Effect of a 90° Elbow on the Accuracy of an Insertion Flowmeter, Results and Comparisons for 4 and 6 in. Diameter PVC Pipe

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ABSTRACT

Thermal energy consumption in buildings with chilled or hot water distribution systems is often monitored through the use of some type of flow metering device. These flowmeters can be fixed types, such as venturis or orifices, or insertion flowmeters which can be more easily installed and removed. The easy removal and reinstallation of the insertion type flowmeters makes them good choices for use in existing buildings or in retrofit projects. Besides the installation benefits, insertion flowmeters can also be installed while the pipe is in service or "hot tapped". With any type flowmeter however, location in the pipe is a critical problem and deserves special consideration. Ideally, the meter should be inserted in existing pipe with a minimum of 10 to 15 diameters of straight pipe upstream of the meter location. This is rarely the case in existing piping distribution systems. It is much more common to be faced with only one or two candidate metering locations and these often are very short straight runs or will have elbows upstream and downstream of the proposed metering location.

This paper reports on flow measurement error resulting from an insertion flowmeter installed downstream of a 90° elbow. The measurement errors were compared for tests conducted in 4.0 and 6.0 inch (0.1 and 0.15 meter) diameter PVC pipe. The insertion flowmeter was a non-magnetic, tangential paddle wheel type. The flowmeter was located from 2 to 10 pipe diameters downstream from a 90° elbow with fluid velocities ranging from 1.0 to 10.0 ft/s (0.3 to 3.0 m/s). At each flowmeter location, the meter was rotated in 45° increments around the circumference of the pipe to quantify the effect of circumferential location on flow error.

The flowmeters were tested at the energy metering calibration facility at the Texas A&M University Energy Systems Laboratory Riverside campus. Flowmeter output was compared to mass flow measurements obtained from precision load cells mounted beneath a 1342 ft^3 (38 m^3) weigh tank. All output is given in terms of percent error relative to the load cells. Final results are presented as a function of flowmeter downstream location, circumferential rotation angle, and fluid velocity. Circumferential meter location was found to be a very important factor. The percent difference for the tested flow meters ranged from -23% to -5% in the 4.0 in. (0.1 m) pipe and from -33% to 1% in the 6.0 in. (0.15 m) pipe. The "best" location for these flowmeters was at zero degrees rotation angle, regardless of pipe size or meter location relative to the upstream 90° elbow.

INTRODUCTION

Accurately measuring liquid flow rates in circular pipe is important to those involved in monitoring or billing thermal energy usage in a facility. Ideally, a flowmeter should be installed in a straight pipe a minimum of ten diameters downstream of obstructions such as bends, tees, elbows, etc. (ASME 1971). In a new facility, the requirements of the flow metering equipment can be integrated directly into the design and layout of the piping system. Differential pressure type flowmeters, such as venturis or orifices, are common for new applications. For retrofit applications however, the engineer often has no choice about the configuration of the piping network in a facility. A specific piping system may have no long runs of straight pipe that would provide an ideal location for a flowmeter. The costs to modify an existing piping system just the purposes of accurate flowmetering are generally prohibitive. Due to the lack of long, straight accessible pipes, a flow sensor must sometimes be installed near a ninety degree elbow, a tee, or other obstruction that would provide non-uniform flow in the pipe. Few data are available to the user as to the impact the elbow or tee may have on the performance of the flowmeter.

Another difference between new and retrofit applications is that insertion turbine or paddle wheel flowmeters are often used rather than differential pressure type flowmeters. With many retrofit applications, chilled or hot water systems cannot be shut down to install a flowmeter. With an insertion flowmeter, the fitting and shutoff valve that holds the paddle wheel or turbine flow meter can be welded onto the existing pipe. A special drilling fixture is then attached to the valve and used to create the proper flowmeter opening into the pipe. This "hot tap" procedure allows the flowmeter to be inserted directly into the piping system without having to shut off the flow in the pipes. The meters are then adjusted into the flow at a depth and orientation specified by the manufacturer.

The purpose of this study was to measure the effect that a ninety degree elbow had on the accuracy of a hot-tapped, non-magnetic, paddle wheel flowmeter. The flowmeter was located at various positions downstream of the elbow and at various flow sensor rotation orientations with respect to the elbow.

BACKGROUND

As a fluid flows through a straight pipe and into a sharp bend, such as a ninety degree elbow, the pressure must adjust in the bend to counter the centrifugal forces. In the straight section the pressure is uniform across the flow. Through the elbow the fluid pressure is greatest at the outer wall, farthest from the center of curvature, and least at the inner wall [2]. At the inlet of the bend, the boundary layer on the outer wall experiences the effects of a positive stream wise pressure gradient. Conversely, the boundary layer of the inner wall at the inlet is accelerated. At the exit of the bend, the local pressure gradients are of the opposite sign as the flow adjusts to uniform pressure conditions downstream. With turbulent flow, a strong secondary flow forms on the inner side of the bend. The effect of the secondary flow is to displace the region of maximum velocity from the center towards the outer wall.

Through the use of Laser-Doppler measurements, Enayet found that flow through a ninety degree elbow showed the development of strong pressure-driven secondary flows on the inner side of the bend in the form of a pair of counter-rotating vortices in the stream wise direction [2]. This secondary flow developed in the bend and persisted downstream after the removal of the transverse pressure gradient responsible for its generation. The strong secondary flow was mainly confined to the region of steep velocity gradients near the inner wall. The removal of the transverse pressure gradient in the straight flow downstream of the bend resulted in a shift of the maximum velocity toward the outside. They found that a large secondary flow extended over the entire flow area at the exit (one diameter downstream) and persisted in the plane six diameters downstream of the bend. However, the transverse velocity gradients six diameters downstream decayed to approximately one half of their value at the one diameter downstream location.

Effects of bends, valves, manifolds, etc., upstream of a flow sensor have long been recognized as a source of flow sensor inaccuracy [3]. Numerous studies aimed at establishing acceptable lengths between the flow sensor and the disturbance have been conducted [4]. An alternative approach is to make use of some characteristic of the flow sensor as an index of the effect of the flow distribution and hence build in a self-correcting capability. The present authors are unaware of any studies focused on this alternative approach. The aim of the present study corresponds to this alternative approach of attempting to build in a self-correcting capability.

EXPERIMENTAL SETUP

The facility used to test the effect of a ninety degree elbow on accuracy of the paddle wheel flow meter is illustrated in Figure 1. This facility was used in prior calibrations of liquid flowmeters [5]. It consisted of two 1342 ft^3 (38 m^3)holding tanks, four parallel supply pumps, two test sections with inner diameters of 4.0 in. and 6.0 in. (0.1 m and 0.154 m), a return line and a return pump. The volumetric flow rate of water through the pipe test section was calculated by three devices: 1) dynamic weight load cells, 2) differential pressure across an orifice plate and 3) the flow sensors being tested. Underneath the receiving tank platform were four symmetrically placed strain-bridge load cells. These load cells dynamically weighed the water in the receiving tank during a test run. This information along with water temperature and time was used to calculate the volumetric flow rate. The orifice plate assembly consisted of interchangeable plates of various sizes and utilized corner taps to measure the differential pressure generated across the plate. The volumetric flow rate was determined from the differential pressure measurement and flow constant of the orifice. The purpose of this orifice plate assembly was to verify the values obtained using the load cells. With the load cells and orifice, there was both a primary and a secondary means to determine the flow rate through the test section.

The local flow rate near the vicinity of elbows was measured using a hot-tap, non-magnetic, paddle wheel flow meter. The impeller of this flow meter had six blades, which when rotated, broke an electric field and produced an approximately square wave signal with a frequency proportional to the flow rate.

The flow rate could be varied by using different combinations of the four supply pumps and/or by adjustment of the ball valve and/or gate valve positioned after the test section. The supply pumps consisted of the following displacement capacities: 48, 158, 602, and 650 gpm (10, 38 and 41 l/s). The ball valve and gate valve were used for coarse and fine adjustment, respectively, of a target volumetric flow rate when the pumps alone could not provide a desired flow rate. The supply pumps were approximately 22 diameters upstream of the flowmeter test section. The ball and gate valves were at least 28 diameters downstream of the test section. Perforated plate type flow straighteners were used before the test section and immediately after the tee in the vertical rise leading to the receiving tank to produce fully developed flow across the orifice plate.

As shown in Figure 2, the flowmeter featured a six-bladed, forward swept impeller design. As the flow turned the impeller, a low impedance 8 Vdc square wave signal was transmitted with a frequency proportional to the flow rate. The flow sensor used a coupled transformer to detect flow, to maximize signal to noise performance and enhance low-end performance and turn-down ratio. To assure reporting total flow, the sensor was visually aligned parallel with the flow through the use of an alignment indicator located immediately under the sensor's cap.

The flow sensor was located in one of three stations between the second and third 90° elbows (Section B), shown in Figure 3 for tests in the 4.0 in. (0.1 m) diameter pipe. The flowmeter location was changed to the station between the first and second 90° elbow (Section A) for the tests in the 6.0 in. (0.15 m) pipe. Both sections A and B could be rotated to provide numerous flow sensor orientations. The rotation angles used in this test are shown and defined in Figure 4.

A data acquisition system was used to record the scan time, the water temperature, the number of flow sensor pulses, the cubic feet of water pumped (from load cells), and the differential pressure across the orifice plate. Data were collected at five second intervals.

TEST PROCEDURE

Straight 4.0 and 6.0 in. (0.1 and 0.15m) inside diameter test sections and 4.0 and 6.0 in. (0.1 and 0.15m) inside diameter elbowed test sections with flow sensor stations at various diameters downstream of a ninety degree elbow were used to determine the percent difference between the flow rate reported by the load cells and the flow rate reported by the flow sensors. For all the test runs (every meter location and orientation), the orifice plate reported a flow rate which was within ±1.0 percent difference of the flow rate indicated by the load cells over the flow rate range. Therefore, only comparisons to the primary standard, the load cells, will be used to avoid redundancy. A negative percent difference meant that the flow sensor reported a lower flow rate than did the load cells. A test run consisted of checking this percent difference through a range of flow rate points, from 1.0 to 10.0 ft/s (0.3 to 3.0 m/s), at a particular flow sensor location and rotation orientation.

To ensure that the results were not flowmeter specific, two flowmeters, of the same type and model, were independently tested. One flowmeter was inserted into the test section and a test run was recorded. This meter was then replaced with the second flowmeter and the tests were repeated over the flow range.

To provide a base case, the two flowmeters were independently tested in straight sections of pipe with the flowmeters located as recommended [1]. The straight test sections were then replaced with the elbowed test sections as shown in Figure 3. The two flowmeters were also independently tested at the station immediately after a 90 degree elbow (two diameters downstream of the elbow). After viewing the results of this elbowed station and the straight section, it was found that the flowmeters were providing similar results.

Both flowmeters were within ± 1.4 percent difference of the flow rate measured by the load cells. This value was within the uncertainty of the measurements (see following section). Therefore, testing was continued using only one flowmeter. All reported results were with this flowmeter. The flowmeter was then tested at 5.7 and 9.8 diameters downstream of the elbow in the 4.0 in. (0.1m) pipe and at 6.0 diameters in the 6.0 in. (0.15m) pipe. The results of the elbow tests were compared graphically to the results of the straight section.

The flowmeters were inserted into the 4.0 and 6.0 in. (0.1m and 0.15m) pipe to a depth of 1.5 in. (3.8 cm) which was the manufacturer's recommended insertion depth. The insertion depth was determined with the aid of a caliper, which could measure to $\pm$ 0.001 in. (0.025 mm).

For a particular flow rate, data were recorded for 315 seconds by the data acquisition system. This provided a total of 63 data points. However, when calculating the average flow rates, only the middle 265 seconds of data were used (53 data points). This technique eliminated any effects due to transient start up or shut down flow fields. Therefore, the flow analyzed was fully developed.

UNCERTAINTY ANALYSIS

An uncertainty analysis was performed to estimate the experimental uncertainty in the determination of the percent error difference between the load cell's flow rate and the flow sensor's flow rate. The flow rate derived from the load cells was calculated from measured water weight in the receiving tank and the water temperature. The flow rate derived from the flow sensor was calculated from the measured water temperature, the sensor pulses, and the measured inner diameter of the test section pipe. The experimental uncertainties of these measured variables are given in Table 1.

Data used in this uncertainty analysis were taken from data collected during a test run. The uncertainty was calculated using the ANSI/ASME method [6]. Using this approach, the uncertainties of the specific weight ($\omega_{sp\,wt.}$), the volume of water (ω_{vol}), the volumetric flow rate ($\omega_{\dot{V}}$), and the percent difference between the load cell and the flow sensor ($\omega_{\%diff}$) were calculated. The precision portion of the uncertainty measurements was found to be negligible throughout the flow range. The total uncertainty results are shown in tabular and graphical forms in Table 2 and Figure 5, respectively. As the flow rate increased from 1.0 to 10.0 ft/s (0.3 to 3.0 m/s), the uncertainty of the percent difference decreased from 10.1% to 1.0%. Thus, there was a much larger uncertainty at lower flow rates.

RESULTS

The output from the flowmeters were compared to the measured results of the load cells. The load cells served as the reference for all measurements. The percentage error was defined as:

$$\%error = \frac{\dot{V}_{f.s.} - \dot{V}_{l.c.}}{\dot{V}_{l.c.}}$$

where

$\dot{V}_{f.s.}$ = volumetric flow rate of the flow sensor (ft^3/min, m^3/s) and $\dot{V}_{l.c.}$ = volumetric flow rate of the load cells (ft^3/min, m^3/s)

It was observed that the flow sensor for a particular location and rotation orientation reported nominally constant percentage errors through the entire test flow rate range (1.0 to 10.0 ft/s (0.3 to 3 m/s)), as shown for both pipe diameters in Figure 6. This was especially true of the upper portion of the flow rate range (2.0 to 10.0 ft/s (0.6 to 3 m/s)). For the selected data series, Figure 6 shows that there was more variation in the percent differences at flow rates below 2.0 ft/s (0.6 m/s) than there was between 2.0 to 10.0 ft/s (0.6 to 3 m/s). This could indicate that there were slightly different flow patterns for the velocities below 2.0 ft/s (0.6 m/s). Additionally, as shown in Table 2, the uncertainties associated with the flow measurements at lower flow rates was much greater than for higher flow rates. The measurement uncertainty at 1.0 ft/s (0.3 m/s) was ten times higher than that for 10.0 ft/s (3 m/s). A negative percent difference in Figures 6 and 7 indicated that the flow sensor was reporting a lower flow rate than the load cells. Because the data points were approximately constant through most of the flow rate range (2.0 to 10.0 ft/s (0.6 to 3 m/s)) for a given flow sensor location and orientation, the data points were averaged yielding a single point for the flow sensor through the entire flow rate range. Thus, each data point would represent an entire flow run through the flow rate range 1.0 to 10.0 ft/s (0.3 to 3 m/s).

The flowmeters were tested at five different rotation angles from 0° to 180° in increments of 45° for a given downstream location with the flowmeter placed at the manufacturer's recommended insertion depth. The results obtained from this experimental study on the effect of a ninety degree elbow on the reported accuracy of a non-magnetic, impeller flow are illustrated in Figures 7 and 8. These figures present the results in different formats, allowing insight into the interpretation of the results.

The graphs show that the flowmeters performed within the manufacturer's stated uncertainty for the straight section tests. The specifications of the flow sensor's accuracy was ± 0.1 ft/s (0.03 m/s), which could also help explain the -0.7% reported flow rate error by this sensor in a seemingly ideal location.

As shown by Figure 8, there was a significant flow distortion after the elbow for both pipe sizes. The largest errors occurred at the following configurations: 2.0 diameters downstream, 180° rotation position, 4.0 in. (0.1 m) pipe: 2.0 diameters downstream, 180° rotation position, 6.0 in. (0.15 m) pipe; and 5.7 diameters downstream, 90° rotation, 4.0 in. (0.1 m) pipe: 6.0 diameters downstream, 135° rotation, 6.0 in. (0.15 m) pipe. The optimum rotation angle regardless of position downstream of the elbow or pipe size was the zero degree rotation angle. This was true except at 6.0 diameters downstream in the 6.0 in. (0.15 m) pipe where the best rotation angle was 45°.

Figure 8 shows the large spread in the flow measurement due to rotation angle for a particular downstream meter location. The greatest gains in reducing error by correct flow sensor rotation angle could be achieved at the 2 diameters downstream of the elbow location for either of the two pipe sizes tested. The possible error correction for this position was from -23% to -5% in the 4.0 in. (0.1 m) pipe and from -33% to 1% difference in the 6.0 in. (0.15 m) pipe.

CONCLUSIONS

An experimental investigation into the effects of a ninety degree elbow on the reported accuracy of an insertion type, non-magnetic, impeller flowmeter has been conducted. These tests were performed using 4.0 and 6.0 inch (0.1 and 0.15 meter) nominal diameter PVC pipes. Noting that the inserted flowmeter's impeller was located near the center line of the 4.0 in. (0.1 m) pipe, the results are consistent with Enayet's study reporting the flow pattern through and following a ninety degree elbow.

In the present study, it was found that locating an insertion flowmeter in the immediate downstream vicinity of a ninety degree elbow significantly disturbed the accuracy of the flow sensor in general. However, by correct flow sensor rotation placement, these errors can be greatly reduced. The error data given in Table 3 together with Figure 8 could be used to reduce the error associated with flow measurement downstream of a 90° elbow.

If flow in a pipe needs to be measured and an optimum location for a flowmeter does not exist, then the results in this study could be used to provide corrections to meters that are installed downstream of 90° elbows. For example, if a flowmeter had to be placed in a 6.0 in. (0.15m) diameter pipe, 2 diameters downstream of an elbow, and with a rotation angle of 135° with respect to the elbow, a correction factor of 24.6% could be calculated into the reported flow rate to obtain a significantly more accurate value. These type corrections could also be applied to insertion-type impeller flowmeters in existing 4.0 and 6.0 in. (0.1 and 0.15m) piping systems.

The distortions in the velocity flow field are evident in the error data of Figure 8. Equally evident, is the dissipation of these distortions with distance away from the 90° elbow. The flowmeter in the larger diameter pipe indicated better flow measurement over all rotation angles than in the smaller diameter pipe. This would seem to indicate that the flow distortions caused by the 90° elbow are more persistent in the smaller pipe. With a larger diameter pipe, it appears that rotational position is not as critical provided the meter is placed at least 6 diameters downstream of the elbow.

This study was limited to two specific diameters of schedule 40 PVC pipe (4.0 and 6.0 in. (0.1m and 0.15m)) and one type of insertion, paddle-wheel, flowmeter. The flowmeter had a specific recommended insertion depth into the flow stream. There are similar flowmeters made by different manufacturers that have different insertion depths. Because the flow in the pipe would be expected to vary, depending on the location in the pipe, the results from this study must be used with caution if applied to other flowmeters. Due to the uncertainty involved in the measurement at the low flow rates, the reader should use caution when applying the results found in this study to low flow situations.

It is recommended that this study be extended to other pipe diameters and flowmeters. With the extension to other diameters, a more general set of corrections to the measured flow could be developed. The correction factors would be applicable to differing pipe sizes, rotation angles and location in the pipe. Extending the study to other flowmeters could isolate some types of flowmeters that would be able to obtain an average flow across the pipe section as compared to the paddle wheel flowmeter used here.

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NOMENCLATURE

C	Celsius
D	diameter
F	Fahrenheit
Ft	feet
gpm	gallons per minute
ID	inner diameter
l	liter
lb	pound
m	meter
N	Newton
s	second
Sp.Wt	specific weight
T	temperature
$\dot{V}$	volumetric flow rate
Wt	weight

Subscripts

f.s.	flow sensor
l.c.	load cells
sp.wt.	specific weight
$\dot{V}$	volumetric flow rate
Vol	volume

Greek symbols

ω	uncertainty of measurement

Table 1. Experimental Uncertainties of Measured Variables.

Measured Variables	Experimental Uncertainty
Temperature (T)	± 0.5°F (0.3°C)
Weight (Wt)	± 151.1 lb (672.1 N)
Pipe Inner Diameter (ID)	± 0.02 in (0.00051 m)

Table 2. Experimental Uncertainties of Percent Differences Between Load Cell and Flowmeter.

Vel.	Wt.	Sp.Wt.	Vol.	$\dot{V}$	ω Vol.	ω $\dot{V}$	ω%diff. (%)
0.65 ft/s (0.2m/s)	906.1 lb (4027N)	62.24 lb/ft^3 (9774N/m^3)	14.5 ft^3 (0.41m^3)	0.07 ft^3/s (0.002 m^3/s)	2.5 ft^3 (0.07m^3)	9.4e-3 ft^3/s (2.66e-4 m^3/s)	14.9
1.0 ft/s (0.3m/s)	1414 lb (6284N)	62.24 lb/ft^3 (9774N/m^3)	22.6 ft^3 (0.64m^3)	0.11 ft^3/s (0.003 m^3/s)	2.5 ft^3 (0.07m^3)	9.36e-3 ft^3/s (2.65e-4 m^3/s)	10.1
1.6 ft/s (0.5m/s)	2246 lb (9985N)	62.24 lb/ft^3 (9774N/m^3)	36 ft^3 (1.02m^3)	0.14 ft^3/s (0.004 m^3/s)	2.5 ft^3 (0.07m^3)	9.4e-3 ft^3/s (2.66e-4 m^3/s)	6.6
2.3 ft/s (0.7m/s)	3201 lb (14227N)	62.21 lb/ft^3 (9771N/m^3)	51.5 ft^3 (1.46m^3)	0.21 ft^3/s (0.006 m^3/s)	2.5 ft^3 (0.07m^3)	9.4e-3 ft^3/s (2.66e-4 m^3/s)	4.4
2.9 ft/s (0.9m/s)	4085 lb (18154N)	62.21 lb/ft^3 (9771N/m^3)	65.7 ft^3 (1.86m^3)	0.25 ft^3/s (0.007 m^3/s)	2.5 ft^3 (0.07m^3)	9.36e-3 ft^3/s (2.65e-4 m^3/s)	3.6
4.3 ft/s (1.3m/s)	6071 lb (26983N)	62.21 lb/ft^3 (9771N/m^3)	97.5 ft^3 (2.76m^3)	0.39 ft^3/s (0.011 m^3/s)	2.5 ft^3 (0.07m^3)	9.4e-3 ft^3/s (2.66e-4 m^3/s)	2.4
5.2 ft/s (1.6m/s)	7435 lb (33046N)	62.21 lb/ft^3 (9771N/m^3)	119.3 ft^3 (3.38m^3)	0.46 ft^3/s (0.013 m^3/s)	2.5 ft^3 (0.07m^3)	9.4e-3 ft^3/s (2.66e-4 m^3/s)	1.9
6.2 ft/s (1.9m/s)	8774 lb (38995N)	62.21 lb/ft^3 (9771N/m^3)	140.9 ft^3 (3.99m^3)	0.53 ft^3/s (0.015 m^3/s)	2.5 ft^3 (0.07m^3)	9.36e-3 ft^3/s (2.65e-4 m^3/s)	1.6
7.2 ft/s (2.2m/s)	10466 lb (46515N)	62.21 lb/ft^3 (9771N/m^3)	168.1 ft^3 (4.76m^3)	0.63 ft^3/s (0.018 m^3/s)	2.5 ft^3 (0.07m^3)	9.4e-3 ft^3/s (2.66e-4 m^3/s)	1.4
8.2 ft/s (2.5m/s)	11498 lb (51104N)	62.2 lb/ft^3 (9774N/m^3)	184.7 ft^3 (5.23m^3)	0.71 ft^3/s (0.020 m^3/s)	2.5 ft^3 (0.07m^3)	9.4e-3 ft^3/s (2.66e-4 m^3/s)	1.2
10.0 ft/s (3.0m/s)	13914 lb (61840N)	62.2 lb/ft^3 (9774N/m^3)	223.5 ft^3 (6.33m^3)	0.85 ft^3/s (0.024 m^3/s)	2.5 ft^3 (0.07m^3)	9.36e-3 ft^3/s (2.65e-4 m^3/s)	1.0

Table 3. Percent Differences Between the Load Cells and Flowmeter (Note: Each point represents an average difference over the flow range of 1.0 to 10.0 ft/s (0.3 to 3 m/s)).

		Rotation Angle				
Pipe I.D.	Meter Position	0°	45°	90°	135°	180°
4.0 in (0.10 m)	2.0 D's	-4.8%	-5.9%	-15.2%	-22.2%	-22.8%
6.0 in (0.15 m)	2.0 D's	0.7%	-4.6%	-11.0%	-24.6%	-32.2%
4.0 in (0.10 m)	5.7 D's	-9.1%	-10.9%	-15.6%	-12.8%	-9.9%
6.0 in (0.15 m)	6.0 D's	2.5%	0.8%	-2.5%	-7.3%	-7.1%
4.0 in (0.10 m)	9.8 D's	-8.1%	-8.4%	-8.3%	-5.4%	-4.9%
4.0 in (0.10 m)	Straight section	-0.7%	-0.7%	-0.7%	-0.7%	-0.7%
6.0 in (0.15 m)	Straight section	*	*	1.4%	*	*

* not tested

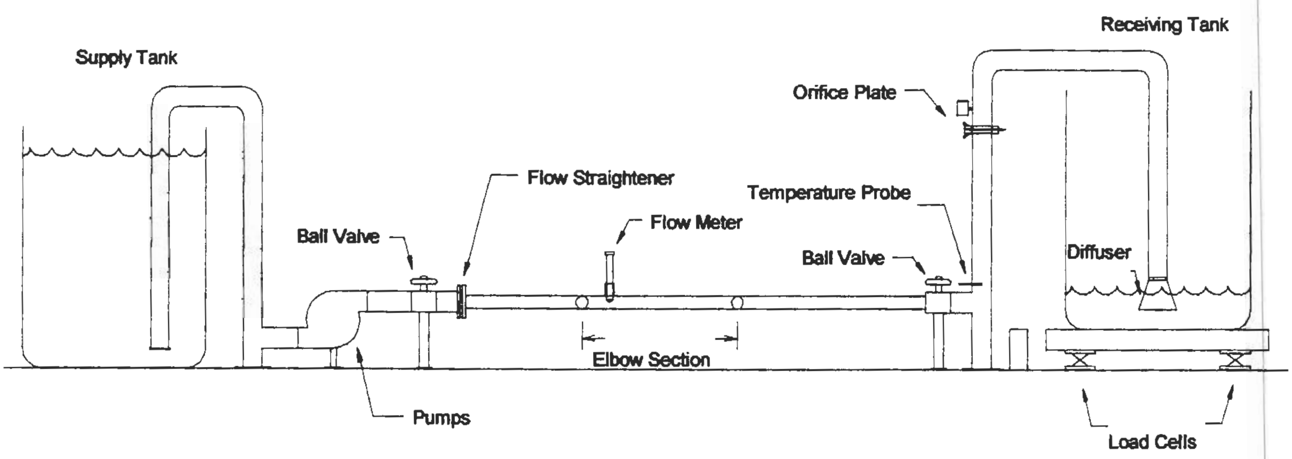

Figure 1. Liquid Flow Loop Layout.

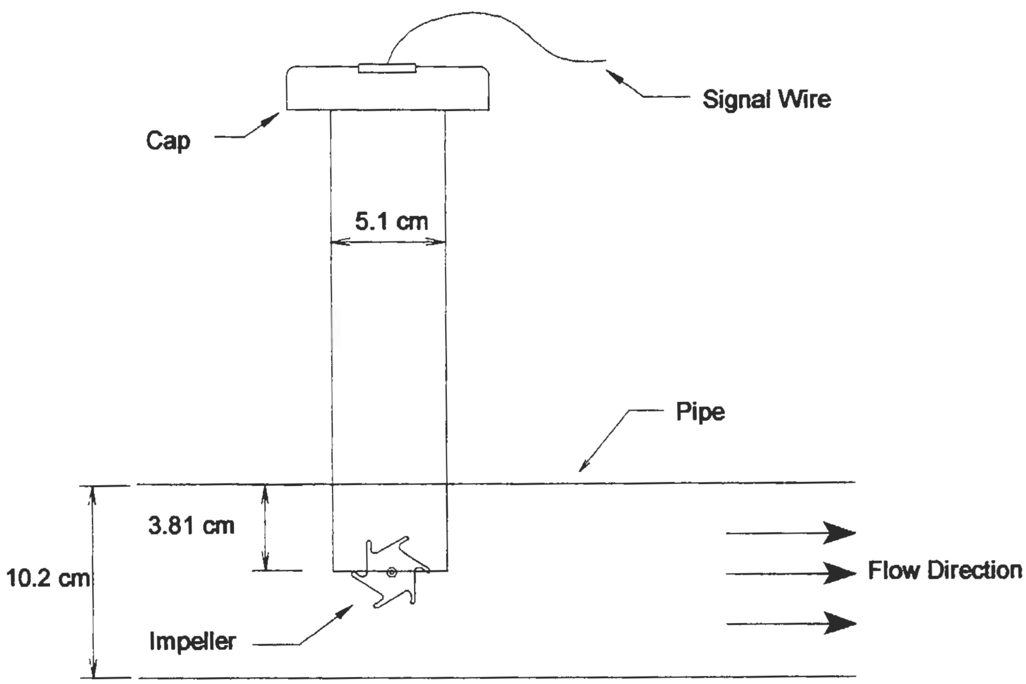

Figure 2. Cross-sectional View of Impeller Flowmeter.

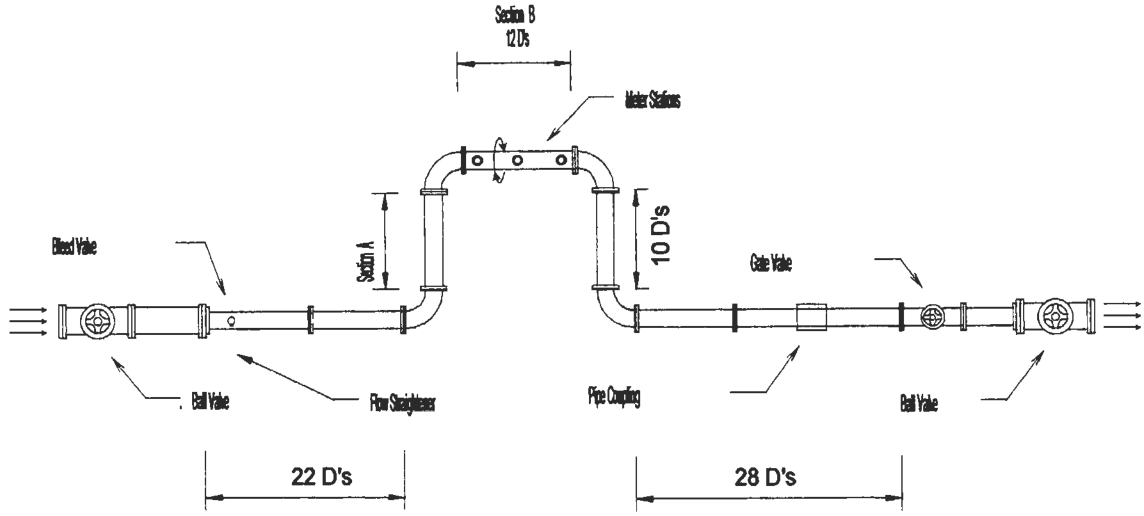

Figure 3. Schematic of Flow Loop 90° Elbow Test Section.

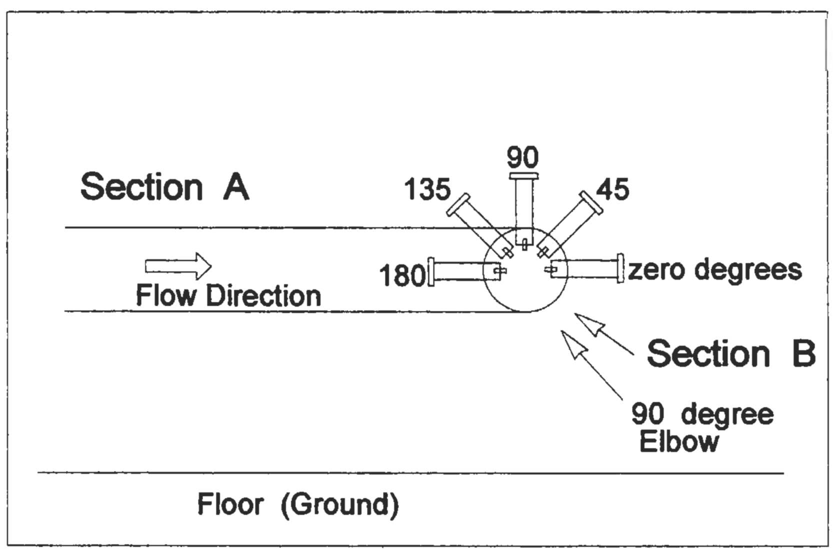

Figure 4. Definition of Flow Sensor Rotation Angles.

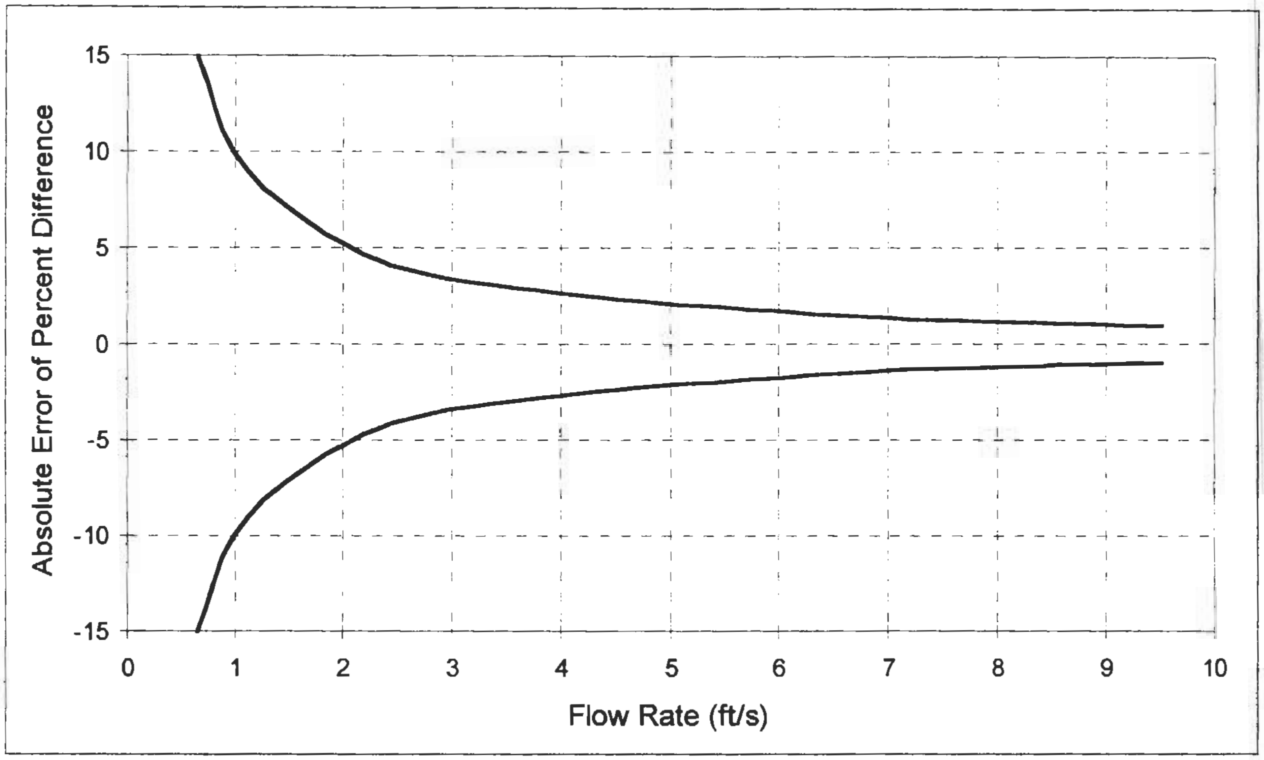

Figure 5. Representation of the Uncertainty of the Percent Difference Between the Load Cells and Flowmeter.

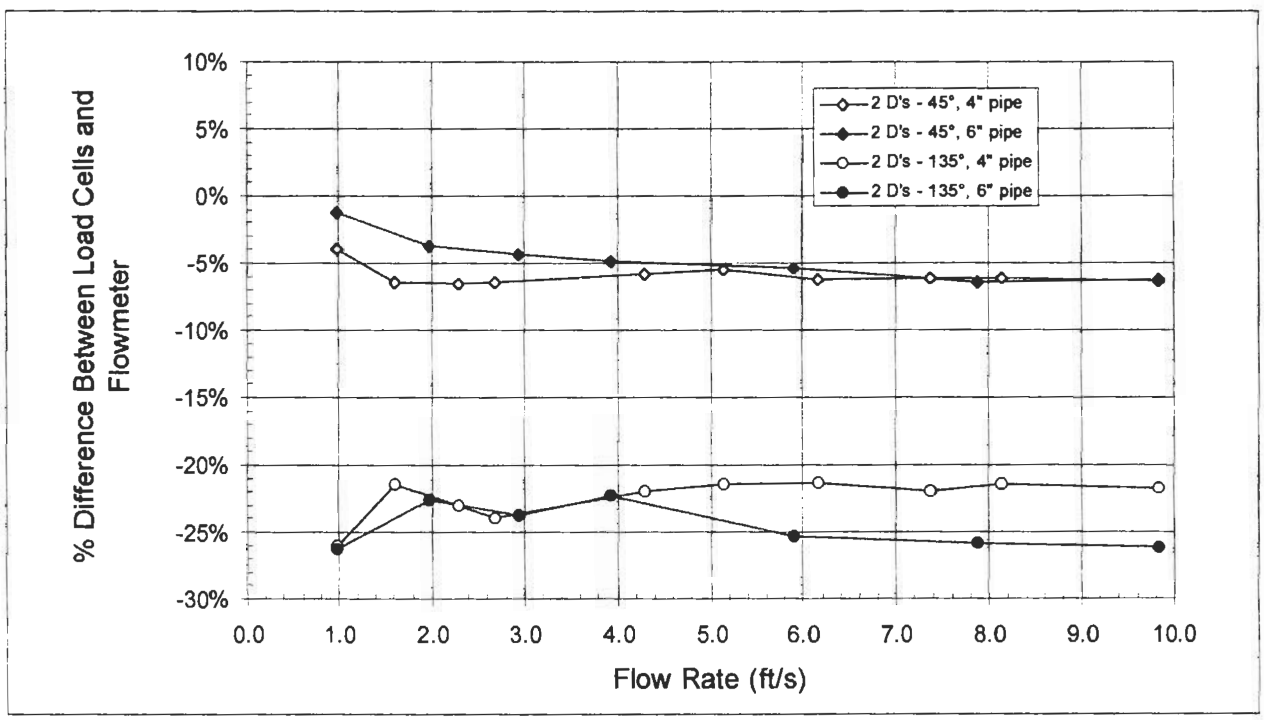

Figure 6. Flowmeter Test Data for 4 in. and 6 in. (0.1 and 0.15m) Pipe at Selected Positions and Rotations.

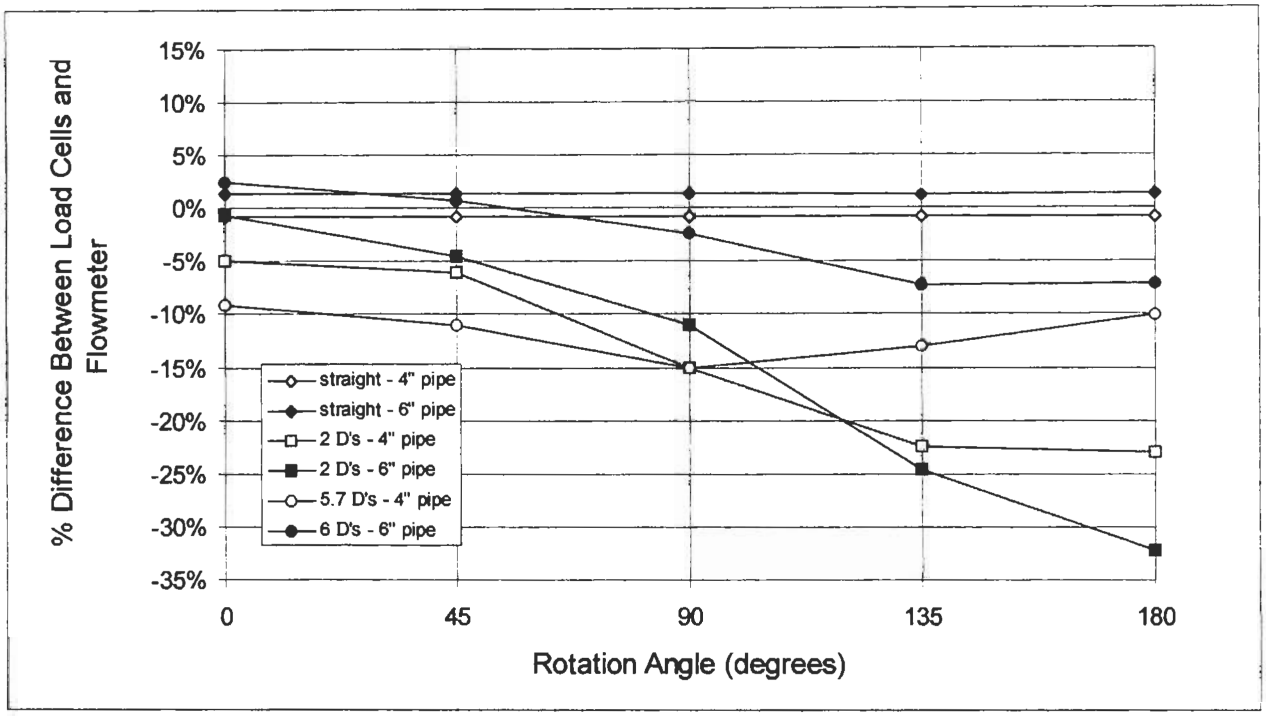

Figure 7. Comparison of Average Percent Differences for 4 in. and 6 in. (0.1 and 0.15m) Pipes as a Function of Rotation Angle and Location Downstream from a 90° Elbow.

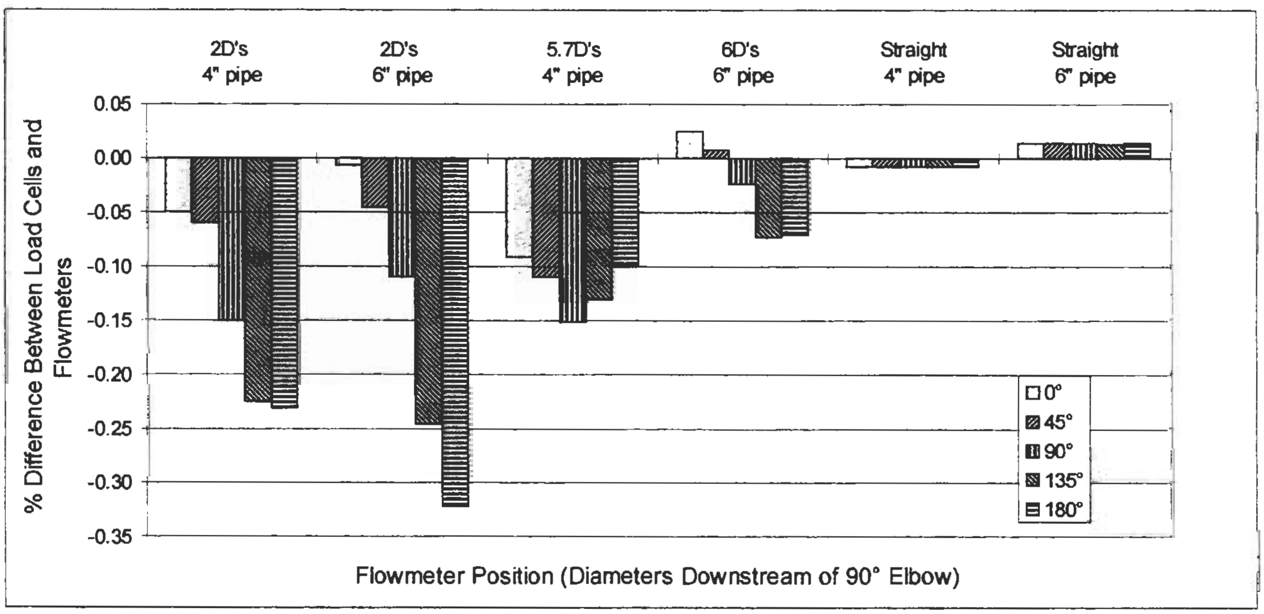

Figure 8. Comparison of Error for Flowmeters at Different Locations Downstream of a 90° Elbow, Rotational Orientations, and for Different Diameter Pipe.