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Effects of Upstream Flow Disturbances on Elbow Meter Performance

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Abstract: In order to fill gaps in research into the use of elbow flow meters and to reconcile both a lack of published standards and differing recommendations on the necessary minimum lengths of straight pipe that should be installed upstream of an elbow flow meter to ensure sufficiently accurate flow measurement, physical data were collected on 50 mm nominal (52.5 mm or 2.067 inch actual), 150 mm nominal (154.05 mm or 6.065 inch actual), and 305 mm nominal (304.8 mm or 12.00 inch actual) long-radius elbow meters to determine discharge coefficients in a straight-line pipeline configuration. The 150 mm (6-inch) long-radius elbow meter was further tested in order to determine the effects of different upstream disturbances on the accuracy of its metering performance. Three different upstream disturbances were tested at upstream distances of 25, 10, and 5 diameter-lengths, including: a single elbow in-plane "S" orientation, a single elbow in-plane "U" orientation, and a double elbows out-of-plane orientation. Discharge coefficients were calculated for each configuration at the three variable upstream distances between the upstream flow disturbance and the meter and compared to the straight-line calibration values to identify the percent difference shifts in the average discharge coefficients. Most importantly, findings from the present study conclude that the discharge coefficients for all elbow meter installations stabilize for pipe Reynolds numbers greater than 300,000. Additionally, even at upstream distances of 25 pipe diameter lengths (3.81 m or 12.5 feet) each of the three upstream flow disturbances continued to exhibit effects on the calculated discharge coefficients for the elbow meter; the observed difference in the average discharge coefficient for the two single elbow in-plane configurations "S" and "U" were within 1.00% of the straight-line values. Finally, the double elbows out-of-plane discharge coefficient values remained constant, regardless of the three tested distances between 5 and 25 diameter lengths between the elbow meter and the upstream flow disturbance, showing a more predictable shift in discharge coefficient than the two single elbow in-plane configurations.

Keywords: Differential Pressure Flow Meter, Discharge Coefficient, Elbow Meter, Flow Measurement, Laboratory Studies

1. Introduction

Accurate flow measurement is an essential part of numerous industrial, manufacturing, and water treatment processes. Within these processes, pipe elbows are commonplace fittings. Elbow meters utilize the commonality of these fittings and are able to measure flow rates through a system by the simple addition of two pressure taps (Figure 1) without adding any additional pressure losses to the system than would otherwise already occur as a result of a normal pipe elbow.

A difference in the fluid pressure occurs between the inside and outside radii of the elbow fitting as a result of acceleration of the fluid and change in the momentum of the fluid. Using pressure taps located on the inside and outside radii of the elbow at the longitudinal midpoint of the elbow (45°), pressure difference is used to calculate the flow rate if the discharge coefficient for the elbow is known.

The distribution of fluid particle velocities within a pipe, the velocity profile, can have a varying effect on a flow meter, depending on the type of meter and the distribution of the fluid particles. Fully developed flow refers to a flow profile where the highest velocities are concentrated in the center of the pipe and the lowest velocities are concentrated alongside the pipe wall as visualized in Figure 2.

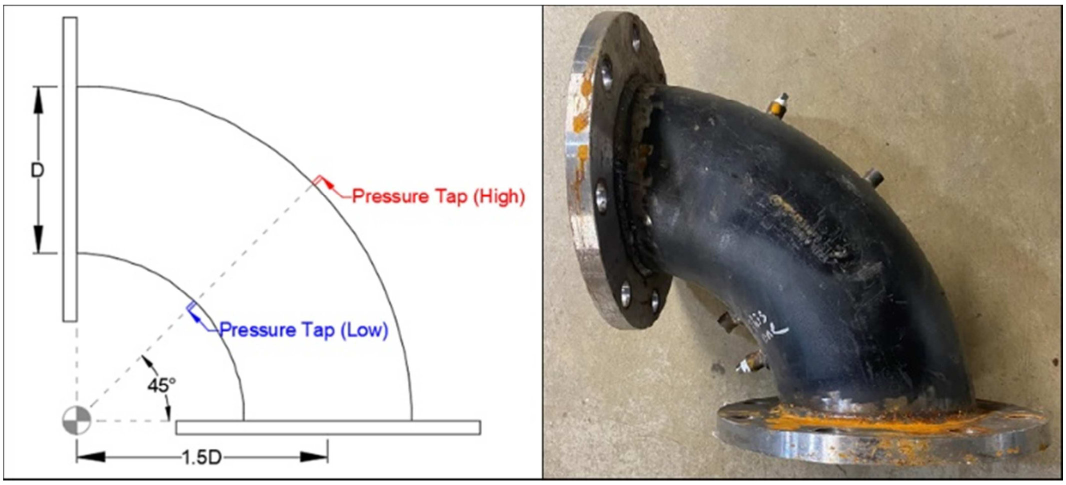

Figure 1. *Diagram and photo of a 150 mm (6 inch) long-radius elbow meter.*

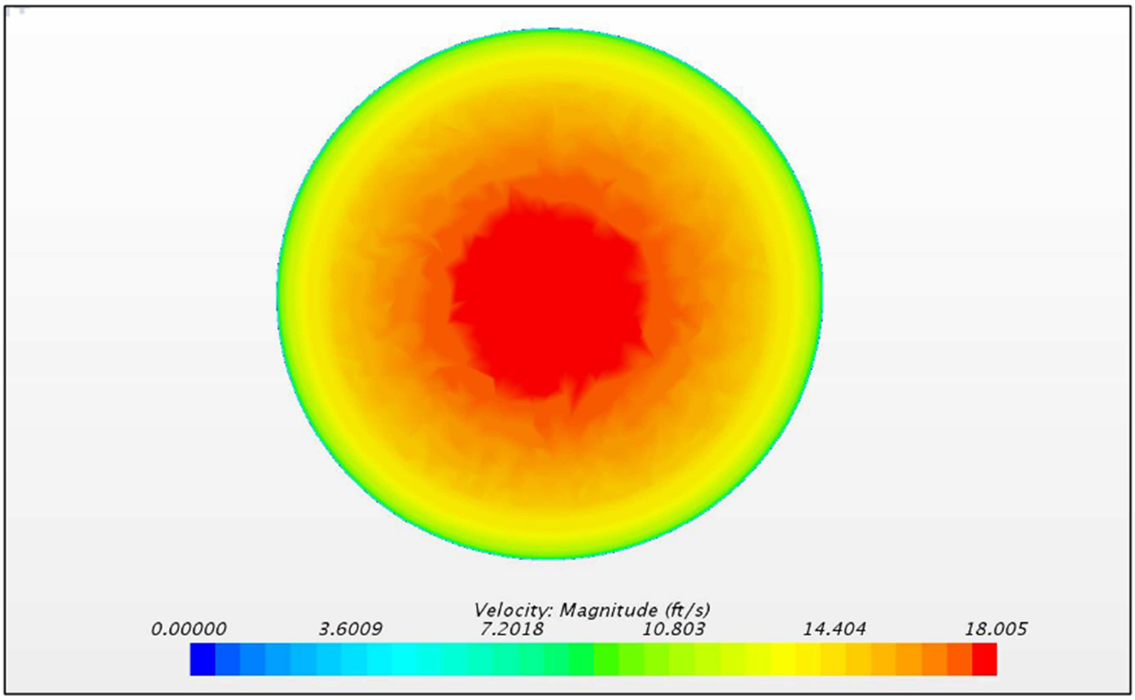

Figure 2. *Example of a Fully-Developed Flow Profile.*

It is generally accepted that the most accurate flow metering results for most flow meters occurs when the flow profile entering the meter is fully-developed. For this reason, published standards specify favorable installation conditions for specific flow meter types which may include information such as minimum recommended distances of smooth, straight pipe upstream or instructions as to eliminate any sudden offsets or changes in pipe wall smoothness by specifying the use of specific pipe connections in order to achieve a sufficiently high level of metering accuracy [1].

In this study of a long-radius, 150 mm (6-inch) elbow meter, the differential pressures observed ranged between 0.08 to 48.3 kPa (0.33 and 194 inches) with flow rates between 6.3×10^{-3} to 1.5×10^{-1} (100 gal min^{-1} to 2,350 gal min^{-1}). This range of flow conditions result in line velocities and pipe Reynolds numbers ranging between 0.3 to 7.9 m s^{-1} (1 to 26 ft s^{-1}) and 38,000 to 940,000, respectively for the 150 mm (6-inch) elbow meter.

2. Literature Review

A considerable quantity of research exists on quantifying the effects of different upstream flow disturbances for a large variety of different flow meters from researchers such as Stauffer [2] and Sharp [3], who both researched the effects that upstream flow disturbances have on Venturi flow meters and how to improve metering accuracy in those installations.

2.1. Origins of Research into Using Elbows as Flow Measurement Instruments

With regard to elbow meters, specifically, Jacobs and Sooy [4] were the first researchers with widely available experimental data on elbow flowmeters, testing 90 mm (3.5-inch), 100 mm (4-inch), and 150 mm (6-inch) flowmeters. While most of the tests performed as part of this study maintained straight pipe upstream of the flowmeter free from disturbances, a limited number of tests were performed placing an obstruction upstream of the 150 mm (6-inch) flowmeter. While the authors conclude that a distance between the elbow meter and the upstream disturbance of approximately 10 diameters is sufficient to maintain acceptable flow metering accuracy when compared to tests without the upstream flow disturbance; however, the results from this study offer limited insight into the effects of upstream flow disturbances due to the lower range of pipe velocities (0.2 m s^{-1} or 0.7 ft s^{-1} to 2.2 m s^{-1} or 7 ft s^{-1}) and Reynolds numbers (25,000 to 250,000) achieved during the study when compared to the current and other modern studies.

Murdock et al. [5] evaluated the state-of-the-practice of the time and compared data compiled from previous studies involving elbow flowmeters with standardized flowmeters such as orifices, nozzles, and venturis. The research shows that when the pipe Reynolds number is held constant, elbows having a ratio of the radius of curvature to the internal elbow diameter of 1.5 or greater show less variability with respect to discharge coefficient than elbows with a ratio of curvature to the internal elbow diameter less than 1.5. The research also showed that discharge coefficient varied with respect to pipe Reynolds number up until approximately 300,000 but noted that previous data was limited. Additionally, the research explored the effects of up- and downstream flow disturbances on elbow meter accuracy. Collected data consisted of a globe valve (Navy Type B-135) placed both up- and downstream of the elbow meter and showed no effects on discharge coefficient when the valve was placed downstream and effects as great as 4.5% to 2.5% when the valve was installed within 10-diameters upstream of the elbow meter.

2.2. Published Standards on the Installation of Elbow Meters with Respect to Distances Between the Meter and Upstream Flow Disturbances

From *Principles and Practice of Flow Meter Engineering 8th Edition* [6], it is recommended that an elbow meter be installed with at least 25 diameter-lengths of straight pipe downstream of any flow disturbance and with at least 10 pipe diameter lengths of straight pipe downstream of the elbow meter.

Also, in *Fluid Flow Measurement: A Practical Guide to Accurate Flow Measurement 2nd Edition* [7], the recommendation is that only 10 diameter lengths of straight pipe be installed before the elbow meter, with at least 5 diameter lengths of straight pipe installed downstream of the meter.

Finally, in *Instrument Engineers' Handbook, Volume 1: Process Measurement and Analysis 4th Edition* [8], it is stated: 'not enough data exist to establish precise correction factors for effects of upstream disturbances, viscosity, and roughness in pipe and elbow surfaces, and no published standards are available.' Furthermore, the general recommendation of the authors is to install at least 25 diameter lengths of straight pipe upstream of the elbow meter and at least 10 diameter lengths of straight pipe downstream of the meter.

2.3. Additional Research into the Effects of Upstream Flow Disturbances on Elbow Meter Accuracy and Summary

In *Flow Measurement Engineering Handbook 3rd Edition* [9], it is noted that 'Some tests have indicated that the differential measured at 22.5° rather than at 45° is more stable, reliable, and less affected by approach conditions.'

Some research on elbow meter performance has been conducted using computational fluid dynamics (CFD). For example, A. Rawat et al. [10] performed analysis of coal ash slurry flows in elbow meters. They did not, however, explore the effects that upstream disturbances have on metering accuracy; therefore, current published research with respect to the use and accuracy of elbow meters has been completed with the assumption that there is fully developed flow entering the meter.

Eguchi, et al. [11] looked at the effects that different velocity profiles had on the flow separation that occurs on the inside of an elbow fitting. Changes to the flow separation along the inside of the elbow bend could alter the accuracy and repeatability of the pressure readings taken at the low pressure tap. This study looked at the results of using different numerical methods to model the resulting flow separation and did not look specifically at the pressure difference at the standard pressure tap locations for an elbow meter. Laboratory testing, coupled with CFD research, could help to accelerate research into the topic of elbow meter performance in the presence of varying upstream flow disturbances.

Weissenbrunner, et al. [12] investigated the effects of a double elbow out-of-plane fitting installation upstream of ultrasonic flow meters on flow metering accuracy using CFD. Results showed that the difference in flow rate is between 1.5% – 4.5% when compared to an ideal, straight-line installation of the flow meter when the distance to the upstream disturbance is less than 40 pipe diameters.

Mazumder [13] used CFD to test the effects that elbows of varying radius-to-diameter ratios had on the pressure drop between the inside and outside radii of the elbow in multiphase flows. The author also compared the CFD results of the different test scenarios and resulting pressure differentials with empirical lab testing results and found good agreement between the CFD results and the empirical data.

2.4. Summary of Findings

Therefore, research into the topic of the effects of upstream flow disturbances on the accuracy of elbow flow meter measurement is lacking and published standards to provide best practice guidance on the use of elbow flow meters are not available. From the sources previously cited; however, a conservative recommendation for the proper installation of an elbow flow meter is to provide at least 25 diameter lengths of straight pipe before the flow meter and at least 10 diameter lengths of pipe after the flow meter to achieve sufficiently accurate meter performance. Furthermore, currently available research is lacking on what effects specific different upstream flow disturbances have on elbow metering accuracy. Consequently, the purpose of this research is to provide expanded information and empirical data that may benefit users of elbow meters for flow measurement.

3. Method

To calculate the theoretical flow rate of an incompressible fluid through an elbow meter by measuring the difference in pressure between the two pressure taps both located at an angle of 45°, the orifice equation can be used [14].

$$Q_{theory} = A \cdot F_a \sqrt{2 \cdot g \cdot \Delta H \cdot \frac{\gamma_{20°C}}{\gamma}} \quad (1)$$

As a result of energy loss in the fluid due to friction and a change in direction as it flows through the elbow, the actual flow through the elbow is less than the flow rate calculated using the theoretical flow rate equation (1). Therefore, the use of a discharge coefficient to account for these cumulative losses in the flow is introduced (2). The discharge coefficient is obtained through a laboratory calibration of the flowmeter where the theoretical flow rate is calculated, and the actual flow rate is measured. The ratio of these two values used to calculate the discharge coefficient becomes:

$$C_d = Q_{actual}/Q_{theory} \quad (2)$$

The resulting equation (3) for actual flow measurement comes from combining (1) and (2):

$$Q_{actual} = C_d \cdot A \cdot F_a \sqrt{2 \cdot g \cdot \Delta H \cdot \frac{\gamma_{20°C}}{\gamma}} \quad (3)$$

4. Laboratory Testing and Results

All of the tests conducted for this study occurred at the Utah Water Research Laboratory, a part of Utah State University, in Logan, Utah. All data were collected using calibrated flow meters and differential pressure transducers and have a maximum expanded uncertainty of 0.25% at 95%confidence according to the American Society of Mechanical Engineers Performance Test Code (ASME PTC) 19.1 2005 Test Uncertainty National Standard [15].

4.1. Comparison of 150 mm (6-Inch) Straight-Line Calibration Data with 2-Inch and 12-Inch Straight-Line Calibration Data

In order to assess whether size scale effects exist, baseline testing of each meter size was conducted. Each of the three elbow meters were calibrated in a straight-line configuration having at least 25 diameters of straight upstream pipe and 10 diameters of downstream pipe. The resulting data are shown in Table 1 and plotted in Figure 3.

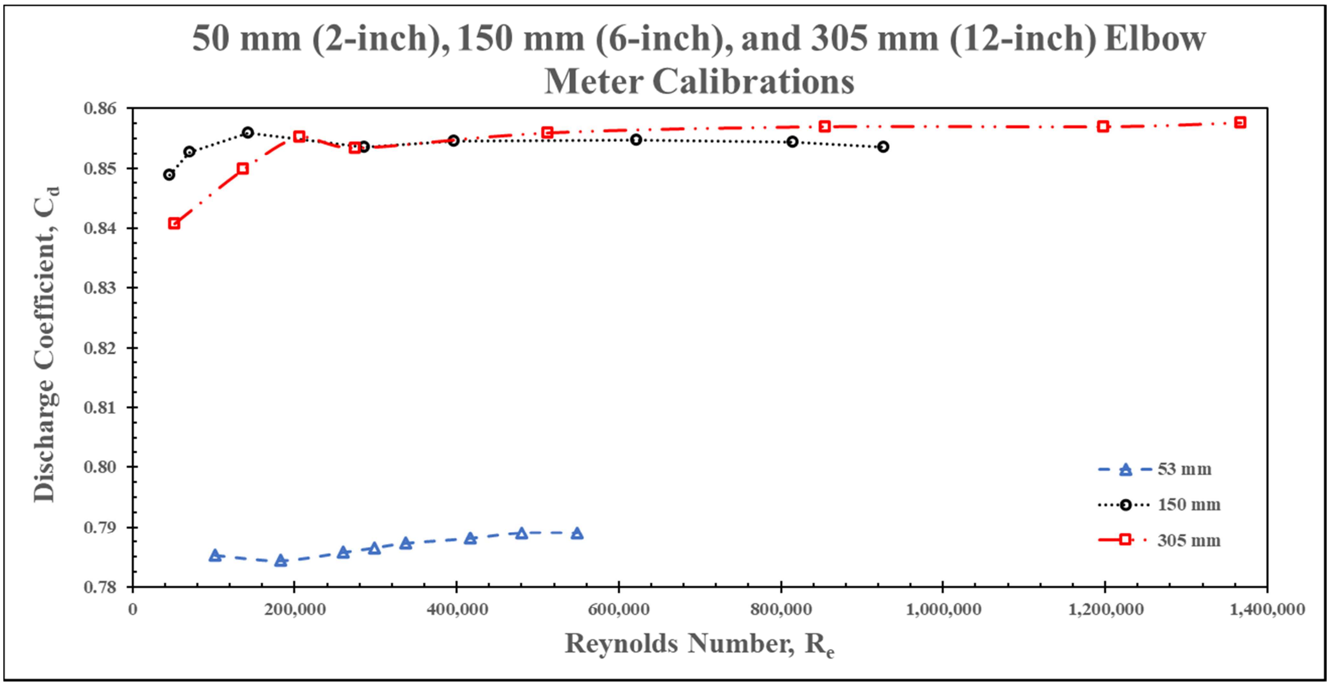

Figure 3. *Straight-line long-radius elbow meter calibration results for all elbow meter sizes.*

Table 1. *Straight-line long-radius elbow meter calibration data for all meter sizes.*

Meter Size (mm)	Average C_d	Reynolds Number		Flow Rate (m^3 s^{-1})		Differential Pressure (kPa)	
		High	*Low*	*High*	*Low*	*High*	*Low*
50	0.7870	548,898	101,938	3.3×10^{-2}	6.2×10^{-3}	187.73	6.54
150	0.8535	916,513	45,170	1.4×10^{-1}	7.1×10^{-3}	42.76	0.10
305	0.8533	1,367,150	51,564	5.0×10^{-2}	1.9×10^{-2}	32.94	0.05

Table 2. *Flow conditions for a pipe Reynolds number of 300,000 for all elbow meter sizes.*

Meter Size (mm)	Differential Pressure (kPa)	Volumetric Flow Rate (m^3 s^{-1})	Average Line Velocity (m s^{-1})
50	56.05	1.8×10^{-2}	7.92
150	3.99	4.4×10^{-2}	2.44
305	1.25	1.0×10^{-1}	1.52

A review of the data show that for the 150 mm (6-inch) and 305 mm (12-inch) meter sizes, once the Reynolds number at the inlet of the bend reaches about 300,000, the discharge coefficient value become nearly constant for the installation of interest. Therefore, with the understanding that the discharge coefficient for an elbow flow meter trends with the pipe Reynolds number until reaching a threshold approximately equal to or greater than 300,000 where the discharge coefficient stabilizes, and maximum flow metering accuracy can be achieved. However, for the 52.5 mm (2-inch) elbow meter, while the lower flows exhibited less variation in the discharge coefficient values, the values above a Reynolds number of about 300,000 show the same consistent trend as the other two elbow meter sizes. In addition, the differences between average discharge coefficient values for the three elbow meter sizes were much smaller between the 154.05 mm (6-inch) and 304.8 mm (12-inch) meters than between the 52.5 mm (2-inch) and 154.05 mm (6-inch) meters indicating the likelihood of size scale effects. Table 2 shows the flow conditions for which a Reynolds number of 300,000 was observed for each of the three tested elbow meter sizes.

4.2. Testing of the 150 mm (6-Inch) Long-Radius Elbow Meter

Next, the 150 mm (6-inch) elbow meter was installed and tested downstream from three different flow disturbances commonly found in pipelines: a single elbow in-plane in a ‘S’ shape (SE-IP ‘S’), a single elbow in-plane in a ‘U’ shape (SE-IP ‘U’), and double elbows out-of-plane (DE-OP). The amount of straight pipe preceding the elbow meter were 25, 10 and 5 pipe diameters. Figure 4 shows the three different pipeline configurations. For the double elbows out-of-plane configuration, the two upstream elbows were installed without any straight pipe in between them for all tests of this configuration.

Discharge coefficients were calculated for each pipeline configuration at each upstream distance and compared to the straight-line calibration data obtained during the initial tests in order to determine trends between the different elbow meter installation conditions. Table 3 lists the results for each pipeline configuration, which are also shown in Figure 5.

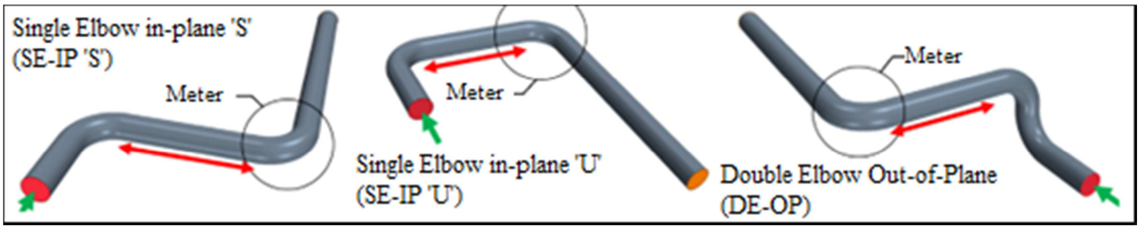

Figure 4. *Variation of pipeline configurations tested for the 150 mm (6-inch) elbow meter.*

Table 3. *150 mm (6-inch) long-radius elbow meter physical results summary table.*

Pipeline Configuration	Diameters from Upstream Disturbance	Average C_d	Shift from Straight-Line C_d
Straight-Line		0.8535	
	25	0.8464	-0.84%
Single-Elbow In-Plane “S”	10	0.8293	-2.84%
	5	0.8194	-3.99%
	25	0.8464	-0.83%
Single Elbow In-Plane “U”	10	0.8478	-0.67%
	5	0.8524	-0.14%
	25	0.8318	-2.55%
Double Elbow Out-of-Plane	10	0.8305	-2.70%
	5	0.8307	-2.67%

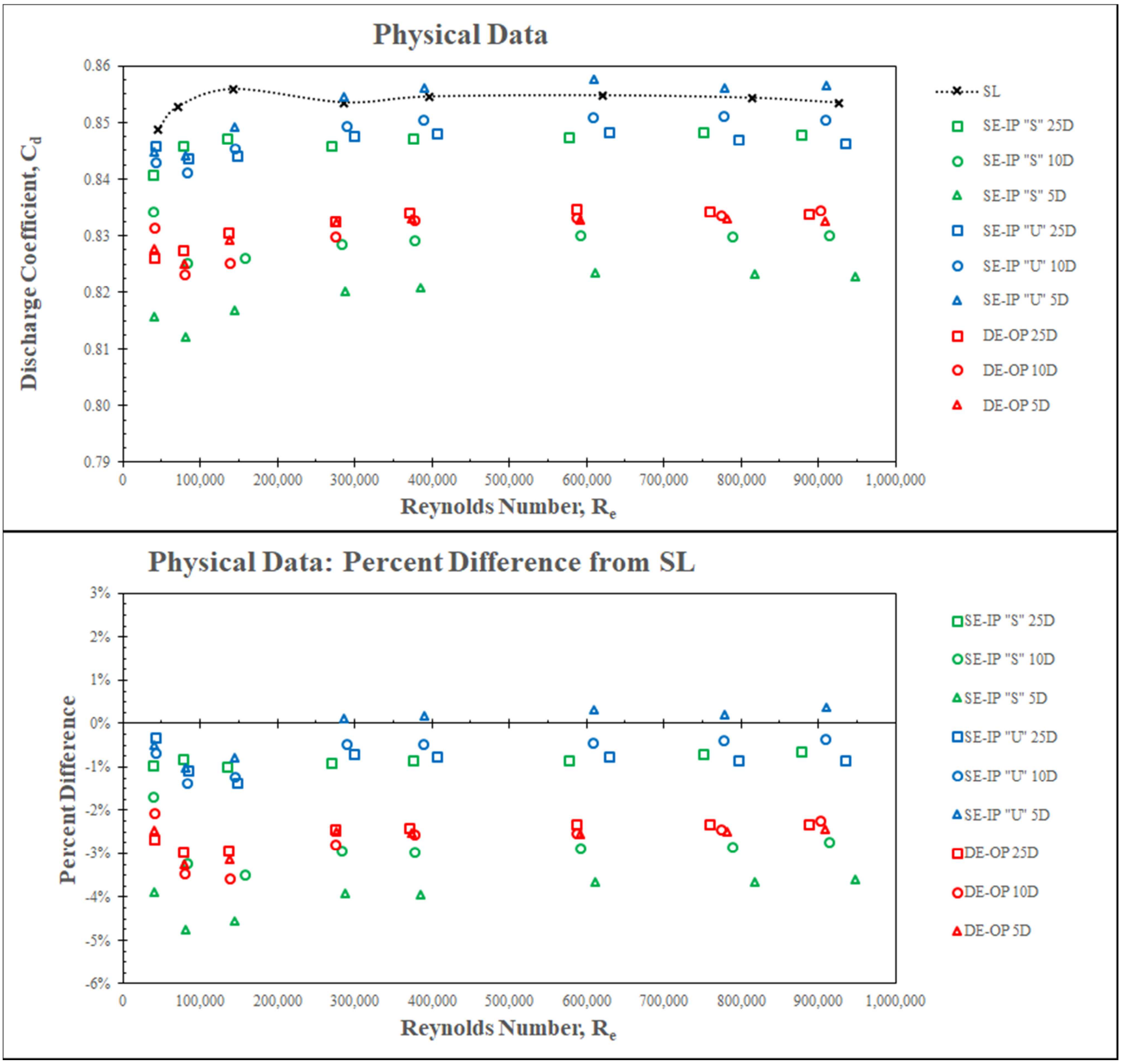

Figure 5. *Plots of C_d and percent difference shift in C_d from straight-line results for all configurations over Reynolds number, Re, for the 150 mm (6-inch) elbow meter.*

A review of the data show that for any tested configuration, including the straight-line test, once again, beyond a pipe Reynolds number threshold of about 300,000, the discharge coefficient values become nearly constant for the installation of interest.

Results from the single elbow in plans "S" configuration show that the discharge coefficient varies greater for changes in the distance between the flow meter and the upstream flow disturbance than in either the single elbow in plane "U" or double elbow out-of-plane configurations. Also, as the distance is increased between the elbow flow meter and the upstream flow disturbance in the single elbow in plane "S" configuration, discharge coefficients trend back towards the straight-line values more quickly than in the other two pipeline configurations tested as shown in Figure 6.

Testing also reveals that discharge coefficients for elbow flow meters installed in the single elbow in-plane "U" configuration with upstream distances from the flow disturbance between 10 to 25 diameter lengths remain between 0.50% and 1.00% below the straight-line discharge coefficient values. However, at a distance of just 5 diameter lengths from the upstream flow disturbance, the discharge coefficient was closer to the straight-line value with only a 0.14% difference.

Testing of the elbow meter installed in a double elbow out-of-plane configuration resulted in average discharge coefficients consistently between 2.55% to 2.70% below the average straight-line values at all three upstream distances between the flow disturbance and the elbow flow meter. The tests performed in this configuration were unable to capture any trending of the average discharge coefficient back towards the straight-line values within 25 diameter lengths.

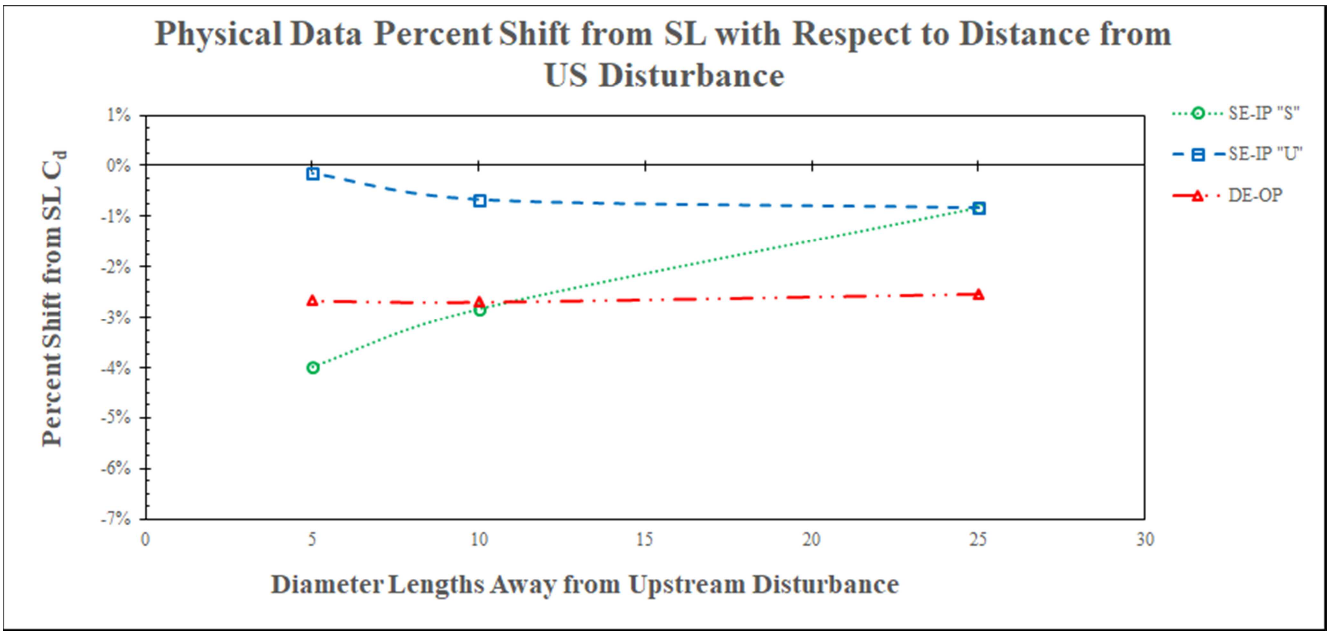

Figure 6. *Plot of change in average discharge coefficient with respect to distance between upstream flow disturbance and 150 mm (6-inch) elbow meter.*

4.3. Summary of Results

Within the maximum distance of 25 pipe diameter lengths tested for all three pipeline configurations, average discharge coefficients did not return to match those of the straight-line calibration values. Therefore, further research into what distances are necessary for the average discharge coefficients for all three configurations tested to return to the straight-line value is warranted. However, while the data may not agree with previously cited guidelines for the installation of elbow flow meters, the shifts in the average discharge coefficients for the two single elbow configurations are less than one percent when compared to the straight-line values. Therefore, further research into the effect that specific upstream flow disturbances not tested in this study is warranted.

As a result, it is important to consider both the level of metering accuracy and the nature of the upstream disturbance when specifying the distance of straight pipe upstream of an elbow flow meter.

5. Conclusions

If accurate flow measurement for an elbow meter is desired (within 0.25% calibrated and 4% uncalibrated), flows having Reynolds numbers greater than about 300,000 result in the most desirable conditions for nearly constant discharge coefficient values. When operating conditions result in pipe Reynolds numbers of less than 300,000, it is observed that the discharge coefficient values trend away from the average, and unless a precise calibration is completed, the user should be aware of the limits of the elbow meter's accuracy under such operating conditions. This research is intended to offer additional data and guidance as to the operation of elbow meters in the presence of common upstream flow disturbances.

When comparing the differences in the average discharge coefficient values between elbow meter sizes, the larger variation in values between the 50 mm (2-inch) and 150 mm (6-inch) meters when compared to the values of the 150 mm (6-inch) and 305 mm (12-inch) suggest that as pipe diameters increase, the average discharge coefficient values vary less indicating the presence of size scale effects. Further research into how the elbow meter discharge coefficient changes with respect to the elbow meter diameter could bring more understanding to how flow momentum, flow separation, and fluid viscosity could affect the pressure readings at the inside and outside pressure taps on the meter.

While fully developed flow created by a sufficiently long length of straight pipe is always the most desirable installation condition for any flow meter, various constraints may prevent this and a sub-optimal flow condition resulting from a non-standard flow meter installation may be required. Therefore, when using an elbow meter in the presence of an upstream disturbance, it is necessary to consider both the specific upstream disturbance and the feasibility of providing the conservative recommended guidelines of 25 diameters of upstream pipe when determining whether an installation-specific elbow meter calibration is warranted or not.

For any constraint that results in a sub-optimal elbow meter installation, the current research shows that specific types of upstream flow disturbances can have different magnitudes of effect on the accuracy of the flow meter: between -0.14% for the single elbow in-plane "U" configuration at a distance of 5 diameter lengths and -2.84% for the single elbow-in-plane "S" configuration at a distance of 10 diameter lengths. Furthermore, the observed effects of the upstream flow disturbances appear to last up to and even past the conservative recommendations of the 25 diameter lengths of straight pipe immediately upstream of an elbow meter. Interestingly enough, the double elbows out-of-plane configuration showed a shift in the average discharge coefficient, for distances between 5 and 25 diameter lengths, that appeared to be independent of the distance between the upstream flow disturbance and the elbow meter. Further research into how long this relationship between a shift in the discharge coefficient and the upstream distance between the meter and a flow disturbance in this specific installation configuration is also warranted.

Certainly, users of elbow meters in a unique or complex piping configuration with minimal straight length between the disturbance and the elbow meter may choose to have the elbow meter in its upstream simulated piping calibrated in a laboratory to determine the specific C_d for the meter.

It is anticipated that the data presented in this study will be beneficial for users with applications where elbows are present in the system and adequate straight pipe does or does not exist. Additionally, the data from this study should provide a greater degree of confidence for users desiring to use elbow meters to measure flow rates to within at least 4% of the actual flow without needing to perform a full calibration of the meter in its specific installation conditions.

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