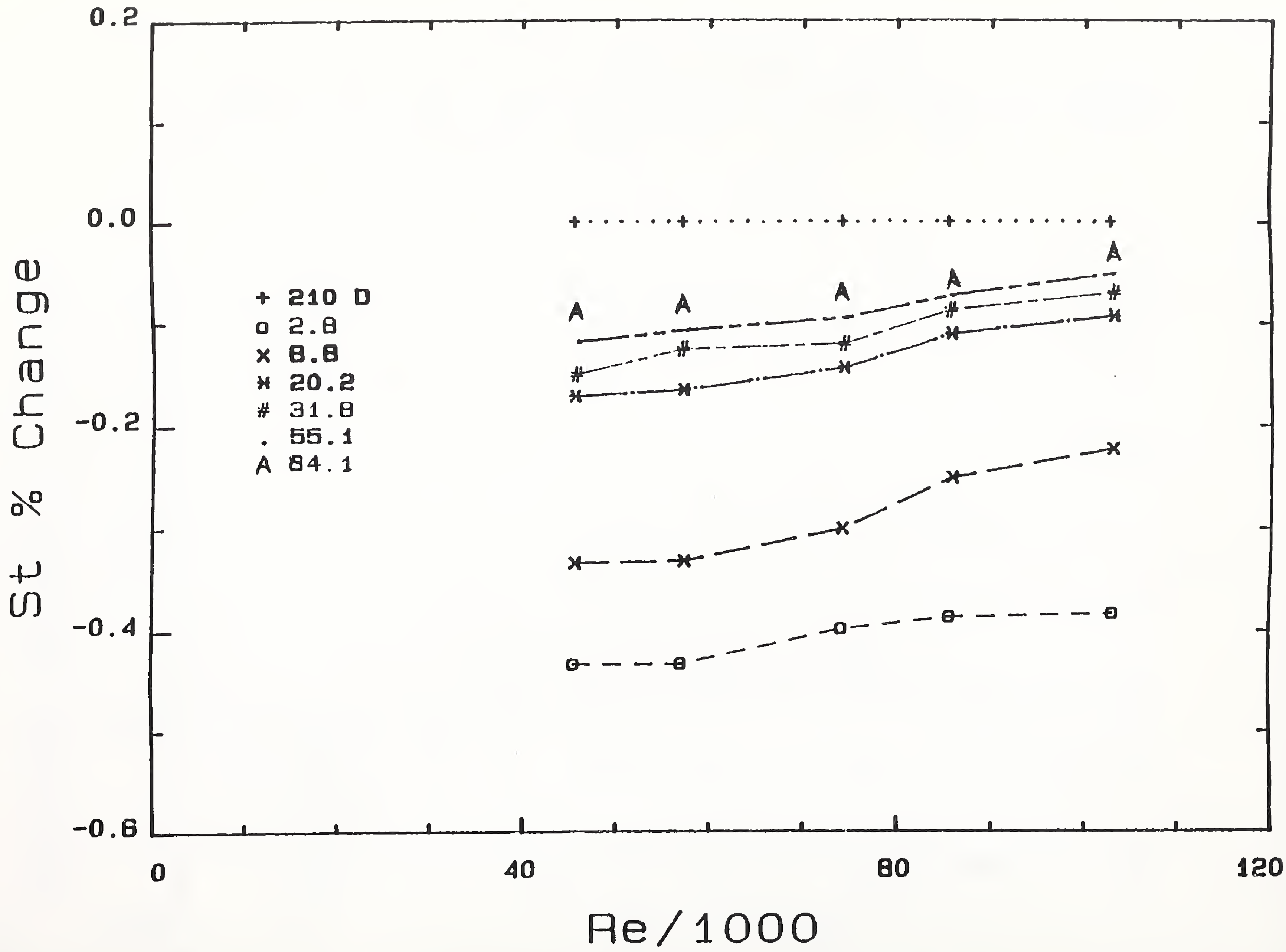
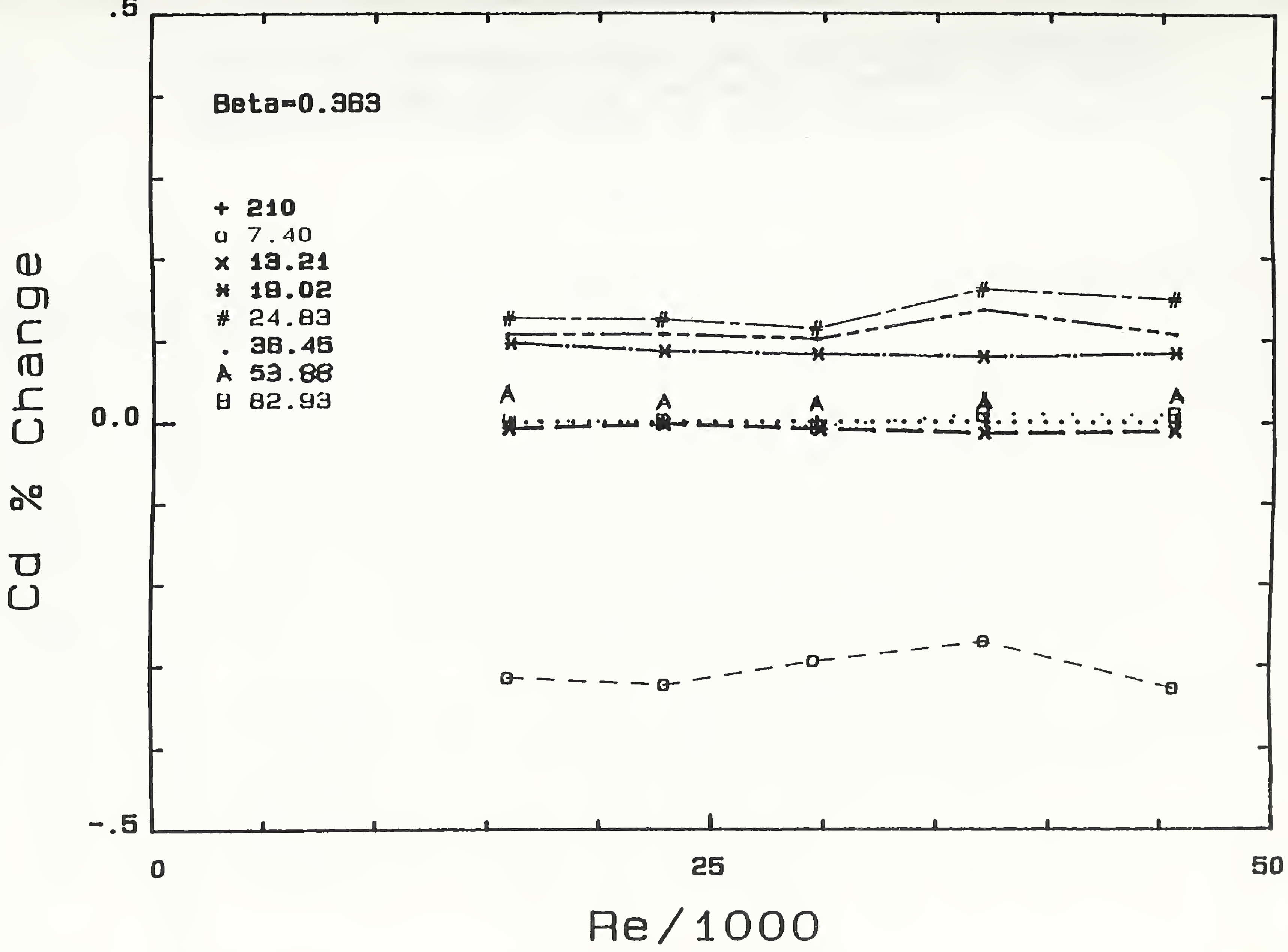


Figure 13 Percentage Change In Turbine Strouhal Number Relative to Ideal Values at Respective Flowrates for Different Locations (Z) Downstream from a Tee.



<u>Figure 14</u> Percentage Change In Orifice Discharge Coefficients Relative to Ideal Values at Respective Flowrates for Different Locations (z) Downstream from a Tee and 19 Tube Straightener.

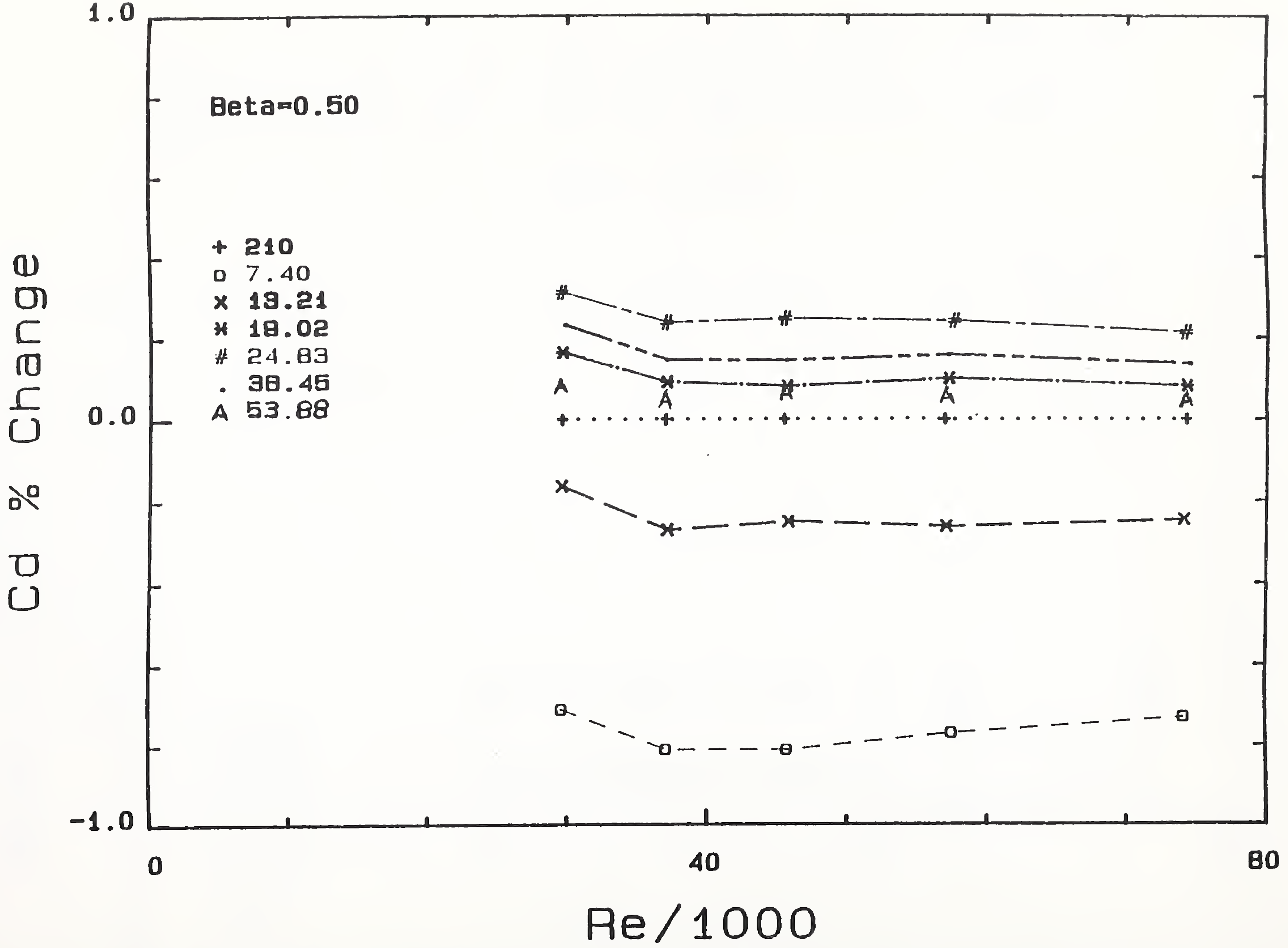


Figure 15 Percentage Change in Orifice Discharge Coefficients Relative to Ideal Values at Respective Flowrates for Different Locations (z) Downstream from a Tee and 19 Tube Straightener.

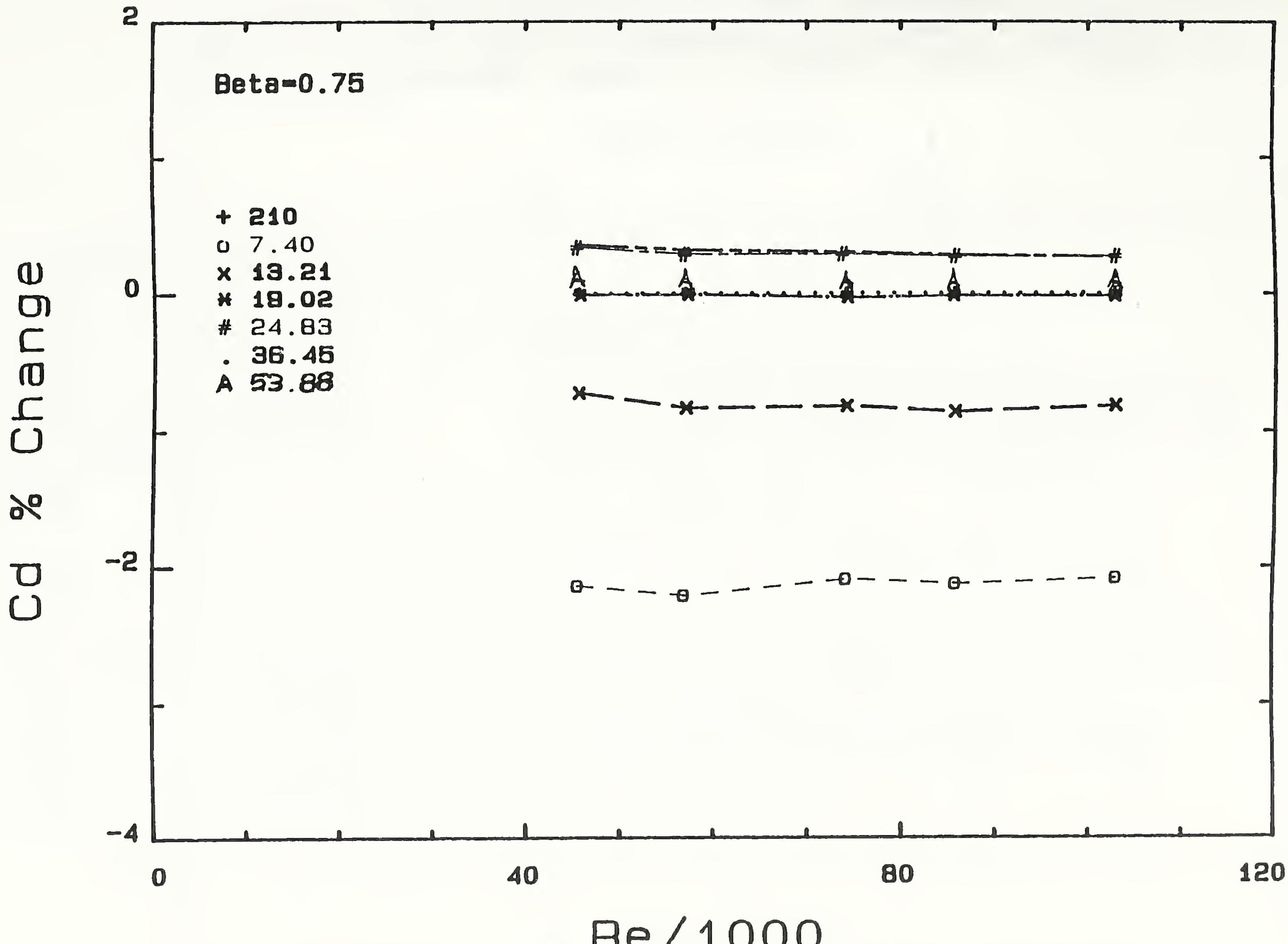


Figure 16 Percentage Change in Orifice Discharge Coefficients Relative to Ideal Values at Respective Flowrates for Different Locations (Z) Downstream from a Tee and 19 Tube Straightener.

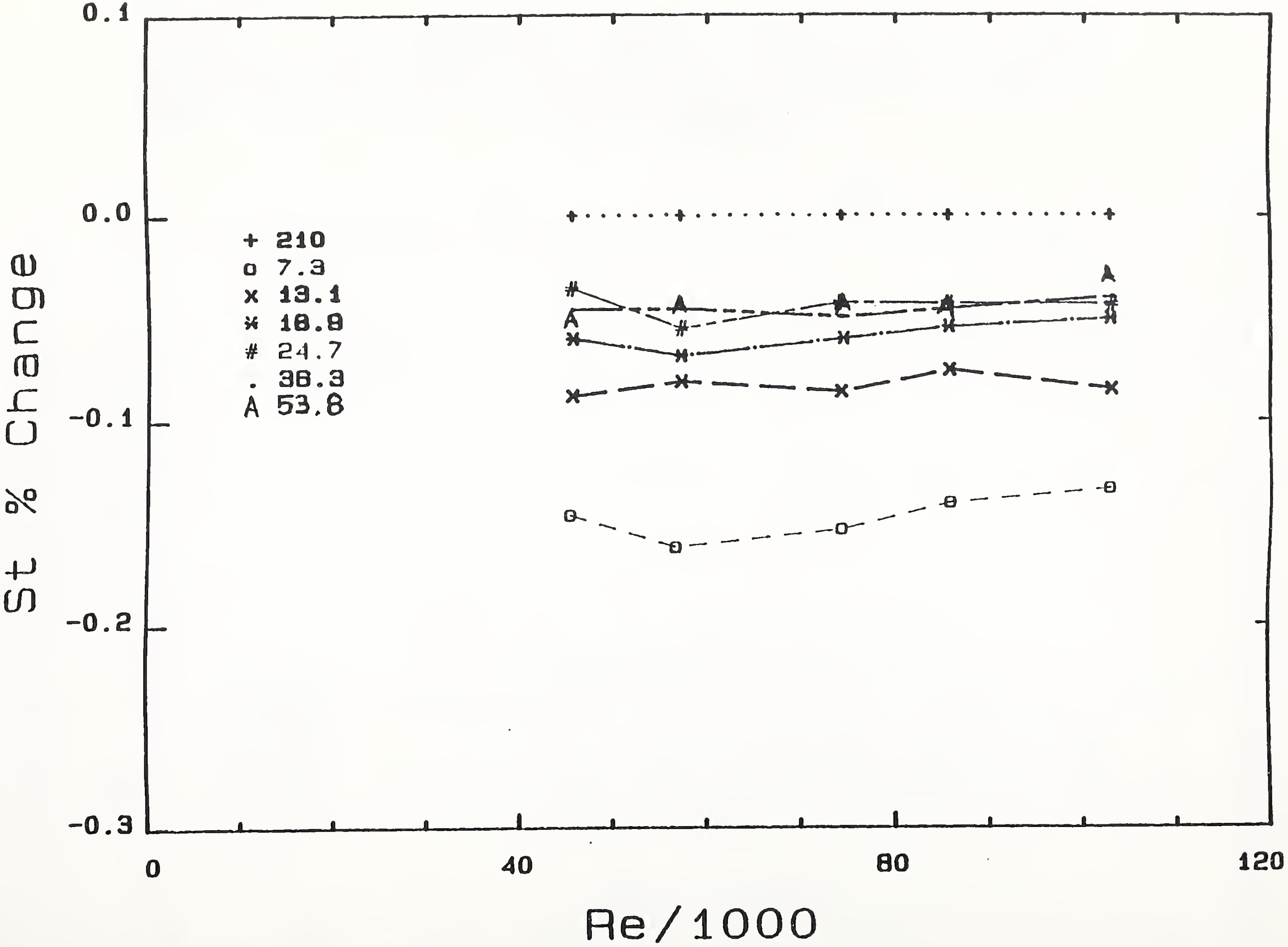
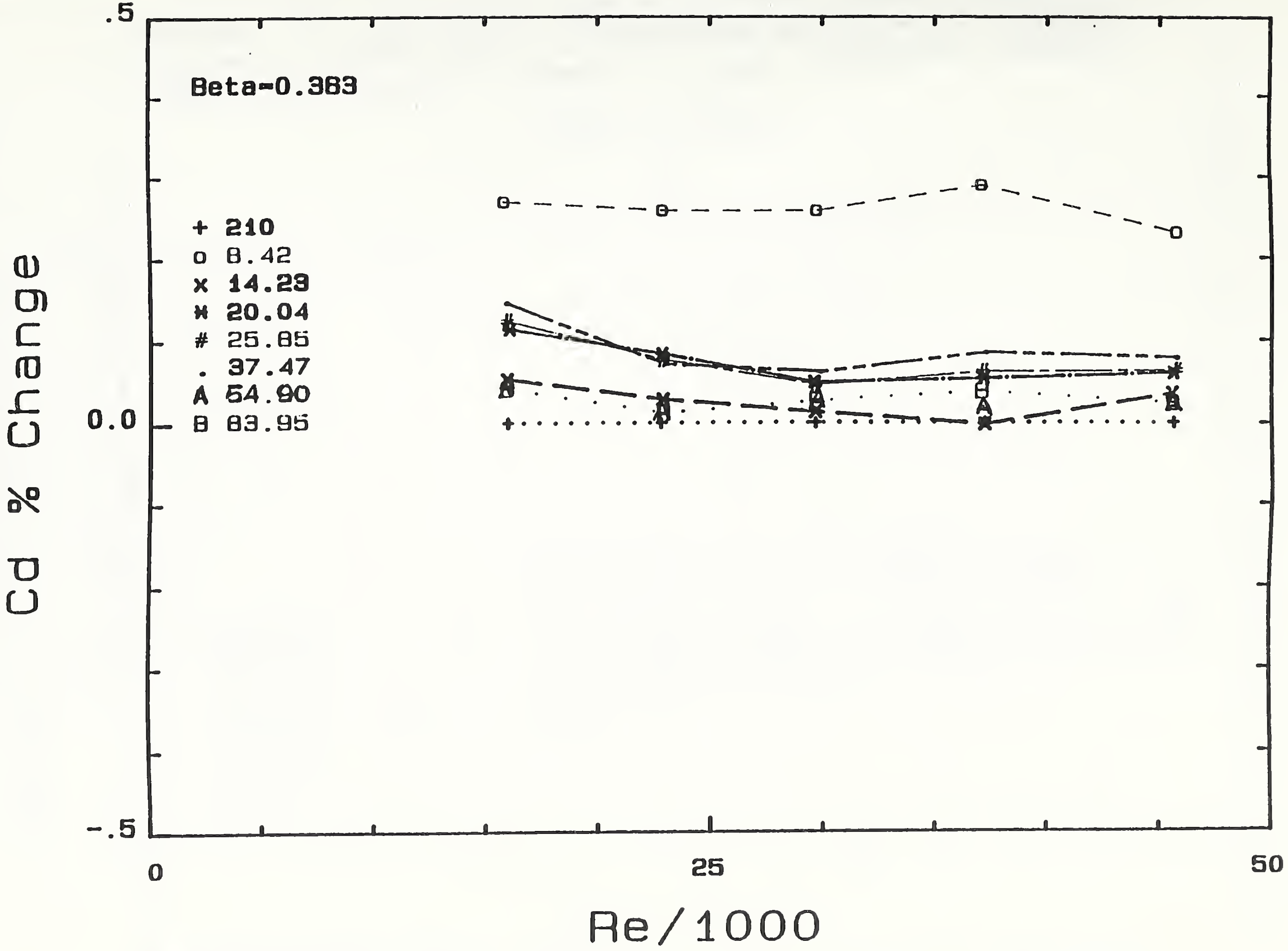


Figure 17 Percentage Change In Turbine Strouhal Number Relative to Ideal Values at Respective Flowrates for Different Locations (z) from a Tee and 19 Tube Straightener.



<u>Figure 18</u> Percentage Change in Orifice Discharge Coefficient Relative to Ideal Values at Respective Flowrates for Different Locations (z) Downstream from a Tee and 7 Tube Straightener.

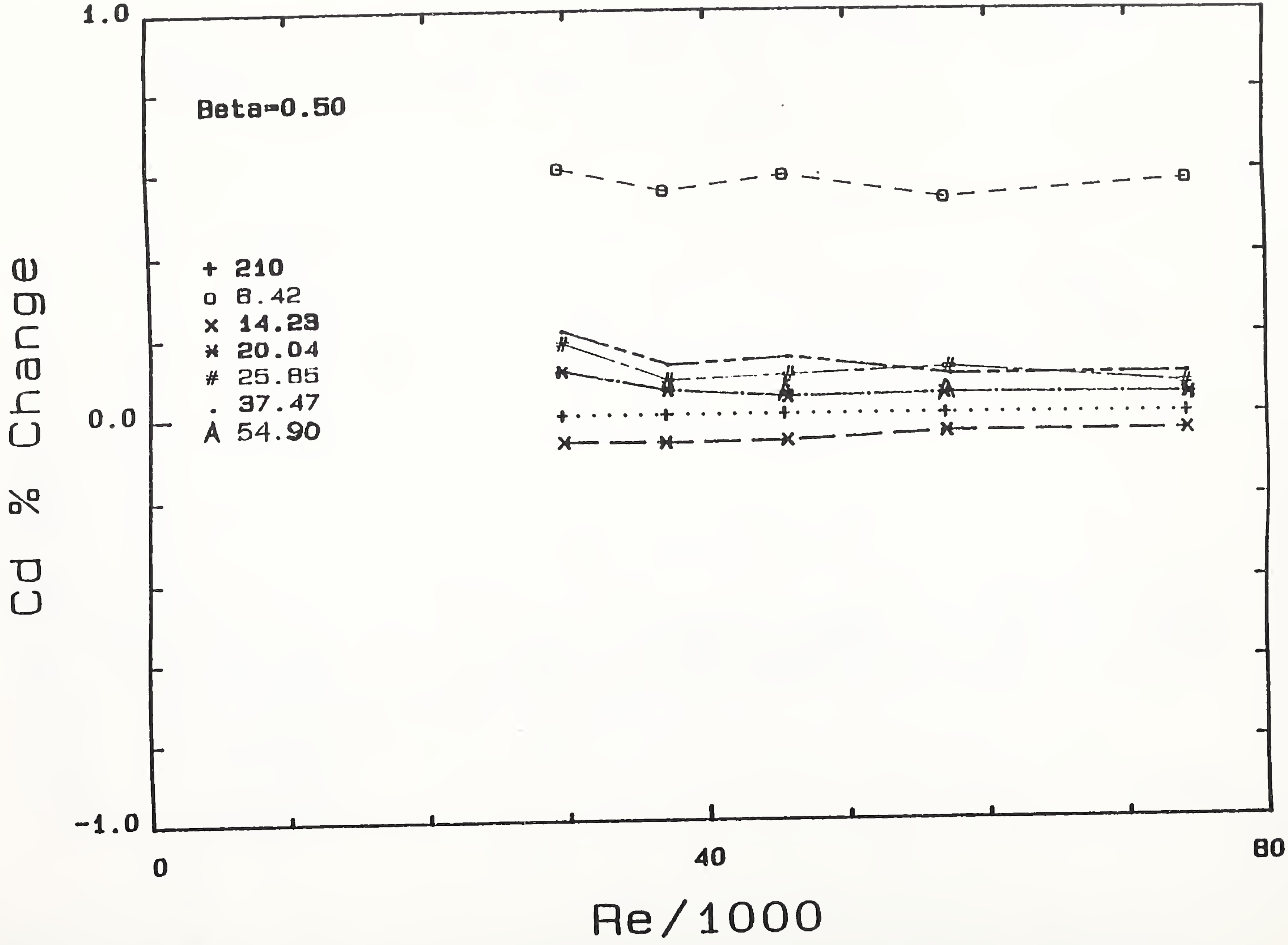


Figure 19 Percentage Change in Orifice Discharge Coefficient Relative to Ideal Values at Respective Flowrates for Different Locations (z) Downstream from a Tee and 7 Tube Straightener.

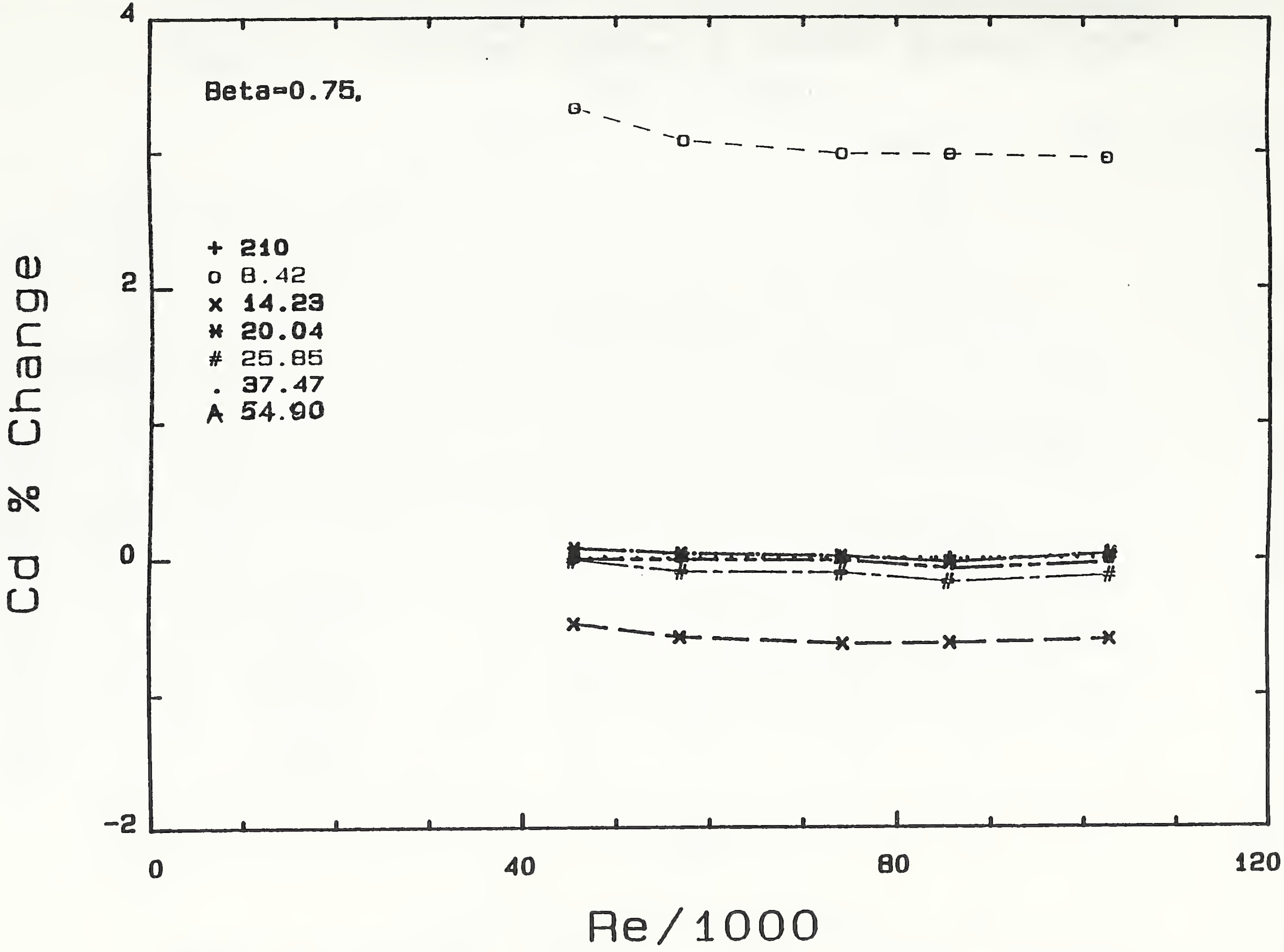
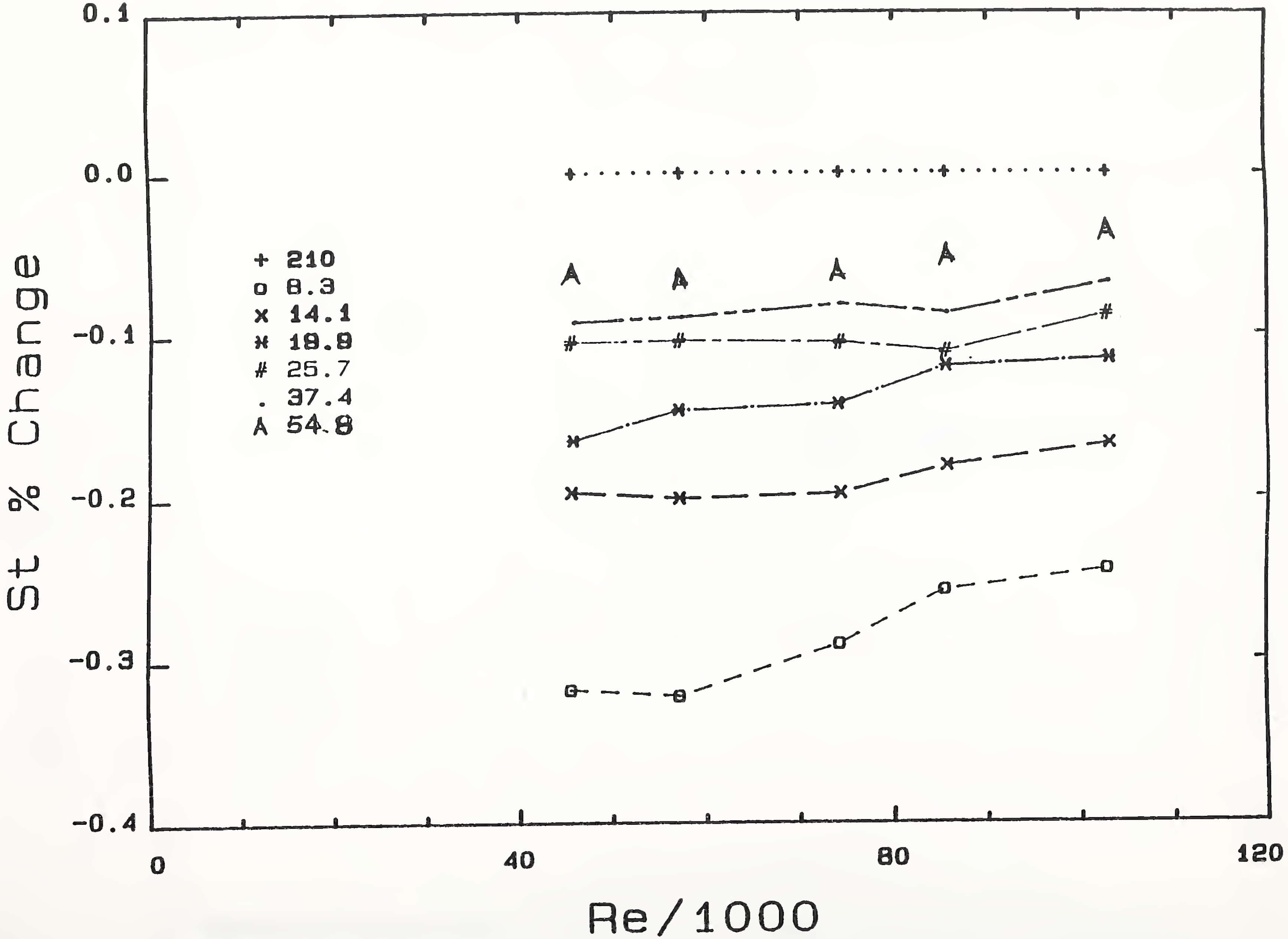


Figure 20 Percentage Change in Orifice Discharge Coefficient Relative to Ideal Values at Respective Flowrates for Different Locations (Z) Downstream from a Tee and 7 Tube Straightener.



<u>Figure 21</u> Percentage Change in Turbine Strouhal Number Relative to Ideal Values at Respective Flowrates for Different Locations (Z) Downstream of a Tee and 7 Tube Straightener.

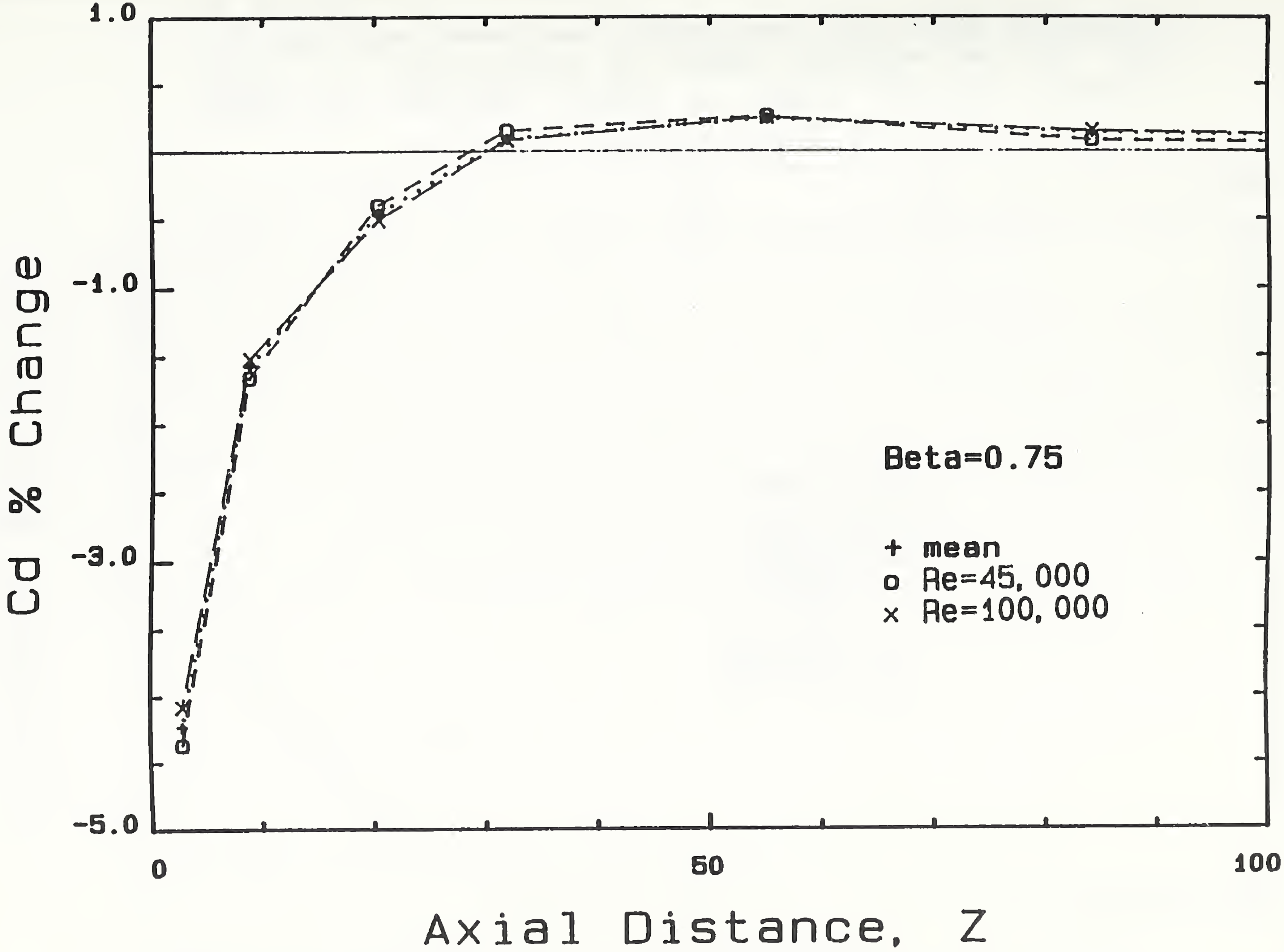


Figure 22 Percentage Change of Orifice Discharge Coefficient Relative to Ideal Values at Specific Flowrates and for Mean Discharge Coefficient over Tested Flow Rate Range Downstream of a Single Elbow.

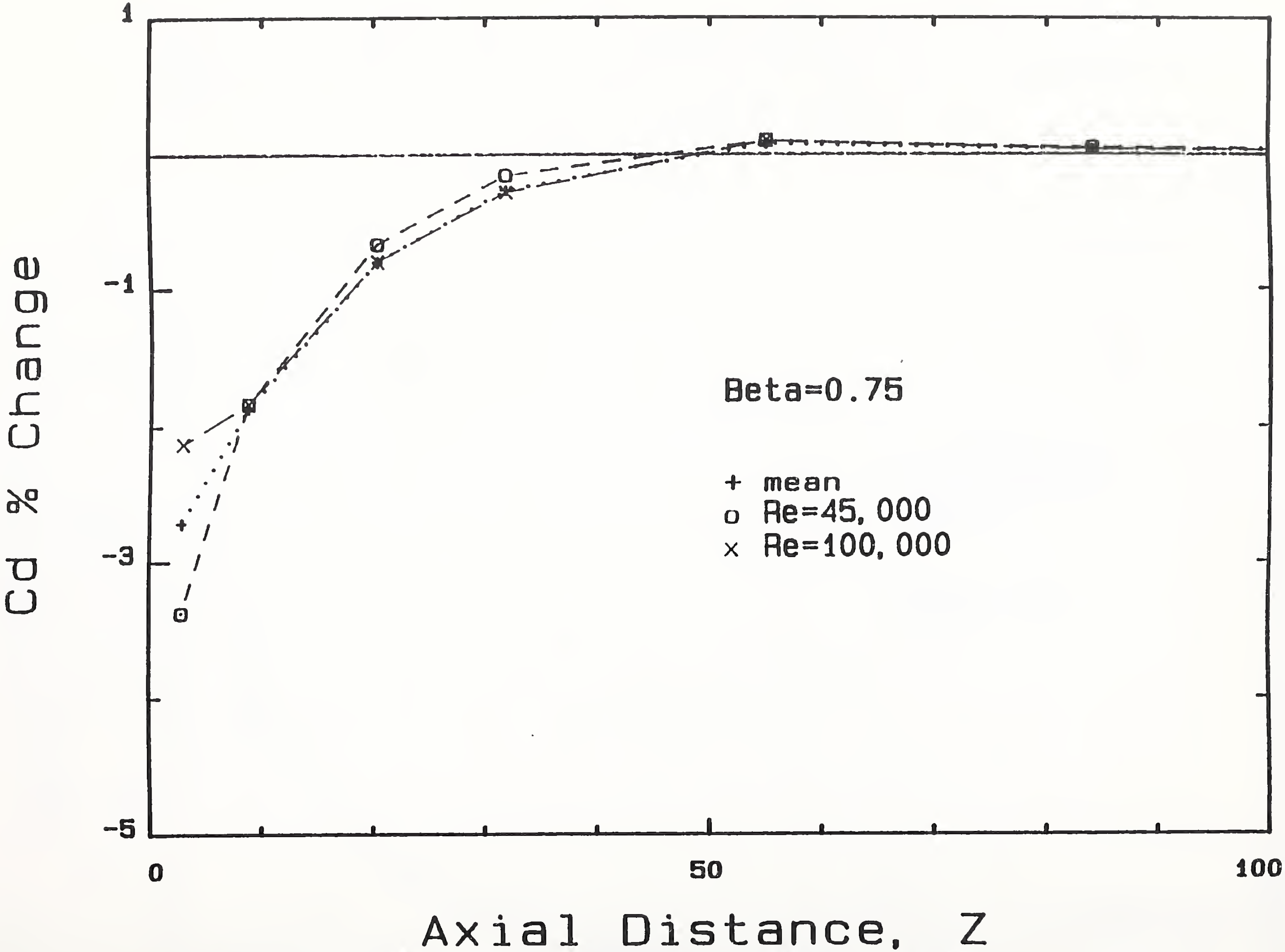


Figure 23 Percentage Change of Orifice Discharge Coefficient Relative to Ideal Values at Specific Flowrates and for Mean Discharge Coefficient over Tested Flow Rate Range Downstream of a Tee.

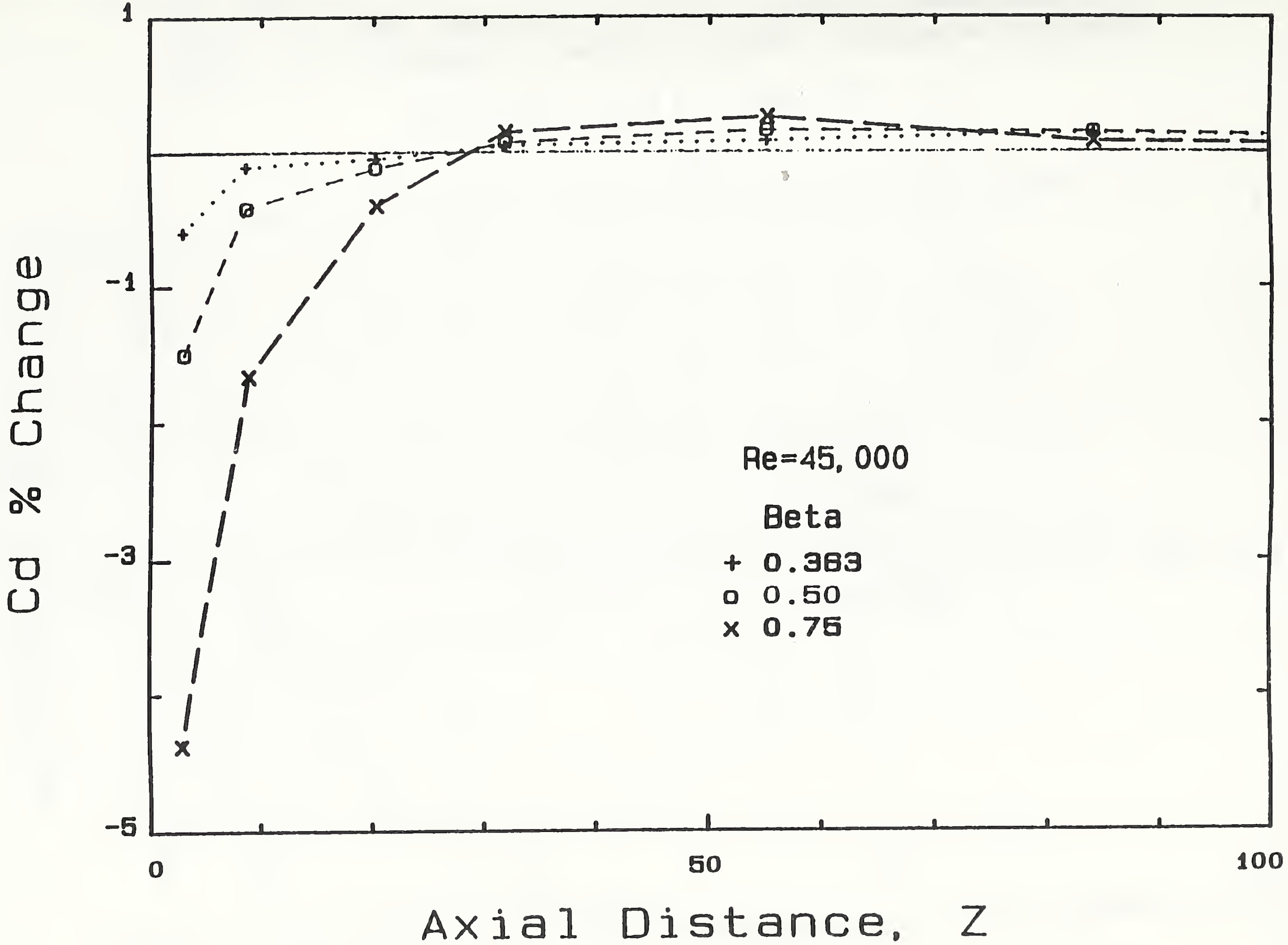


Figure 24 Percentage Change of Orifice Discharge Coefficient Relative to Ideal Values at a Specific Flowrate Downstream from the Single Elbow.

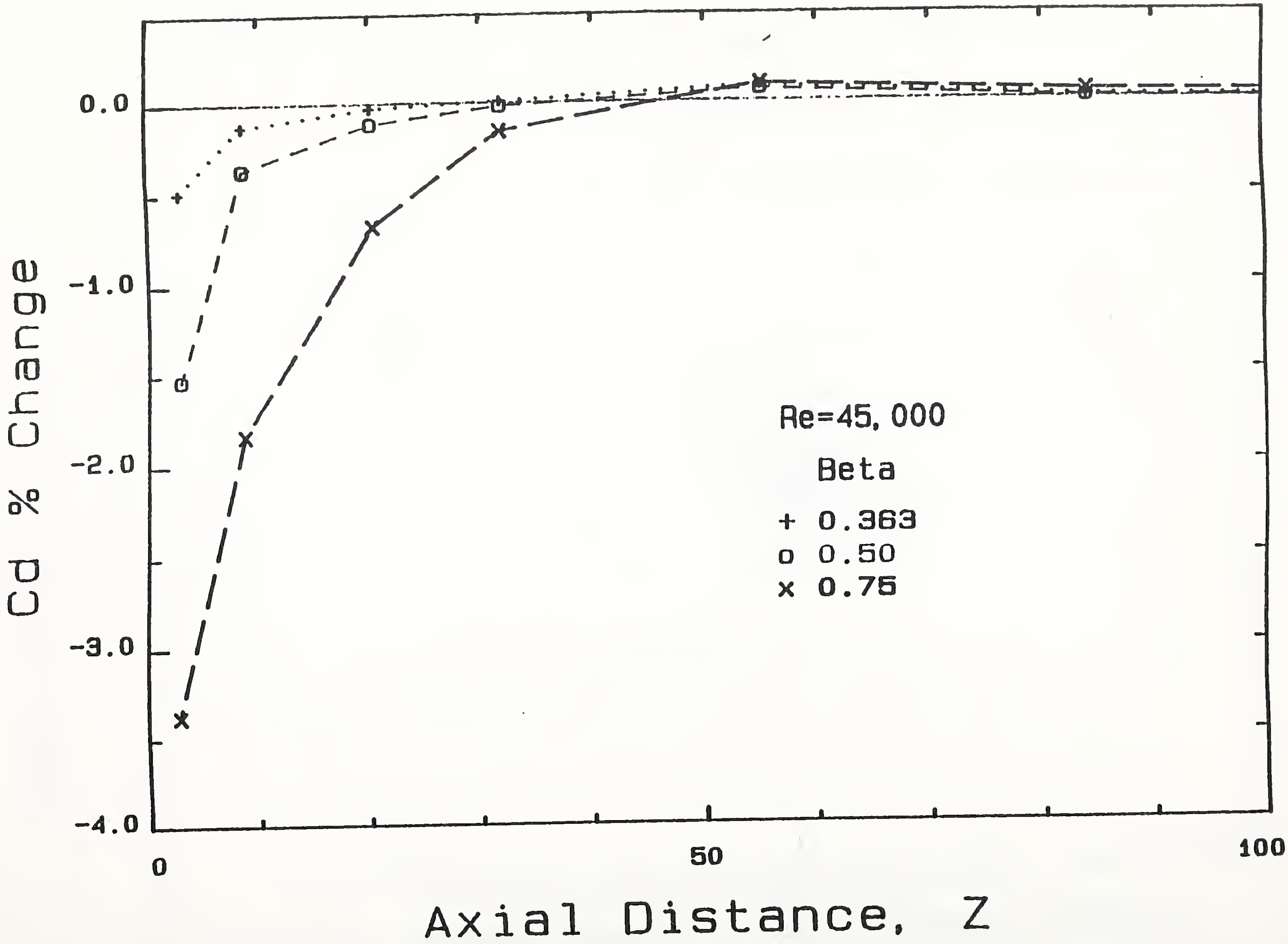


Figure 25 Percentage Change of Orifice Discharge Coefficient Relative to Ideal Values at a Specific Flowrate Downstream from the Tee.

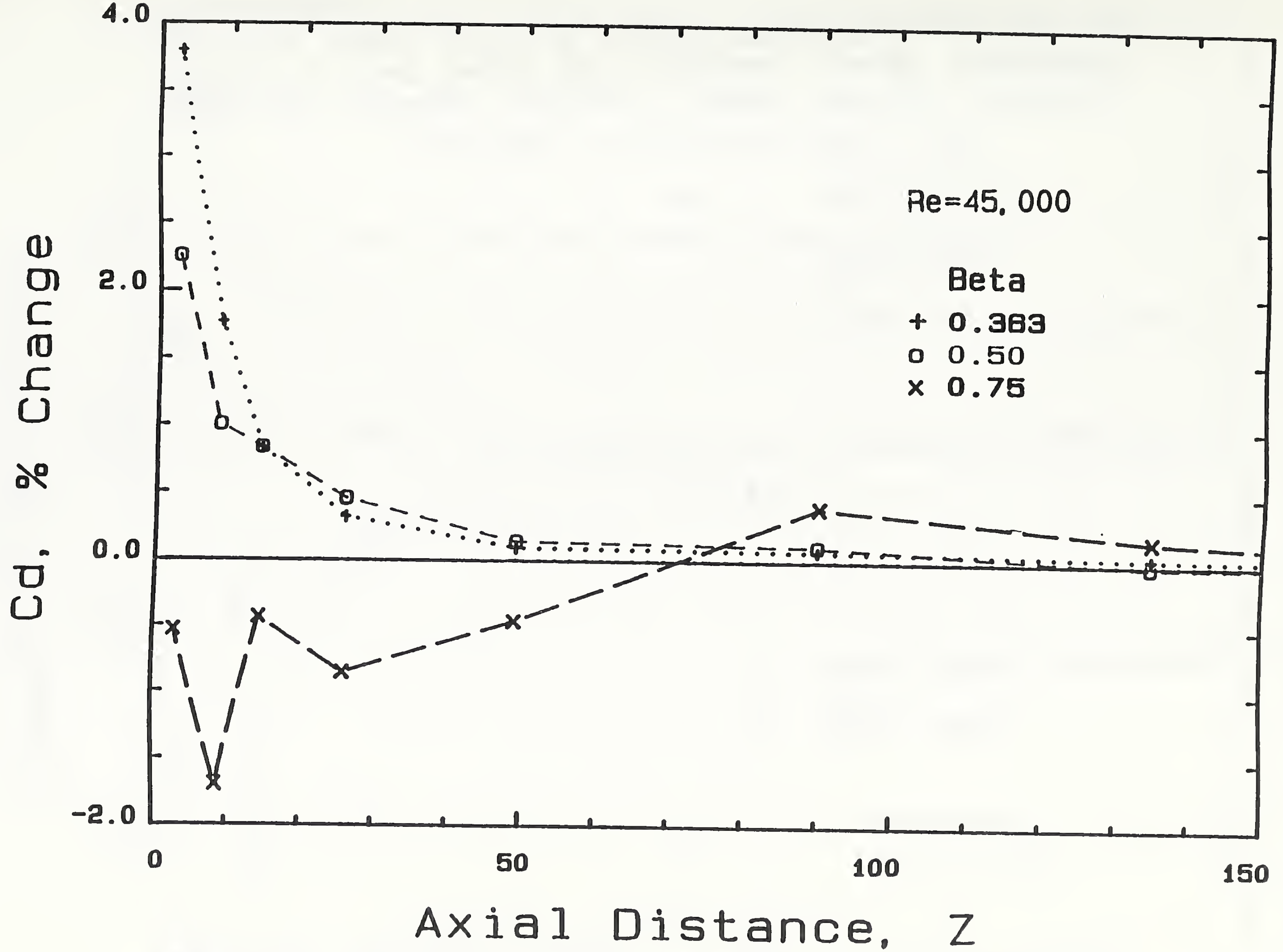
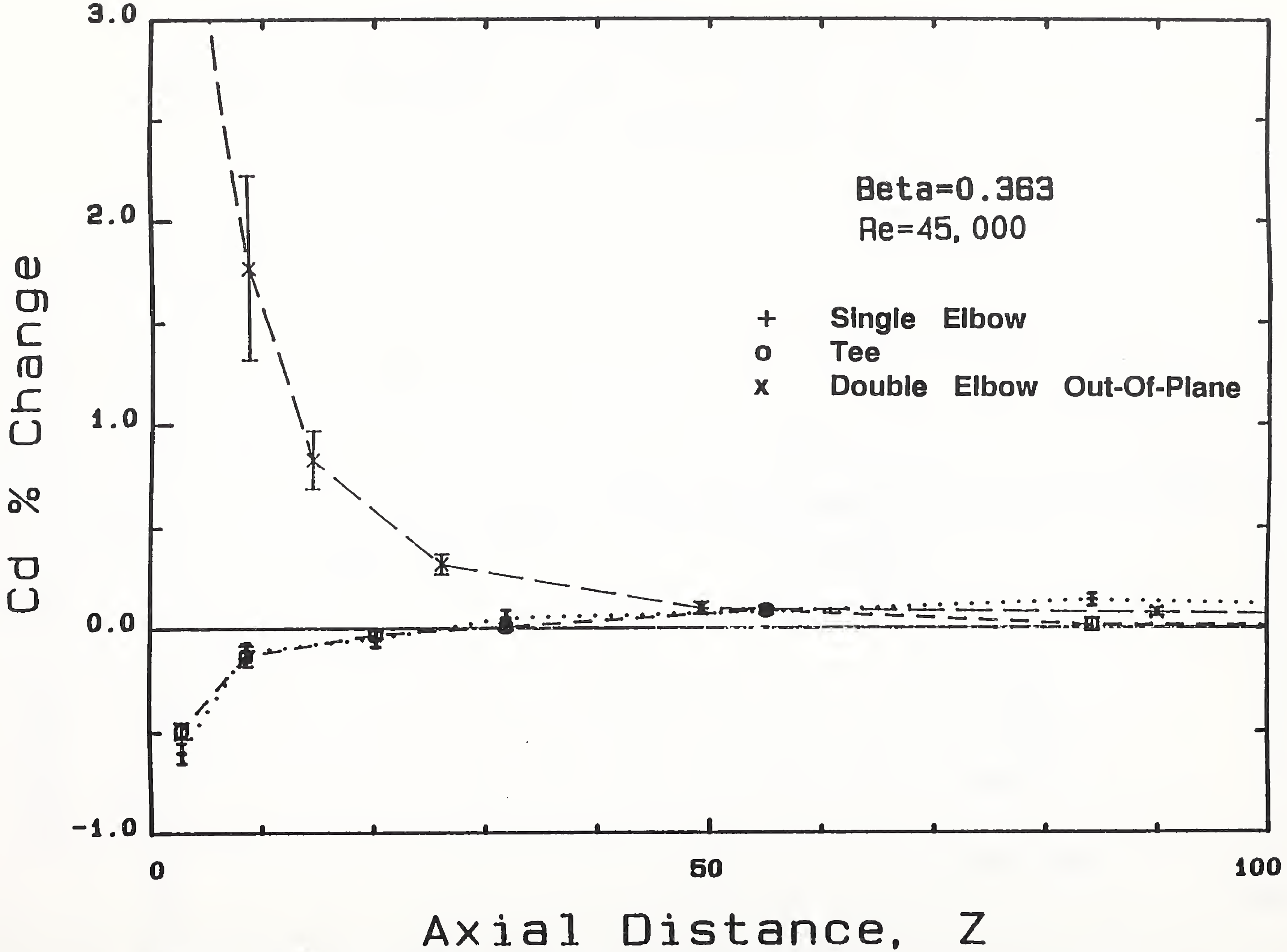


Figure 26 Percentage Change of Orifice Discharge Coefficient Relative to Ideal Values at a Specific Flowrate Downstream from the Double Elbows Out Of Plane.



<u>Figure 27</u> Percentage Change of Orifice Discharge Coefficient Relative to Ideal Values for a Specific Flowrate Downstream from the Single (+) and Double Elbow (X) and Tee (0) Configurations.

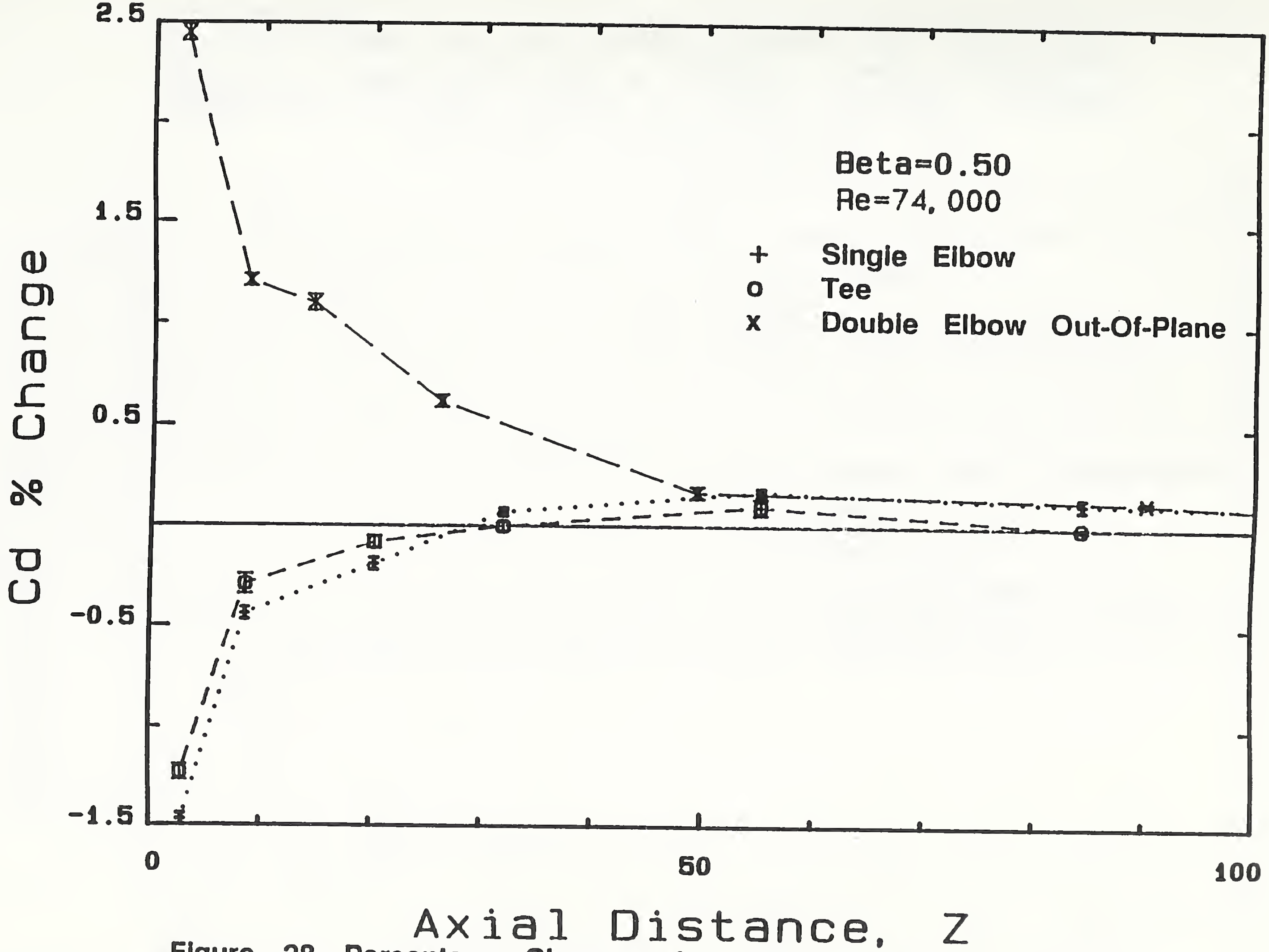


Figure 28 Percentage Change of Orifice Discharge Coefficient Relative to Ideal Values for a Specific Flowrate Downstream from the Single (+) and Double Elbows (X) and Tee (0) Configurations.

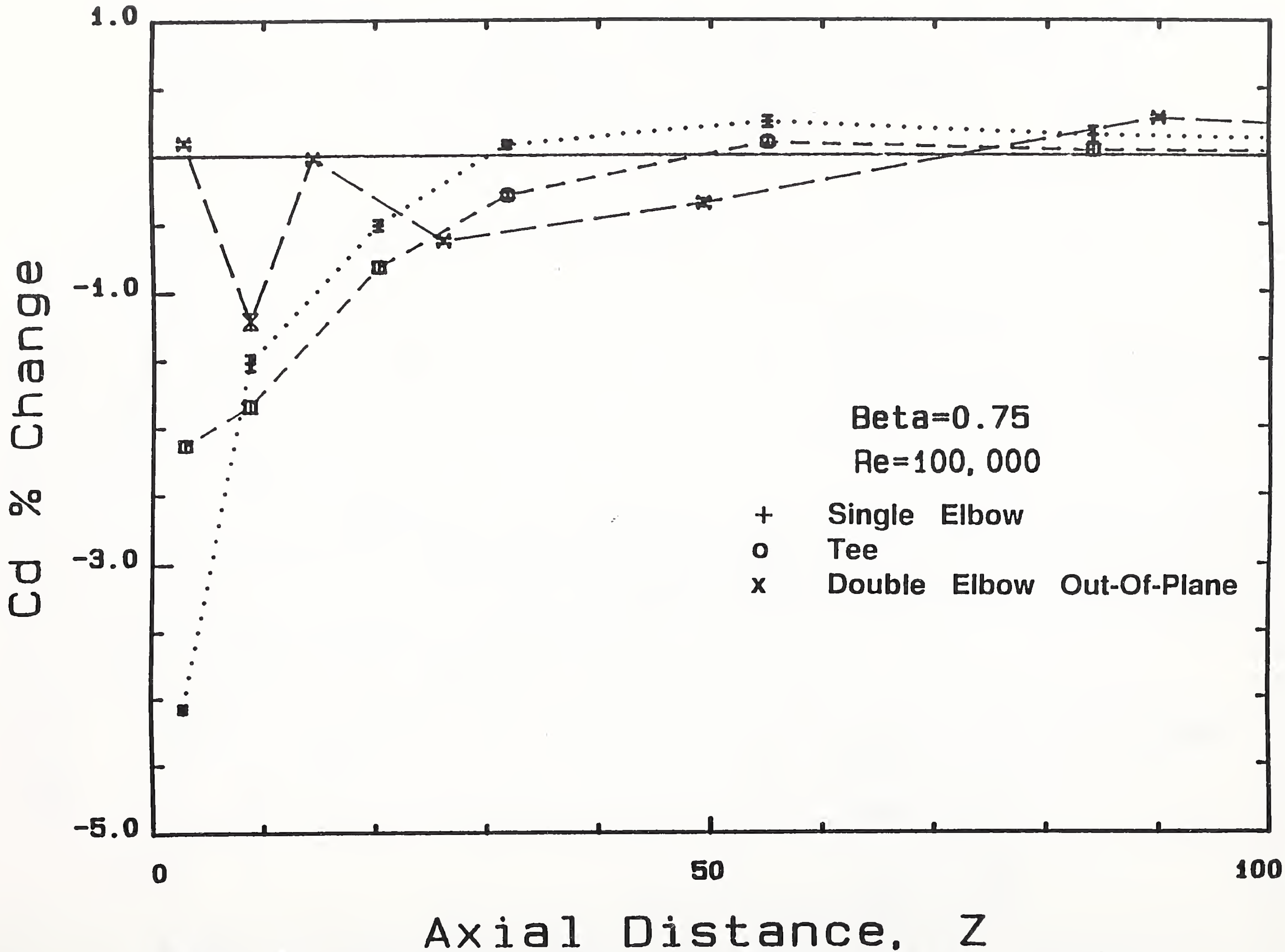


Figure 29 Percentage Change of Orifice Discharge Coefficient Relative to Ideal Values for a Specific Flowrate Downstream from the Single (+) and Double Elbows (X) and Tee (0) Configurations.

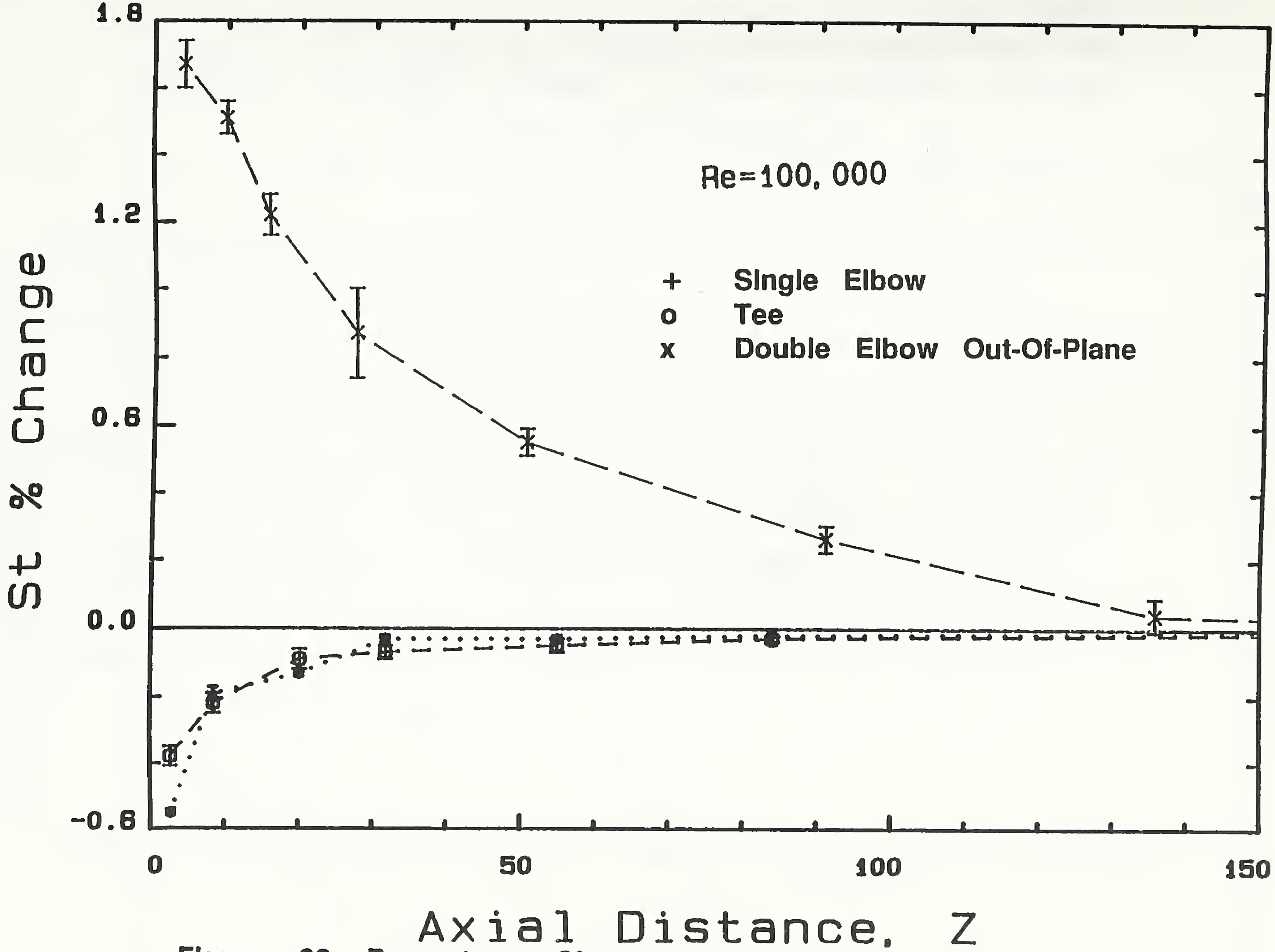


Figure 30 Percentage Change of Turbine Strouhal Number Relative to Ideal Values at a Specific Flowrate Downstream from the Single (+) and Double Elbows (X) and Tee (0) Configurations.

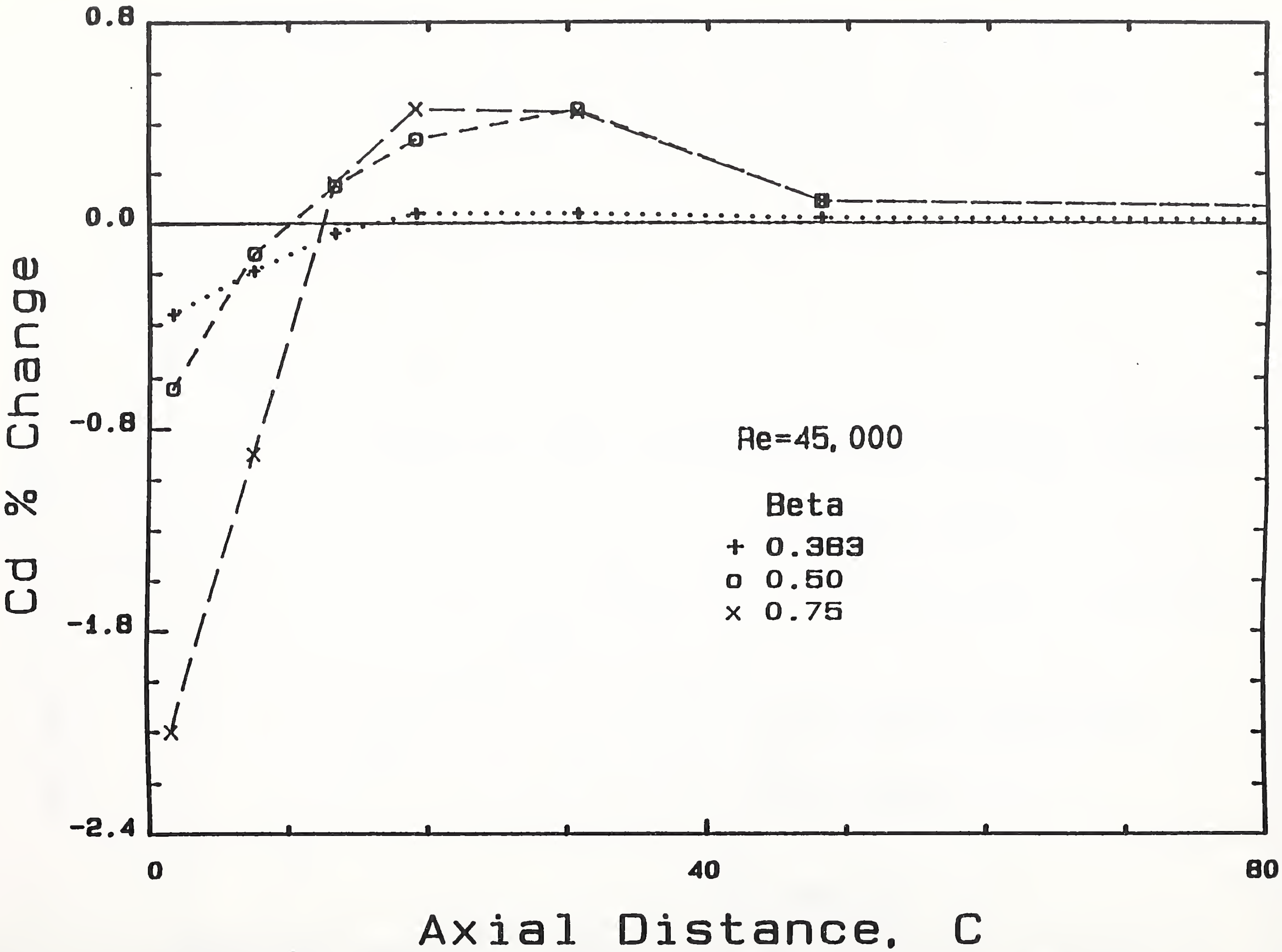
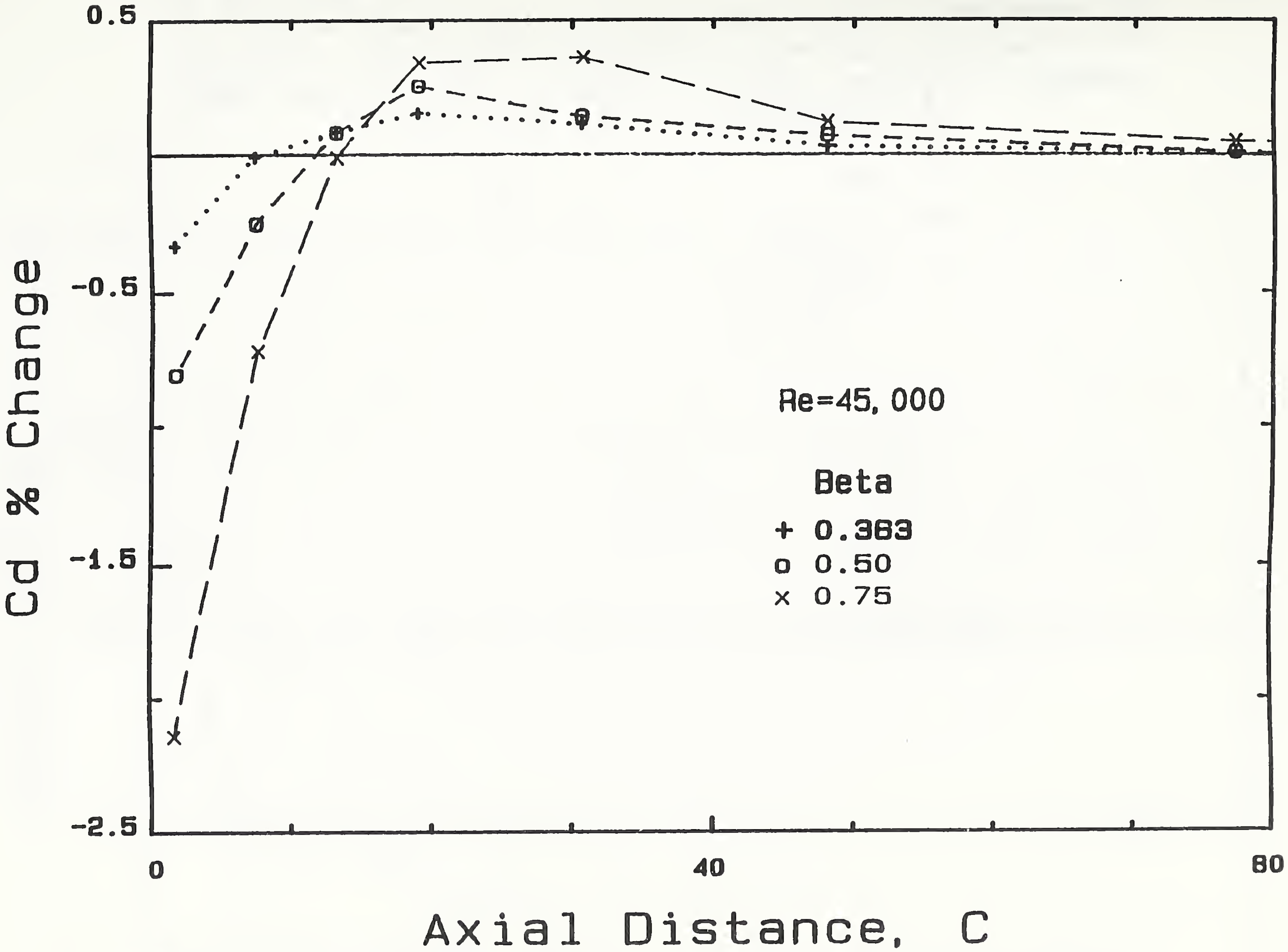


Figure 31 Percentage Change of Orifice Discharge Coefficient Relative to Ideal Values at a Specific Flowrate Downstream from the Single Elbow and 19 Tube Straightener for 3 Beta Ratios.



<u>Figure 32</u> Percentage Change of Orifice Discharge Coefficient Relative to Ideal Values at a Specific Flowrate Downstream from the Tee and 19 Tube Straightener for 3 Beta Ratios.

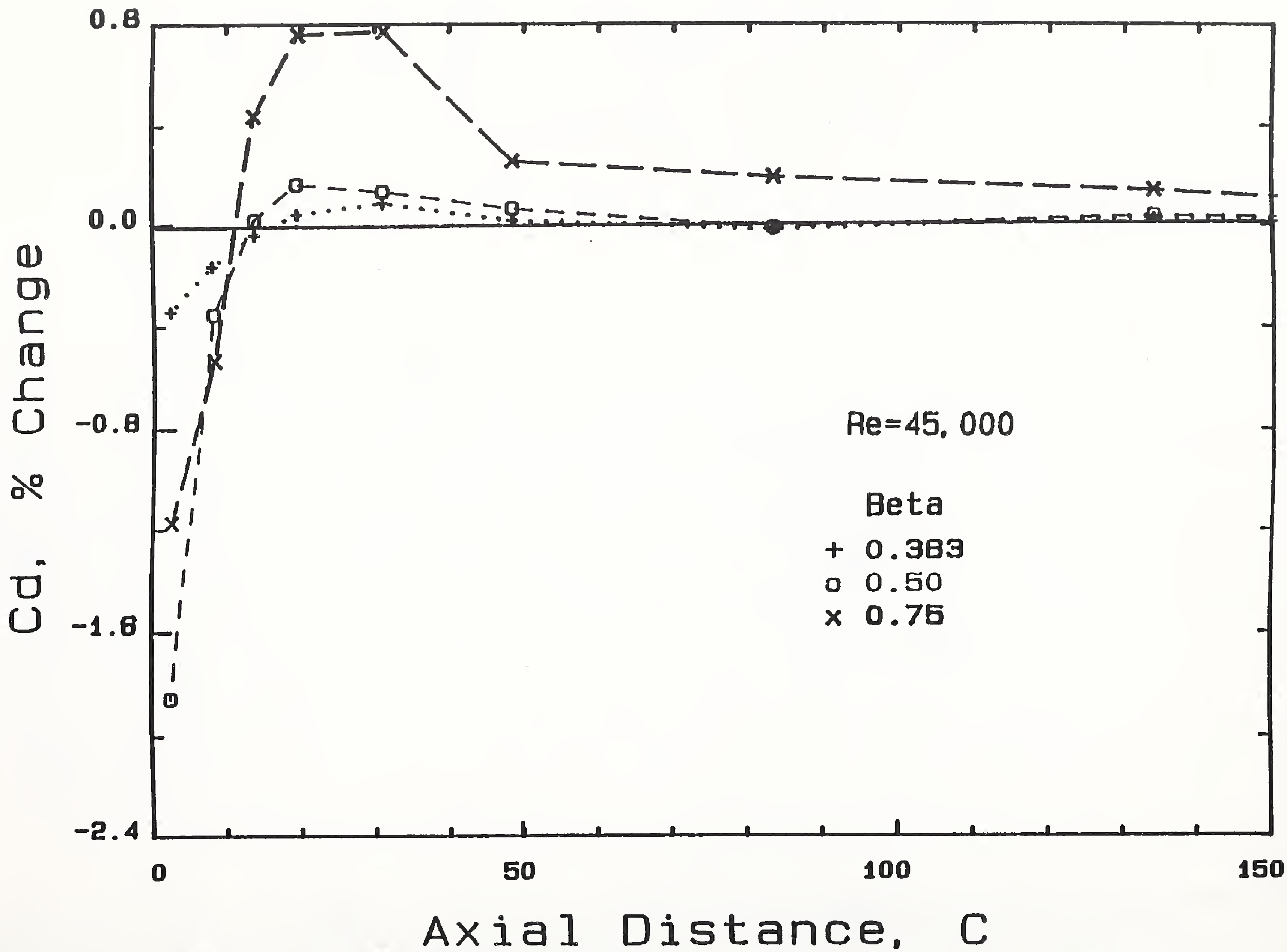


Figure 33 Percentage Change of Orifice Discharge Coefficient Relative to Ideal Values at a Specific Flowrate Downstream from the Double Elbows Out Of Plane and 19 Tube Straightener for 3 Beta Ratios.

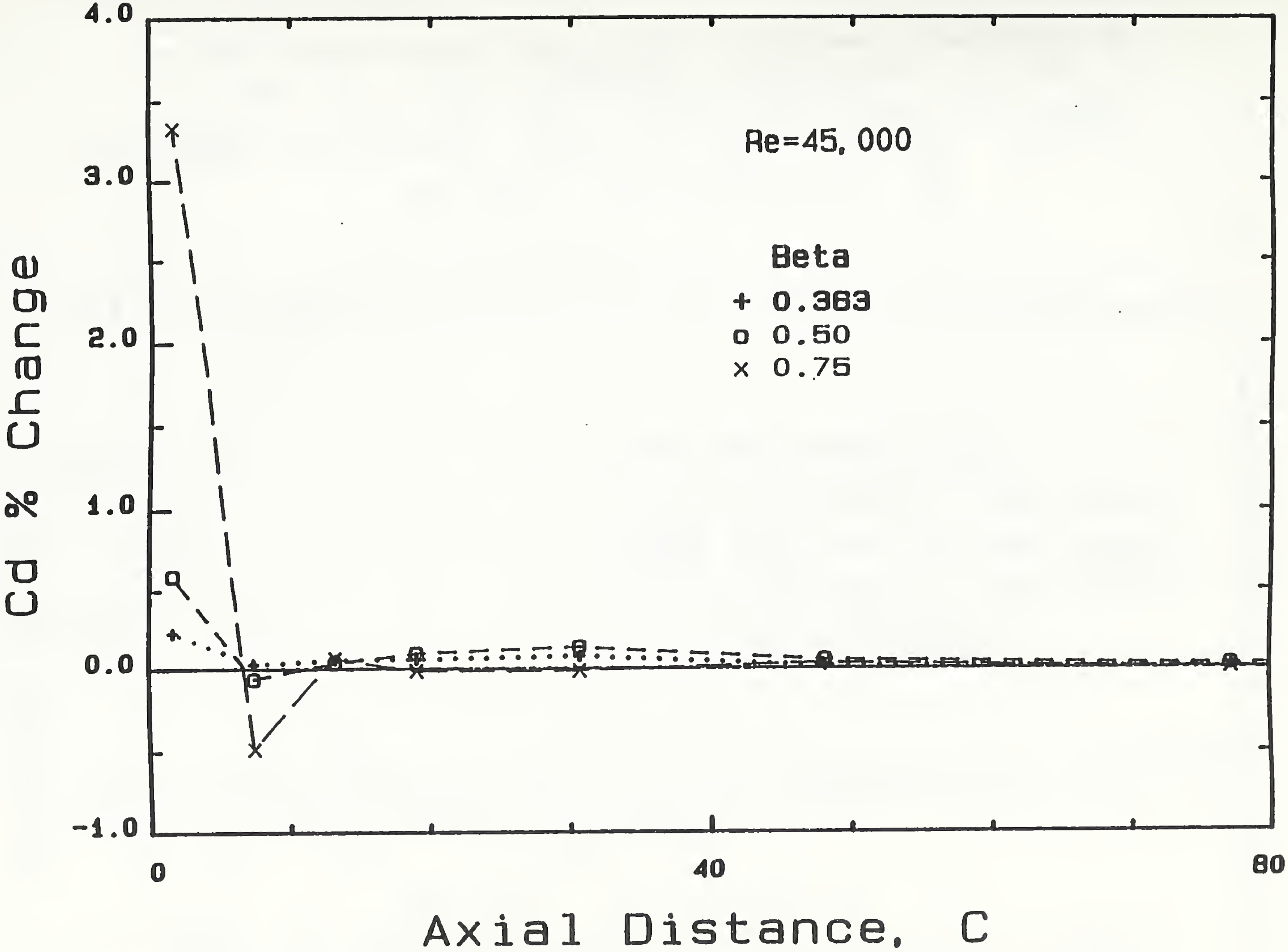


Figure 34 Percentage Change of Orifice Discharge Coefficient Relative to Ideal Values at a Specific Flowrate Downstream from the Tee and 7 Tube Straightener for 3 Beta Ratios.

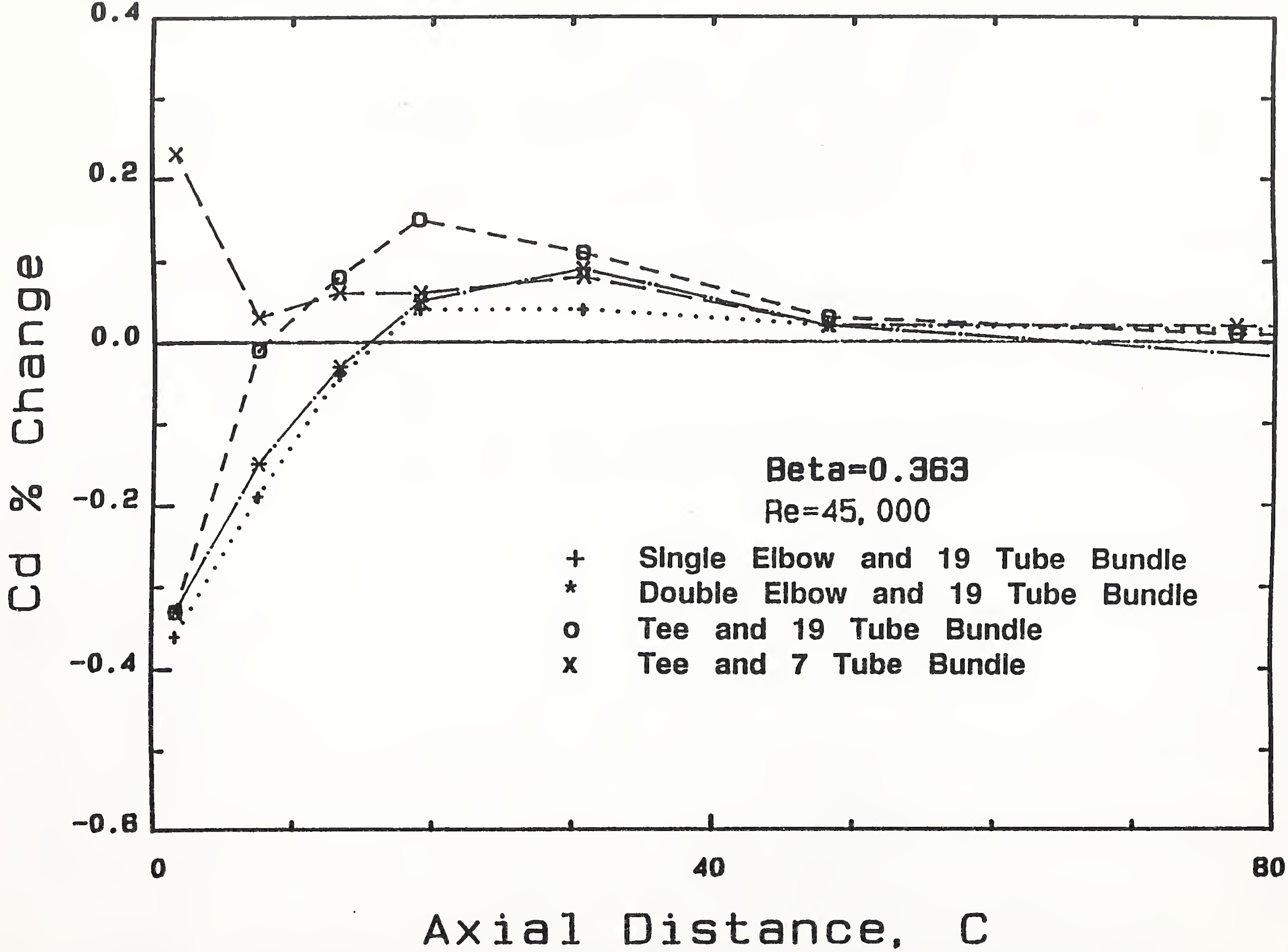


Figure 35 Percentage Change of Orifice Discharge Coefficient Relative to Ideal Values for a Specific Beta Ratio and Flowrate for the 19 Tube Straightener Downstream of the 3 Configurations and for the 7 Tube Straightener Downstream of the Tee.

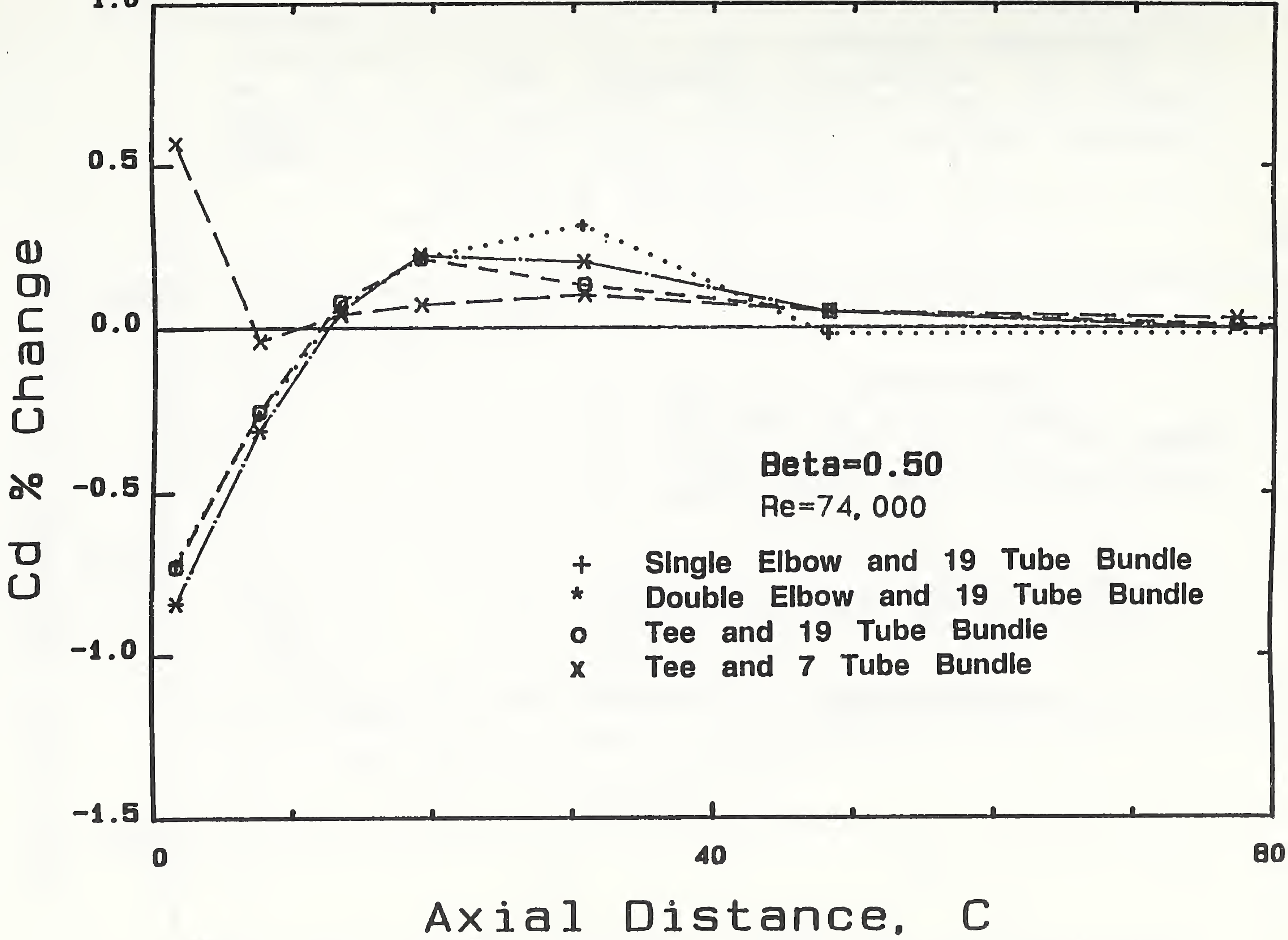
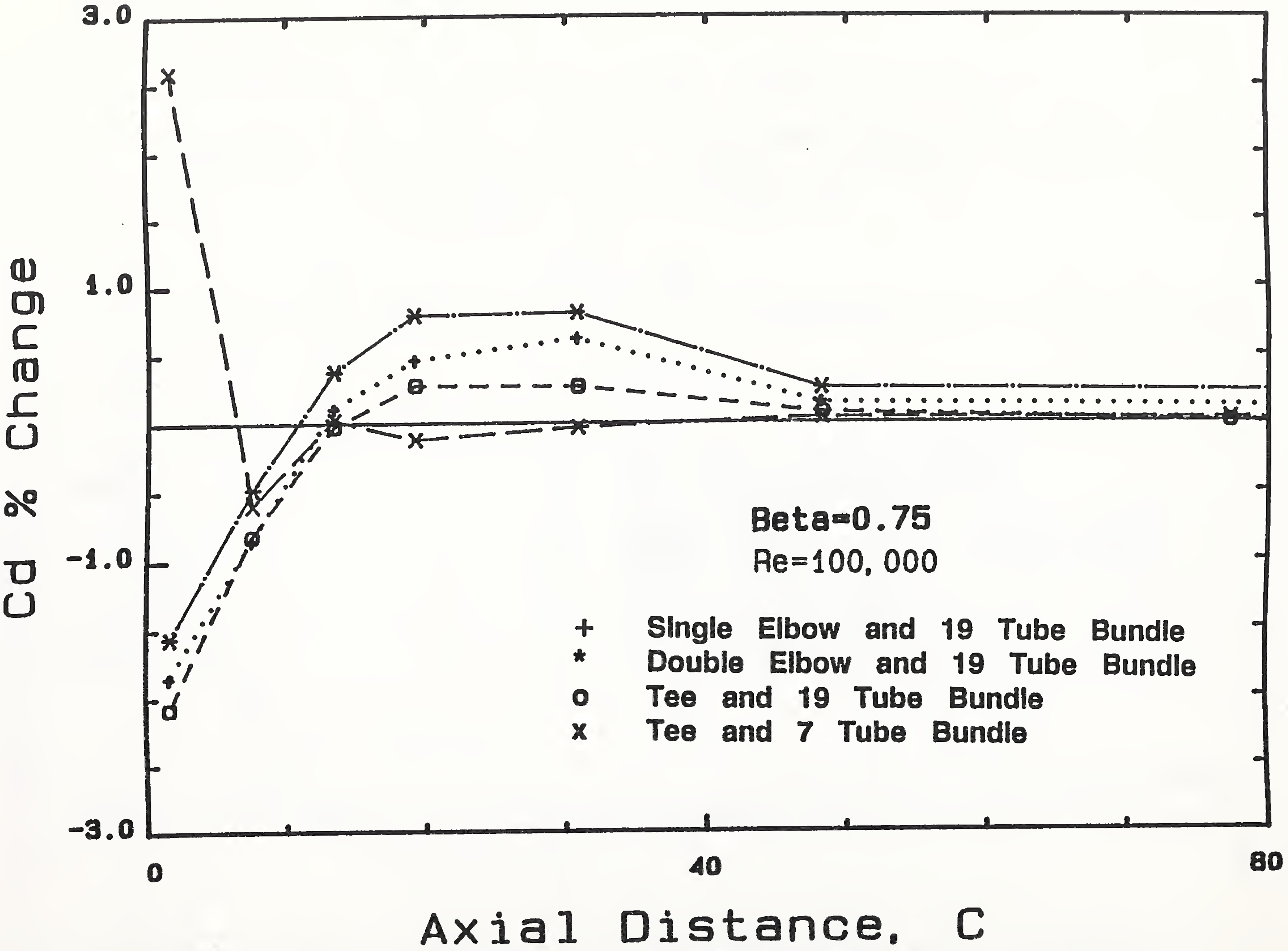


Figure 36 Percentage Change of Orifice Discharge Coefficient Relative to Ideal Values for a Specific Beta Ratio and Flowrate for the 19 Tube Straightener Downstream of the 3 Configurations and for the 7 Tube Straightener Downstream of the Tee.



<u>Figure 37</u> Percentage Change of Orifice Discharge Coefficient Relative to Ideal Values for a Specific Beta Ratio and Flowrate for the 19 Tube Straightener Downstream of the 3 Configurations and for the 7 Tube Straightener Downstream of the Tee.

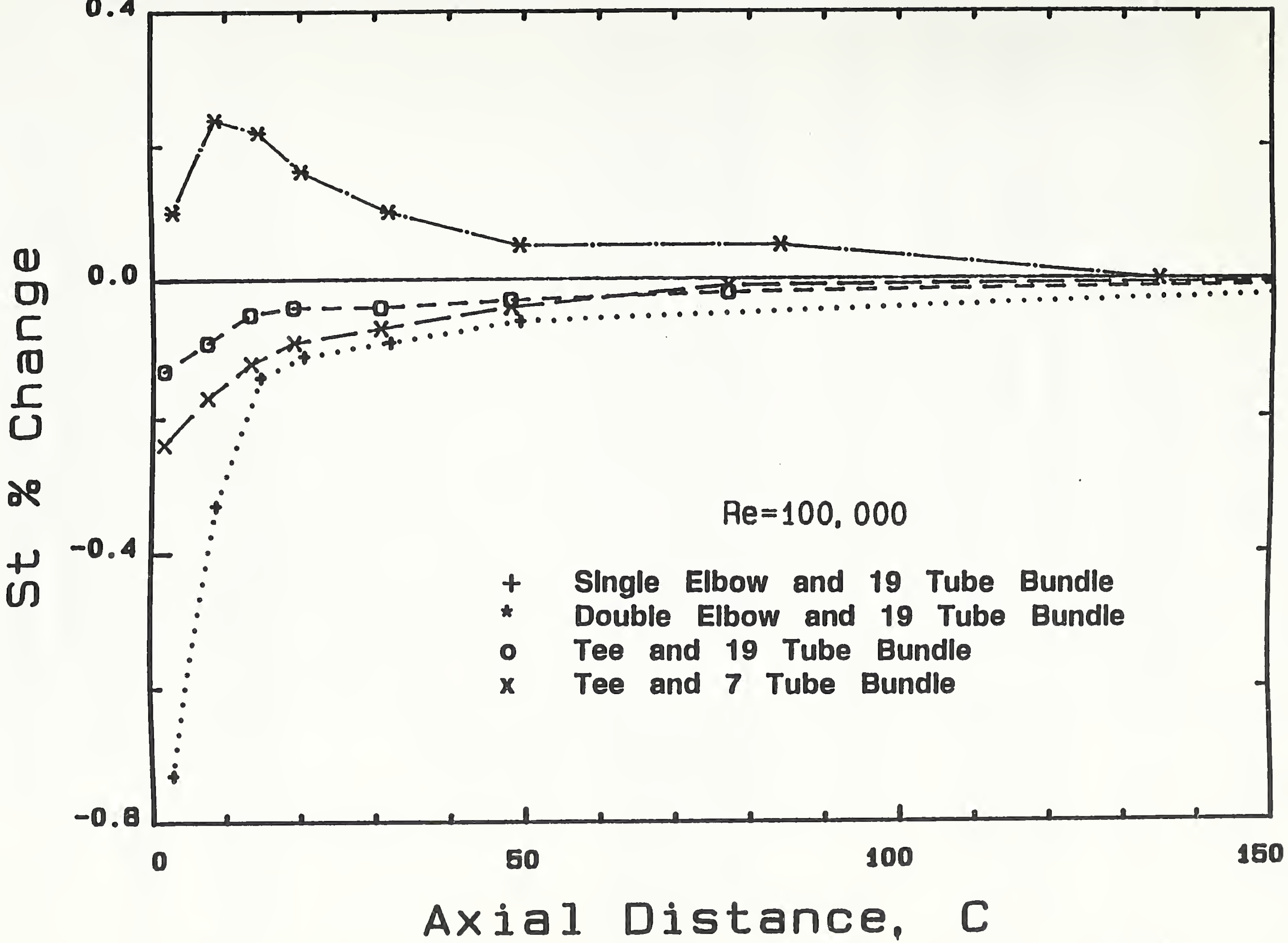


Figure 38 Percentage Change of Turbine Strouhal Number Relative to Ideal Values at a Specific Flowrate for the 19 Tube Straightener Downstream of the 3 Configurations and for the 7 Tube Straightener Downstream of the Tee.

NIST-114A
(REV. 3-90)

U.S. DEPARTMENT OF COMMERCE
NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY

BIBLIOGRAPHIC DATA SHEET

1. PUBLICATION OR REPORT NUMBER
NISTIR 4753

2. PERFORMING ORGANIZATION REPORT NUMBER

3. PUBLICATION DATE
JANUARY 1992

4. TITLE AND SUBTITLE
Summary Report of NIST's Industry-Government Consortium Research Program on Flowmeter Installation Effects with Emphasis on the Research Period February - December 1990: Tee, Used As An Elbow Configuration

5. AUTHOR(S)
G. E. Mattingly and T. T. Yeh

6. PERFORMING ORGANIZATION (IF JOINT OR OTHER THAN NIST, SEE INSTRUCTIONS)
U.S. DEPARTMENT OF COMMERCE
NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
GAITHERSBURG, MD 20899

7. CONTRACT/GRANT NUMBER

8. TYPE OF REPORT AND PERIOD COVERED

9. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS (STREET, CITY, STATE, ZIP)
NIST Industry Consortium

10. SUPPLEMENTARY NOTES

11. ABSTRACT (A 200-WORD OR LESS FACTUAL SUMMARY OF MOST SIGNIFICANT INFORMATION. IF DOCUMENT INCLUDES A SIGNIFICANT BIBLIOGRAPHY OR LITERATURE SURVEY, MENTION IT HERE.)

This report presents results obtained in a consortium-sponsored research program on flowmeter installation effects being conducted at NIST-Gaithersburg. This project is a collaborative one that has been underway for six years; it is supported by an industry-government consortium that meets twice yearly to review and discuss recently obtained results and to plan subsequent phases of the work. This report contains the results and conclusions of the meeting of this consortium at NIST-Gaithersburg, MD in December 1990.

12. KEY WORDS (6 TO 12 ENTRIES; ALPHABETICAL ORDER; CAPITALIZE ONLY PROPER NAMES; AND SEPARATE KEY WORDS BY SEMICOLONS)

disturbed velocity profiles; flow conditioning; non-ideal flowmeter performance; swirl angle; swirl decay; swirled pipeflow; tube bundle

13. AVAILABILITY
☒ UNLIMITED
☐ FOR OFFICIAL DISTRIBUTION. DO NOT RELEASE TO NATIONAL TECHNICAL INFORMATION SERVICE (NTIS).
☐ ORDER FROM SUPERINTENDENT OF DOCUMENTS, U.S. GOVERNMENT PRINTING OFFICE, WASHINGTON, DC 20402.
☒ ORDER FROM NATIONAL TECHNICAL INFORMATION SERVICE (NTIS), SPRINGFIELD, VA 22161.

14. NUMBER OF PRINTED PAGES
60

15. PRICE
A04

ELECTRONIC FORM