The Effect of Elbows on the Accuracy of Liquid Flow Measurement with an Insertion Flowmeter

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ABSTRACT

The measurement error of an insertion flowmeter located downstream of a 90-degree elbow was quantified for water flowing in 4 in. (0.10 m) and 6 in. (0.15 m) diameter pipes. The flowmeter location was varied between 2 and 9 diameters downstream of the elbow. Three metering angle orientations relative to the outside horizontal plane of the elbow were evaluated: 0, 90, and 180 degrees. Three radii of curvature were also evaluated: 2.5 in. (0.06 m), 4.5 in. (0.11 m), and 6.5 in. (0.17 m). For a 4 in. (0.10 m) diameter pipe with a radius of curvature of 2.5 in. (0.06 m), the largest measurement error was 28% at 2 diameters downstream of the elbow and 180-degree orientation. For a 4 in. (0.10 m) diameter pipe with a radius of curvature of 4.5 in. (0.11 m), the largest measurement error was 15% at 2 diameters downstream and 180-degree orientation. For a 6 in. (0.15 m) diameter pipe with a radius of curvature of 2.5 in. (0.06 m), the largest measurement error was 45% at 2 diameters downstream and 180-degree orientation. The length required for measurement error to be less than 5% for 4 in. (0.10 m) and 6 in. (0.15 m) diameter pipes ranged from 6 to 10 diameters downstream of the elbow.

INTRODUCTION

Monitoring energy use in buildings often requires measurement of thermal energy such as chilled or hot water. Accurate metering is critical to the verification of retrofit savings or the billing of energy use. Monitoring thermal energy typically requires a flowmeter, two temperature sensors, and a data logger (or energy management system) that can convert the flow and temperature data to thermal energy. Thus, thermal energy measurement is dependent on accurate measurement of flow and temperature. However, it is difficult to obtain accurate flow data in some buildings because complex piping systems contain numerous devices such as valves, elbows, and tees. These systems offer few locations where flow measurement will not be affected by such devices.

Installation of a flowmeter at a short distance downstream of an elbow or obstruction may produce large errors in flow measurement. Distortions of the velocity and helical swirls (or vortices) can affect the accuracy of the flow measurement. To ensure accurate flow measurement, the fluid should have a fully developed velocity profile without swirls or vortices. Such a condition is achieved when flowmeters are installed with adequate lengths of straight pipe after the elbow or tee. Because a long section of straight pipe after an elbow is required to achieve a fully developed flow field, flowmeters should be installed with at least 10 diameters of straight pipe downstream of an elbow (ASME 1971). However, in buildings, flowmeters are often installed within 5 diameters downstream of an elbow because of the limited lengths of straight pipe in equipment rooms (Corley 1998). Installation of a flowmeter this close to an elbow could result in a large measurement error in flow and, consequently, thermal energy.

Dean (1927, 1928) conducted some of the first studies of flow through curved pipes. He found that the secondary flow field had two vortices in the cross section of pipe. Patankar et al. (1974) used a numerical model to predict the distorted velocity profile for laminar flows through 180-degree pipe bends. Patankar et al. (1975) also extended their previous work into the turbulent flow region with the k (kinetic equation) and ε (dissipation equation) turbulence model. Using a Laser-Doppler anemometer, Enayet et al. (1982) measured the laminar and turbulent flows through a 90-degree elbow. Results showed the development of strong pressure-driven secondary

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flows and highly distorted velocity profiles. Parker and O'Neal (1995) quantified the measurement error caused by installation of a flowmeter downstream of a 90-degree elbow for an insertion-type flowmeter. The largest errors occurred at 2.1 diameters downstream of the elbow and 180-degree rotation angle relative to the outside horizontal plane of the elbow. While there have been numerous studies on the flow structure downstream of an elbow, there has been little work attempting to quantify the effect of the distorted flow field on measurements with flowmeters.

The purpose of this study was to quantify experimentally the measurement error caused by the developing flow field downstream of an elbow for insertion flowmeters installed in commercial piping systems with diameters of 4 in. (0.10 m) and 6 in. (0.15 m). The measurement error was quantified at various positions downstream of the elbow and at various flow sensor rotation orientations.

EXPERIMENTAL FACILITY

The test facility (Figure 1) consisted of a supply tank, a receiving tank, an orifice plate, load cells, four parallel supply pumps, a test section line, and return line and pump. The tanks each had a capacity of 10,000 gal (38 m^3). Flow rate was controlled with different combinations of the four supply pumps, partial closing of ball valves, and/or speed control of the largest pump. A return pump was used to pump water from the receiving to the supply tank. Sampling time, water temperature, number of flow sensor pulses, differential pressure across the orifice plate, and flow rate from the load cells, orifice, and insertion flowmeters were all measured.

The load cells and an orifice were used to measure the reference flow rate of water through the pipe test section and to provide the standard for the flowmeters. Four strain-bridge load cells were placed symmetrically underneath the receiving tank platform. The load cells dynamically weighed the water

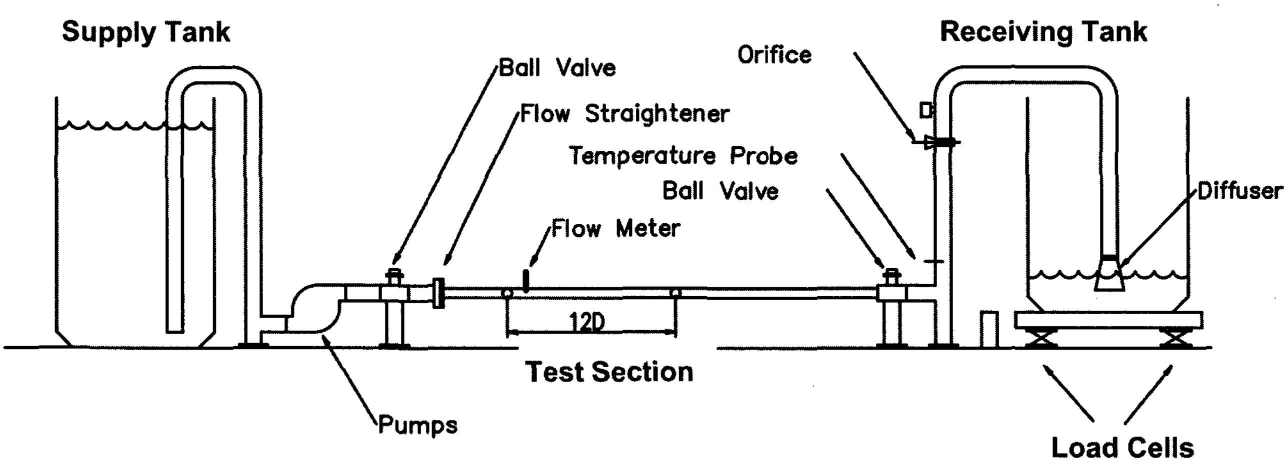

Figure 1 *Schematic diagram of the test facilities in the flow loop.*

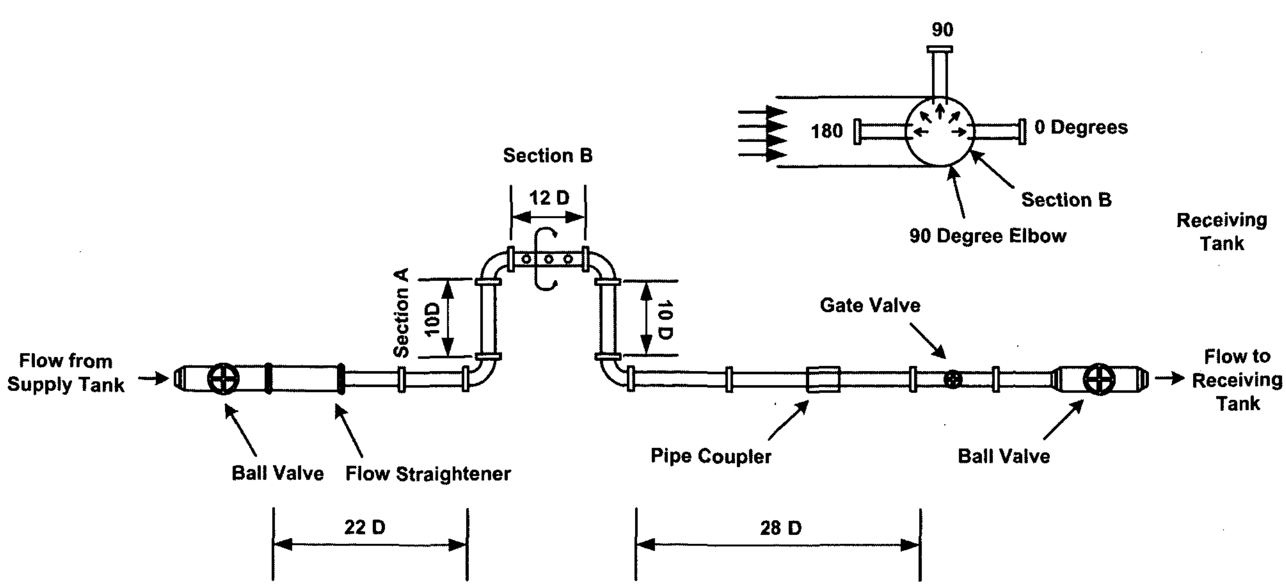

Figure 2 *Test system configuration and piping system.*

in the receiving tank during a test. The pumped water weight divided by the running time of a test provided the average mass flow rate during a test. Water density was estimated from temperature measurements and water property tables. Volumetric flow rate was calculated from water density and mass flow rate. An orifice plate (Figure 1) was also used to provide a secondary measurement of the volumetric flow rate. Pressure drop across the orifice was measured using a differential transducer. The volume of the flow rate from the orifice plate was used as a check on the flow measurement of the load cells.

The measurement location of the flowmeters was varied between 2 and 9 diameters downstream of the elbow (Section B in Figure 2). The radius of curvature, R, and pipe radius, r, for a section of elbow are shown in Figure 3. Three radii of curvature were used in the 4 in. (0.10 m) pipe: 2.5 in. (0.06 m), 4.5 in. (0.11 m), and 6.5 in. (0.17 m). The larger the radius of curvature, the more gradual the 90 degree turn in the elbow. Three flowmeter orientation angles, relative to the outside horizontal plane of the elbow on the pipe, were used: 0, 90, and 180 degrees. A flowmeter is often installed at a range of orientations relative to the plane of the elbow. Two pipe diameters were used: 4 in. (0.10 m) and 6 in. (0.15 m). The sampling flow rates were set to 80, 120, 160, 240, and 320 gpm (5.0, 7.6, 10.1, 15.1, and 20.2 L/s) for the 4 in. (0.10 m) diameter pipe and 200, 300, 450, and 600 gpm (12.6, 18.9, 28.4, and 37.9 L/s) for the 6 in. (0.15 m) diameter pipe. These corresponded to a range of water velocities, from approximately 1.6 to 8.9 ft/s (0.5 to 2.7 m/s), which should span the range in velocities found in commercial buildings' chilled and hot water piping systems. The flow rate was kept constant during each test. The measurement error, E_{meter}, between the load cells (or orifice) and paddle wheel flowmeter is defined as

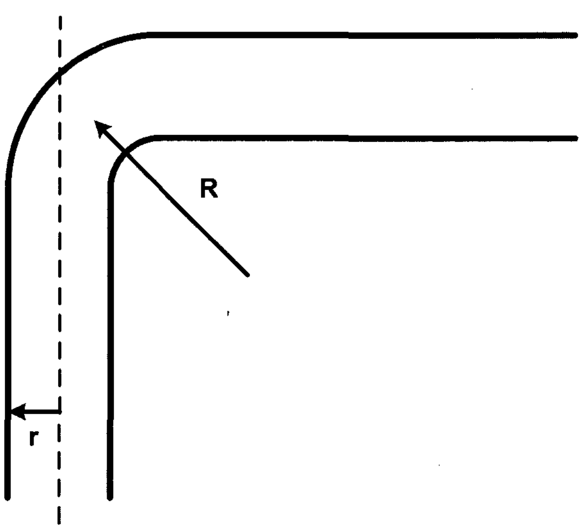

Figure 3 *The radius of curvature (R) of an elbow and pipe radius (r).*

$$E_{meter} = \frac{\dot{V}_{fs} - \dot{V}_{lc}}{\dot{V}_{lc}}, \quad (1)$$

where

$\dot{V}_{fs}$ = average volumetric flow rate of the flow sensor and

$\dot{V}_{lc}$ = average volumetric flow rate of the load cells.

The test flowmeter was a paddle wheel insertion flowmeter. This type of flowmeter (Figure 4) is easy to install in chilled or hot water piping systems. It can be installed without breaking the piping and has been extensively used in energy-monitoring applications. The flowmeters were installed at a constant insertion depth of 1.5 in. (38 mm) in accordance with the manufacturer's instructions. The flowmeter produces a pulse output that is proportional to the flow. During a given sampling time, the volumetric flow was calculated by multiplying the number of pulses by the flow constant (provided by the manufacturer).

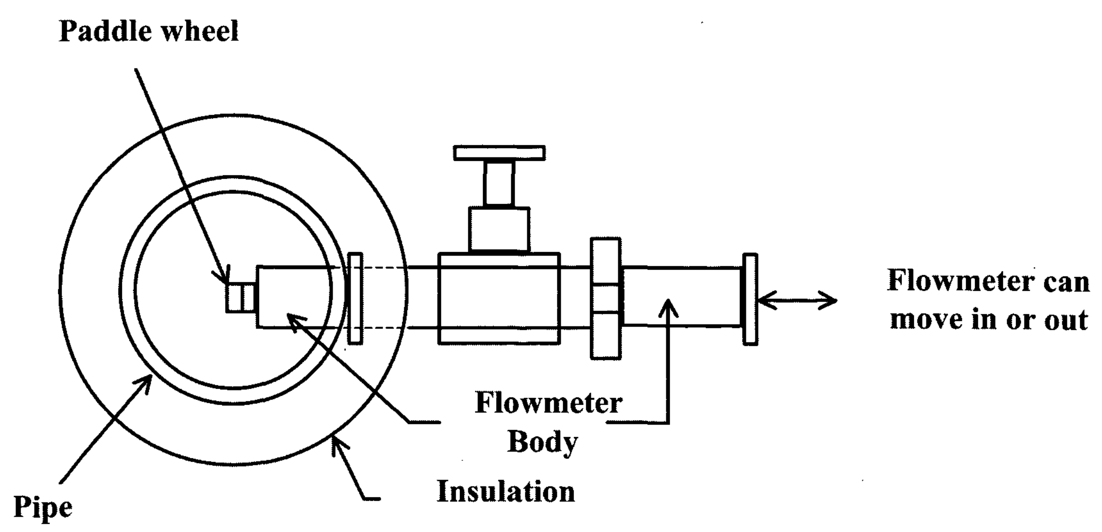

Figure 4 *Paddle wheel insertion flowmeter installation in a piping system.*