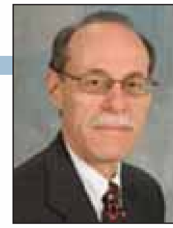
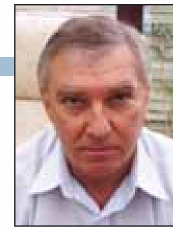
field report

BY DAVID W. SPITZER
AND RICHARD FURNESS


Spitzer


Furness

New Aspects of Flow Measurement Errors in Large-diameter Pipes

In our hectic lives, we sometimes lose track of the importance of our work and often view it as merely providing technical expertise. However, the economic effect of the work we do can be far more significant.

Consider this—a relatively small measurement error can have a large economic effect on custody transfer installations when buying and selling high-value products, large pipelines, or both. For example, assuming that the average flow rate of water in a 24-in. pipe is 100,000 L/min and that the water is valued at $1.00/1,000 L, a flowmeter would pass approximately $52 million worth of water per year (100,000 L/h × 60 min/h × 8,760 h/year × $1.00/1,000 L).

The increasing economic value of water means that even small measurement errors can become significant over time. In this example, a measurement error of 0.01% would result in a billing error of approximately $5,200/year. Even small errors such as those made in rounding or unit conversion can result in significant billing errors, and measurement errors of a few percent can result in billing errors that can exceed $1 million/year. The data show that even larger dollar amounts can be involved.

METER PERFORMANCE

Flowmeters are commonly used to determine the amount of water that is transferred between different business entities. The performance of many types of flowmeters is influenced by limitations of flowmeter technology, installation, calibration, operation, and maintenance. This article focuses on one aspect of flowmeter performance—straight-run requirements for accurate flow measurement and the long-term effect these requirements can have on flow measurement errors.

Velocity profile. For accurate operation, most flowmeters require a fully developed velocity profile that is free from swirl so that the flow is predictable and not distorted

2008 © American Water Works Association

(Figure 1). Flowmeters are calibrated under these conditions in a flow laboratory to establish the meter's characteristic performance curve. In practice, pumps, valves, and fittings such as elbows distort the velocity profile (Figure 2) and can superimpose swirl upon it. If flowmeters are installed where velocity profile distortion exists, measurement errors of a few percent or more can result. To avoid this problem, flowmeters should be installed upstream of control valves and similar obstructions that cause velocity profile distortion.

However, obstructions such as elbows and tees cannot be avoided in many piping systems, and the velocity profile is often distorted upstream of flowmeters. One strategy for removing velocity profile distortion prior to fluid entering the flowmeter is to install a flow conditioner upstream of the flowmeter. The strategy discussed here is limited to attenuating the velocity profile distortions before water enters the flowmeter by installing sufficient upstream straight-run piping that contains no fittings, valves, or other possible obstructions.

Although not explicitly stated in flow measurement standards, swirl and velocity profile distortion can be reduced by providing physical separation between fittings. For example, it is known that two closely coupled bends will induce bulk swirl. Although this piping configuration is common, it should be avoided upstream of a flowmeter to reduce swirl formation, which can affect flowmeter accuracy. A simple rule of thumb is to separate fittings by at least 5 pipe diameters (preferably more) wherever possible.

FIGURE 1 Developed velocity profile free of distortion

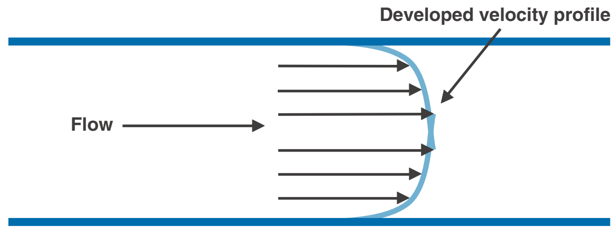
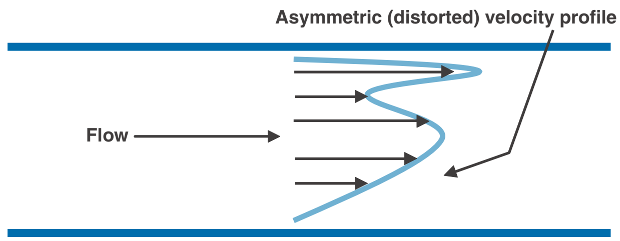


FIGURE 2 Distorted velocity profile



> **The increasing economic value of water means that even small measurement errors can become significant over time.**

Straight-run requirements. It is believed that flowmeters generally need 10 pipe diameters of straight-run piping upstream and 5 pipe diameters of straight-run piping downstream in order to measure accurately. This is a myth. Some flowmeters need more than 40 pipe diameters upstream, while others may not need any straight-run piping. The amount of straight-run piping required depends on the technology used, flowmeter design, and flowmeter installation.

In a flow laboratory, suppliers can experimentally determine the amount of straight-run pipe required to achieve accurate flow measurement. This is done by operating the flowmeter in different piping configurations with different amounts of straight-run piping, increasing the length until the flowmeter measures correctly.

In experiments, the number of pipe diameters required to attenuate the velocity profile distortion was generally not found to depend on pipe size. Therefore, flowmeter installation manuals and flow measurement standards are based on the fundamental premise that the straight-run requirement for a given

2008 © American Water Works Association

flowmeter design (expressed in pipe diameters) is the same for all sizes. However, for practical reasons, testing was generally performed using relatively small pipes. In addition, data for large pipes (e.g., larger than 24 in.) are limited. This means that to date the effect of diameter on straight-run requirements has not been effectively challenged.

Recent work shows that straight-run requirements do vary with pipe size. In particular, attenuating velocity profile distortion requires more diameters in large pipes than in small pipes. On a fundamental level, the momentum to be attenuated does not scale linearly with pipe size. This would help explain why the effects of momentum are more pronounced in large pipes.

Also, rotational distortion (swirl) is even more difficult to attenuate; therefore, an increase in straight-run piping is required when bulk swirl is present in larger pipes. For example, in a small pipe (e.g., 6 in.), the swirling flow is not far from the pipe wall. As a result, frictional effects readily occur and the swirl is effectively attenuated. In addition, the relatively slow velocities in these pipes tend to promote attenuation. Conversely, in a large pipe, the rotating fluid in the center of the pipe does not contact the pipe wall and can travel for many pipe diameters before attenuation.

FIGURE 3 Flow velocity errors in 48-in. straight pipe

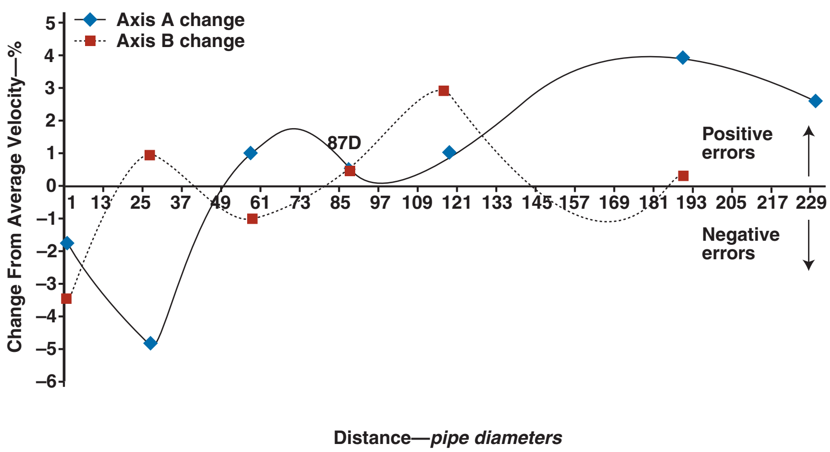
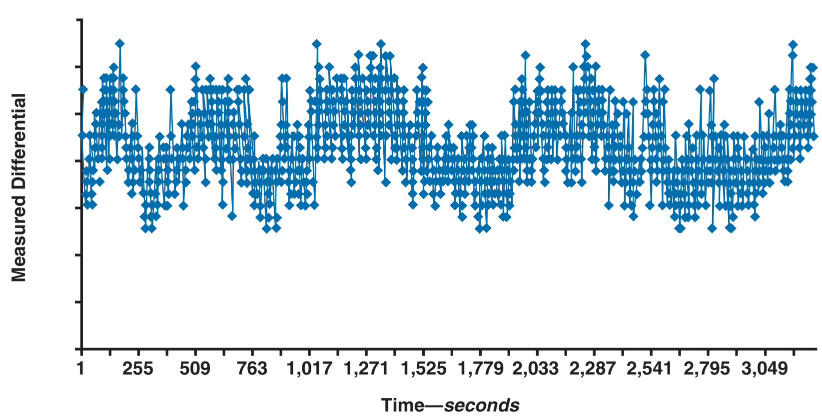


FIGURE 4 Measured differential pressure variations



FIELD TESTING

In a South American installation, velocities were measured in two planes at right angles to each other along a 200-diameter section of straight, 48-in.-diameter pipe. Flow measurement errors were between – 4 and + 4% depending on the position along the pipe where the flow was measured and the flow axis (Figure 3). The errors measured at each location were different on either plane at the same axial position, with the exception of 87D (Figure 3) where the same error was obtained. This would have been an ideal site for permanent location of a flowmeter. This indicates that swirl from the pumps had not decayed and that the swirl was still present 200 pipe diameters downstream of its source.

Based on this and other recent field work, experiments were performed at a large venturi meter installation in North America that supplies bulk water from a large reservoir to a nearby city. The venturi meter was designed and installed according to the manufacturer's recommendation of 5 diameters of upstream straight-run piping. Note that two large bends in the same plane were within 2 pipe diameters of each other and violated the rule of thumb to maintain at least 5 diameters between fittings. Opera-

2008 © American Water Works Association

tors reported differences between flow measurements made on opposite sides of the venturi meter.

As a result, instruments were installed to simultaneously measure upstream and throat pressures on opposite sides of the venturi meter. In the presence of swirl, out-of-phase oscillations would occur between the two sets of measurements. Figure 4 shows that such oscillations were present. Further, the oscillations changed in both period and amplitude when the flow rate changed. This is strong evidence that bulk swirl (likely formed at the inlet elbows) was not attenuated within the upstream straight run of pipe. Therefore, the swirl present in the flowmeter caused pressure instabilities at the pipe wall that were measured by the pressure instruments.

Figure 5 shows the calculated difference between the flow measurements taken simultaneously on opposite sides of the pipe at high flow conditions over a 1-min period. Trend lines show that the instabilities are regular and of high value, with flow measurement bias errors that were low by approximately 1.5%. Further analysis of the data showed strong harmonic effects induced in the pressure readings by the bulk behavior of the flow.

Figure 6 shows the calculated difference between the flow measurements taken simultaneously on opposite sides of the pipe under low-flow conditions over a 1-min period. The effects of short and medium oscillations can be seen. The average difference between the two sets of flow measurements was biased high by approximately 1%, with a period of rotation of approximately 45 s. When flow was doubled under high flow conditions (as explained previously), the bias error became approximately 1.5% low and the period of oscillation was reduced by half. This oscillating flow behavior is similar to that exhibited in the South American installation after pipe size is taken into account.

In addition, flow measurement errors approaching 10% were indicated by limited operating data, with flow through a pipe tied into the inlet of the upstream bend.

STUDY RESULTS

Surprisingly, swirling flow in large-diameter pipes has received little or no attention in the literature. Unstable pressure and/or flow signals are typically addressed by damping the signal electronically or by damping the hydraulic oscillations using capillary tubes. In the studies just discussed, the instability of flow signals indicates the potential of measurement bias

FIGURE 5 Calculated flow differences—high flow

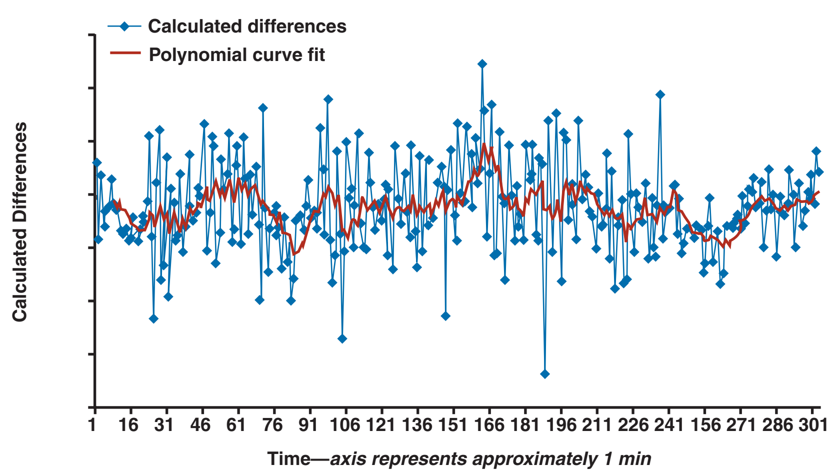
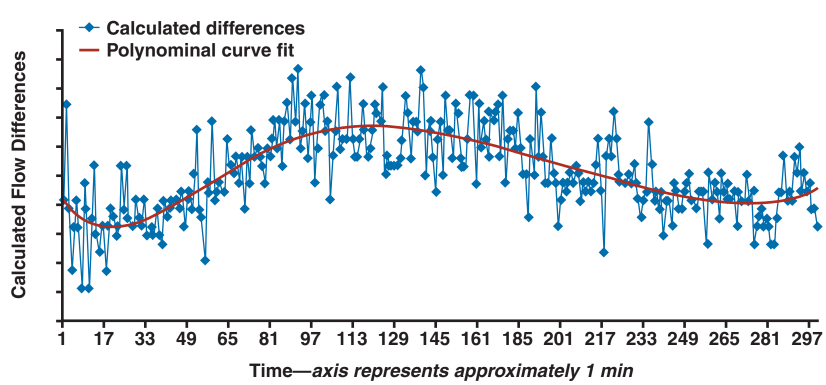


FIGURE 6 Calculated flow differences—low flow



2008 © American Water Works Association

errors—in this case, changing from 1% high to 1.5% low, or a 2.5% shift. Therefore, one set of flow transmitters may or may not accurately measure the flow in large pipes. Detecting the presence of instabilities and compensating the measurements would require at least two sets of instruments. Note that the data reported here are a small fraction of the information collected. Analysis of thousands of such data points shows that flow instability exists and that it is causing measurement errors.

The 2.5% bias shift represents a potential measurement error with an appoximate value of $1.3 million/year using the sample values presented in the beginning of the article. Somewhat larger errors have been measured in other installations, indicating that the amount of money "won and lost" can be staggering. The phrase won and lost is used because the measured (and billed) volume of water may be different from the volume that is actually received. In other words, a flowmeter that is biased to measure lower than the actual flow will make the buyer win and the supplier lose, and vice versa.

The work performed in these studies shows that swirl is more likely to occur as pipe diameter increases and also that the swirl decays more slowly as pipe diameter increases. To reduce or eliminate resultant flow measurement errors, the upstream straight run of pipe should increase as pipe diameter increases. This is currently not reflected in textbooks, standards, or manufacturers' literature. Based on testing, it seems inconceivable that the same turbulence decay rates and behavior would occur in 6-in. pipe and 60-in. pipe.

If flowmeters are installed where velocity profile distortion exists, measurement errors of a few percent or more can result.

Longer-term operation. Standards include specifications regarding smoothness of straight-run pipe but do not address the effects of encrustation that can develop over time. When swirl is present, encrustation on the pipe walls tends to mirror the swirling movement of the water in that pipe section. Once encrustation is formed, it tends to enhance the effects previously described and further increases the flow measurement errors.

In general, differential-pressure flowmeters and their straight runs are considered to be dimensionally stable over time. Using this premise, it can be concluded that calibration of differential-pressure transmitters is sufficient for accurate measurement. This too is a myth. Swirling flow initially forms in new pipes and becomes stronger over time—even in long, straight pipes. This implies that flow measurement errors in transmission systems can increase over time as the condition of the pipe wall changes.

This means the performance of differential pressure flowmeters is subject to change over time, because encrustation and its resultant roughness can affect the geometry and modify pressure measurements at the pressure taps. Differential-pressure flowmeters with encrustation typically measure higher than the actual flow in such situations. Measurement errors of up to 20% have been documented and reported in the literature (Phair, 1997).

The implication of encrustation error is that water flow measurement systems are suspected to exhibit large errors in many large cities around the world. These errors can have profound effects on water balances and can represent billing discrepancies well in excess of $1 million/year. It is likely that these installations are far more prevalent than currently recognized.

CONCLUSION

This article forms part of a growing body of evidence that suggests that more upstream straight-run piping is required to stabilize flow in large pipes. Therefore, flowmeter installation standards should be reviewed with regard to requiring the same upstream straight run (in pipe diameters) for large and small pipes. Properly calibrating the differential-pressure transmitter does not remove these bias errors, because these errors originate with the primary metering element and not the secondary transmitter systems.

The operating conditions of straight-run piping and flowmeters with regard to encrustation can profoundly affect flow measurement accuracy, especially in older flowmeters. Similarly, properly calibrating the differential-pressure transmitter does not mitigate this problem.

Modeling alone cannot accurately identify the effects of swirl formation or encrustation growth. Studies such as those described here can help assess the effects of these influences and be valuable to water districts with unexplained water imbalances.

2008 © American Water Works Association

—David W. Spitzer is an Instrumentation, Systems, and Automation Society (ISA) Fellow with more than 30 years of experience in specifying, building, installing, implementing, and trouble-shooting process control instrumentation. Currently he is a principal in Spitzer and Boyes LLC, and can be reached at www.spitzerandboyes.com. Richard Furness, the only ISA Fellow from the United Kingdom, has close to 40 years of experience in the field of fluid flow in the water and wastewater industry. He is the owner and director at JDF & Associates Ltd., Tirley, Gloucestershire, United Kingdom.

REFERENCE

Phair, D., 1997. Errors Occur Often in Municipal Metering. INTECH Conf., Instrumentation, Systems, and Automation Society, Research Triangle Park, N.C.

BIBLIOGRAPHY

Furness, R.A., 2005. Theoretical Studies in Water Pipelines. Report RAF/1013/0905, September 2005 (client confidential). JDF and Associates, Tirley, Gloucestershire, United Kingdom.

Furness, R.A. & Phatnani, S.P., 2003. Theoretical and Experimental Studies in Large Diameter Water Pipelines. Aquatech Asian Water Conf., New Delhi, India.

Hutton, S.P., 1954. The Prediction of Venturi Coefficients and Their Variation With Roughness and Age. Proc. Institute of Civil Engineers, London, paper 5932.

Spitzer, D.W., editor. 2001. *Flow Measurement: Practical Guides for Measurement and Control.* (2nd ed.). Instrumentation, Systems, and Automation Society, Research Triangle Park, N.C.

Spitzer, D.W., 2005. *Industrial Flow Measurement,* (3rd ed.). Instrumentation, Systems, and Automation Society, Research Triangle Park, N.C.

2008 © American Water Works Association