

INSTALLATION EFFECTS ON FLOW MEASUREMENT

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Abstract

This paper discusses the effects of poor installations on flow measurement and the best practices to achieve highest accuracy and performance. Flow disturbances are everywhere in pipelines and industrial applications. Knowing the types of disturbances, their effect on flow measurement and how to correct those errors is valuable for anyone interested in accurate flow measurement.

Introduction

Most flow meters are designed to operate in ideal flow conditions. Ideal conditions exist when the flow is undisturbed after flowing through long, straight pipe before entering the meter, as in Figure 1. The flow entering the flow meter at this point would be considered well-developed flow. Well-developed does not change with time or distance moved down the pipe. Thus, a flow meter placed at any point in a well-developed pipeline flow will measure as accurately as it was designed to do.

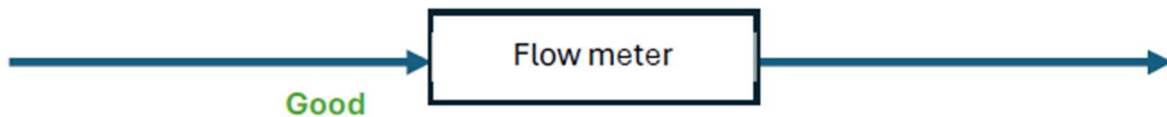


Figure 1

However ideal conditions rarely exist in industrial applications, such as illustrated in Figure 2. The flow entering the meter will not be well-developed and therefore cause inaccuracies in unexpected ways. Common sources of installation disturbances include:

- Pipe elbows, bends and tees
- Control valves, butterfly valves
- Pipe restrictions and expansions
- Pumps, compressors
- Unexpected wall roughness, debris, weld roots, off center gaskets
- Combinations of the above

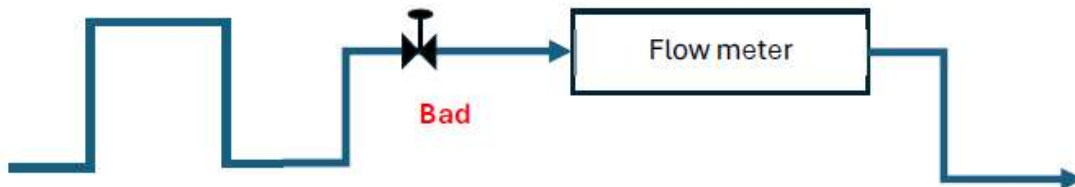


Figure 2

Figure 3 shows photos of disturbances testing on an orifice plate, downstream of double elbows out of plane on the left and single elbow on the right.



Figure 3

Flow profile

Flow profile is a common tool to visualize whether flow is disturbed or not. The flow profile attempts to show the velocity at different points across the diameter of a flowing pipe. This can be physically measured in several ways such as with a single point Pitot tube sensor or with more complex tools such as laser doppler velocimetry. Typically, the view is across a full diameter, crossing through the midpoint of the pipe. A typical flow profile looks like Figure 3 for turbulent flow. Each arrow represents the velocity at points across a diameter of the pipe. The velocities are higher in the center of the pipe and lower near the pipe walls.

The friction on the pipe walls causes drag which slows down the fluid flow nearest the wall. As the flow continues down the pipe, the next layer away from the pipe wall is slowed down slightly less. And so on until the effect of the pipe wall friction no longer affects the velocity. This is called the boundary layer effect and is created whenever flow passes over a surface.

The boundary layer in a pipe will grow and shrink depending on flow velocity and viscosity. The layer will respond more quickly to velocity changes. As flow goes faster over the surface, the layer will shrink. And as flow slows down, the layer will grow. This is shown in Figure 4. Laminar flow will develop a bullet shaped profile when the effect of the boundary layer will extend all the way to the center of the pipe. Turbulent flow typically exhibits a flatter profile because the boundary layer effect is limited to closer to the pipe wall. After the boundary layer effect has diminished, the profile is even across much of the pipe area.

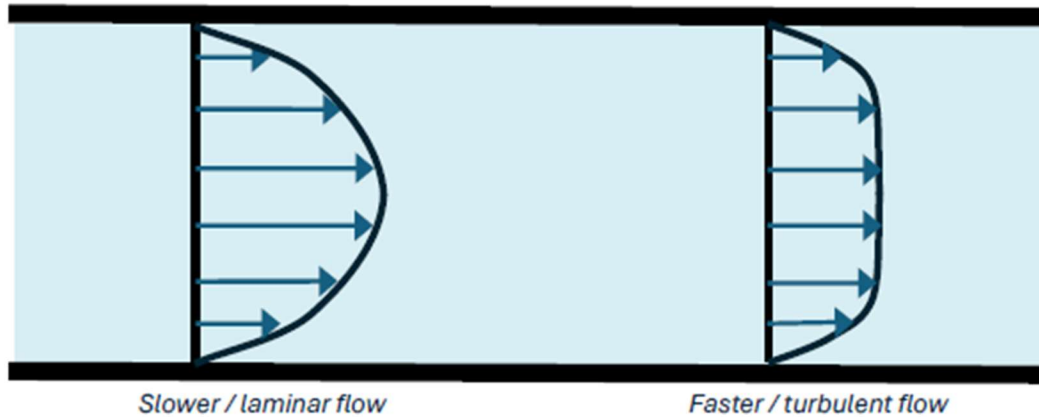


Figure 4

Asymmetric flow

As flow is disturbed with the addition of pipe elements, the flow profile will change. For example, flow through a single elbow creates a skewed profile. The high velocity “core” of the pipe will be pushed to the opposite wall of the pipe, creating an asymmetry where the maximum velocity is no longer in the middle of the pipe. Single elbows and other elements can create asymmetry in the flow profile as shown in Figure 5.

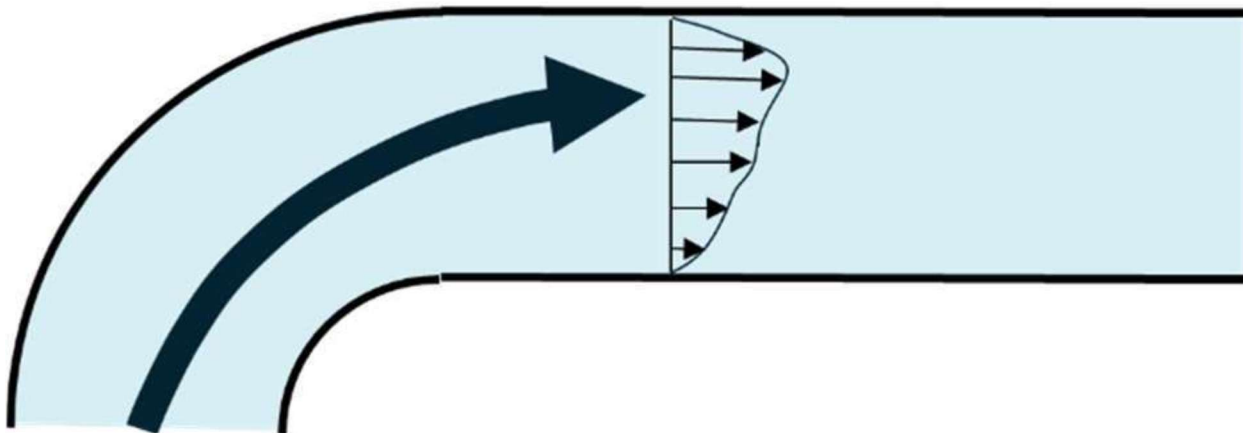


Figure 5

The asymmetry is not an equilibrium condition. As the fluid (gas or liquid) continues to flow down the pipe, the profile will gradually return to well-developed conditions. The conditions will be changing between the disturbance and the point of returning to well-developed conditions. As Kelner¹ shows in Figure 7, the effects of profile distortion diminish over distance from a single elbow. In this case, the profile does not return to ideal conditions until 59 diameters downstream.

If an ideal flow meter could be created, it would measure every point in the cross-sectional area of the pipe. Therefore, asymmetries caused by flow disturbances would be averaged out. This ideal meter would not care if the flow velocity was greater on one side of the pipe and slower on the other side. The average of the readings would cancel out the asymmetrical problem.

But real-life meters do not sample the velocity at each point in the pipe. As a first example, consider a flow meter that only measures at a single point at the pipe wall. In the same example of a single elbow, we could measure at Measurement point A or Measurement point B, see Figure 6. Point A flow meter would measure a higher velocity than the Point B meter. The user, without the luxury of being able to view inside the pipe, would

unknowingly measure incorrectly due to the upstream disturbance. The size and direction (over- or under-reading) would also be unknown to the user.

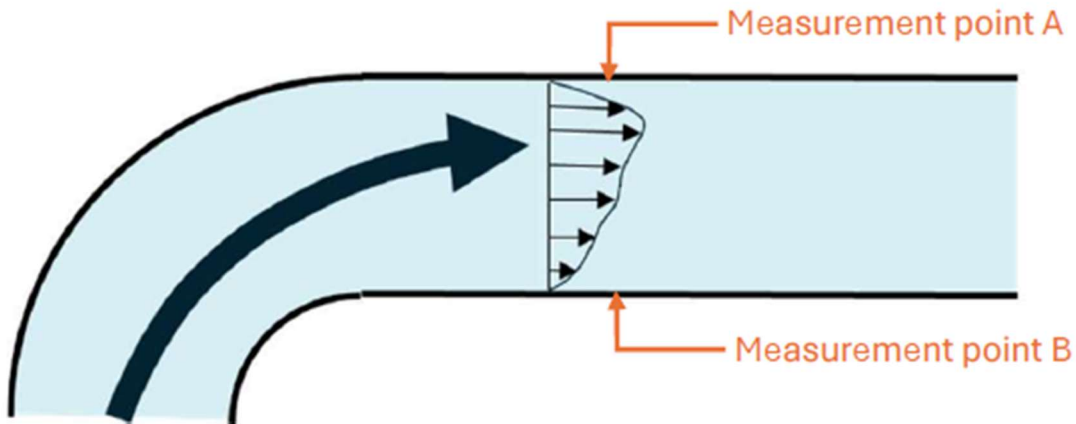


Figure 6

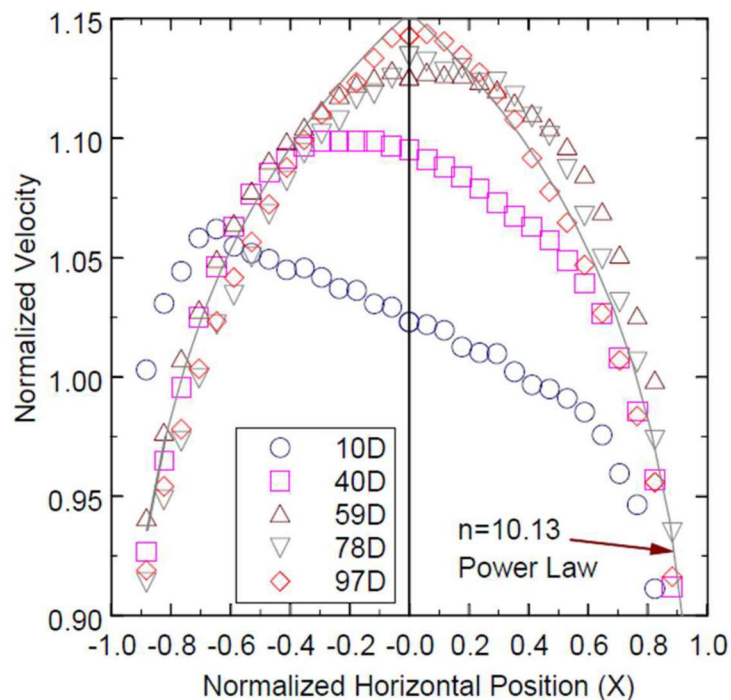


Figure 7

Swirling flow

The flow profile does not capture another type of flow disturbance called swirling flow. Swirling flow is when the flow has a crossflow element. Without swirl the flow will run straight down the pipe at 0° in relation to the centerline of the pipe. If crossflow is present, the flow streams can have a swirl angle, up to 20° in severe cases. There are two general types of swirl disturbances, Type 1 and Type 2 swirls.

1. Type 1 swirl moves in one directional rotation across the pipe. This is also known as whole body swirl, Figure 8. Close-coupled, double elbows out of plane are a common cause of Type 1 swirl, along with headers, pumps and compressors. Type 1 swirl has a sustained effect and can last much longer in the pipeline than asymmetry or type 2 swirl.

2. Type 2 swirl introduces two counter rotating swirls rotating in opposite directions, Figure 9. This is usually created after single elbows.

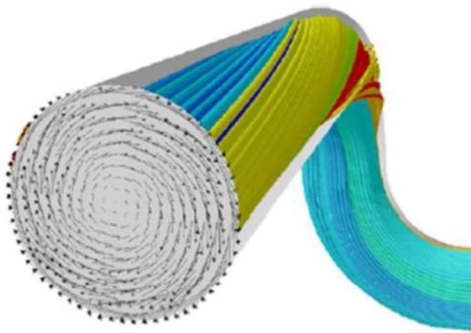


Figure 8

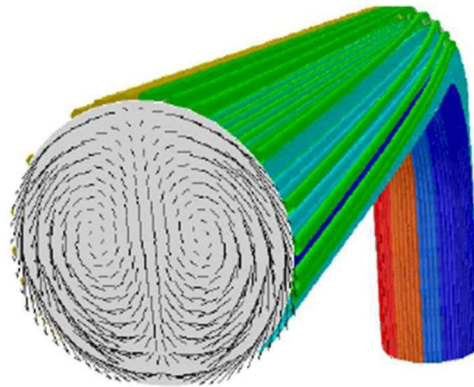


Figure 9

Flow meter geometries

There are numerous types and styles of flow meters on the market for industrial flow measurement. And within those types, manufacturers offer proprietary variations. This paper will try to help the reader understand the effect of flow disturbances on flow meter accuracy. This paper cannot try to define how flow disturbances affect the hundreds of flow meter models available. Rather the paper will help the reader by categorizing the various flow meter designs into groups to help understand their susceptibility or insusceptibility to flow disturbances.

Single point meters, as mentioned above and shown in Figure 10, measure a single point in the flow stream and are therefore susceptible to inaccuracies due to asymmetry. Some single point meters measure at the pipe wall, such as the paddle wheel style. Most other insertion meters measure somewhere between the pipe wall and the midpoint. If the measuring point is placed at the center of the pipe, it will likely measure the highest velocity in the pipe. The average velocity in the pipe would be lower than that and likely calculated with empirical or theoretical factors. Many times, the measurement point is inserted about 1/3 into the pipe, trying to capture the midway measurement between high and low velocities along the major diameter. Types of these meters include insertion: magnetic, vortex, thermal mass, turbine, and Pitot tube sensors.

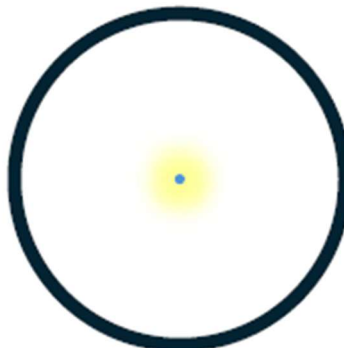


Figure 10

Single path meters improve the installation performance by measuring along a complete axis of the flow stream. This ensures that flow near opposite walls of the pipe is measured, along with a linear section of the center. This is better than a single point meter but still leaves a large section of the pipe that is unmeasured, as shown in Figure 11.

Examples of single path meters include single path ultrasonic meters (both spool type and clamp-on), vortex meters and multi-point pitot tubes.

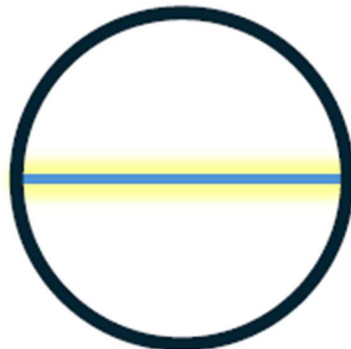


Figure 11

Multipath meters again improve on the flow measurement performance in disturbed conditions. These meters are ultrasonic meters with multiple paths spaced at multiple elevations. The location and distribution of the elevations is scientifically calculated to provide equal area coverage for each path, according to equations like the Gauss Chebyshev quadrature. One- or two-paths can be used per elevation. Figure 12 could be a 3-path meter with one set of transducers at each elevation or a 6-path with two sets of transducers at each elevation. Likewise, Figure 13 could be a 4-path or 8-path meter. Bounce paths are also available, where the path bounces once or twice on the pipe walls. These meters are typically provided in spool section meter bodies.

Multi path meters cover a significantly larger portion of the pipe and therefore less susceptible to flow disturbances than the previous meter types. The manufacturers of multipath meters use weighting factors to adjust for velocity differences between the pipe center and the pipe walls. Asymmetry and swirl can be detected and corrected by some models with diagnostic software, so the user is aware of flow conditions in the meter.

Despite these technological advances, multipath meters are still susceptible to disturbances, though in smaller amounts relative to the previous meters discussed.

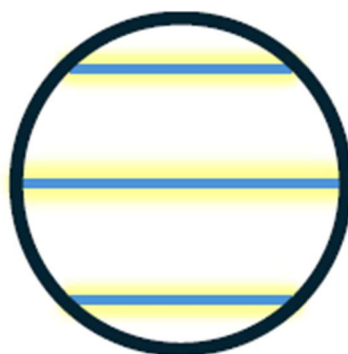


Figure 12



Figure 13

Full cross section meters have primary element of the meter interacts with the full section of the flowing pipe. Examples of these are magnetic meters, turbine meters and most types of differential pressure flow meters. These meters, even though they interact with the majority of the flow field, still are susceptible to disturbances. Magnetic meters, shown in Figure 14, are arguably the best performing meter in this group. The

sensors on diametrically opposite sides of the pipe create a magnetic field that “samples” much of the pipe and therefore have limited errors from asymmetry and swirl flow.

Turbine meters, shown in Figure 15, sample the biggest cross section of the pipe. If the flow is asymmetric, the slower flows will try to reduce the rotation of the turbine while the faster flows will try to increase it. Since the turbine is a one-piece structure, the two opposing forces balance out, and the meter is relatively unaffected. The “Achilles heel” of turbine meters is the rotational movement. If the flow is swirling, the rotation of the turbine will increase or decrease in speed, depending on if the swirling flow is rotating with or against the rotation of the turbine blades.

Differential (DP) meters sample a majority of the flow field. Figure 16 could be a view looking down the pipe at either an orifice plate or a Venturi meter, both popular designs. DP meters use a restriction in the pipe to create the differential pressure signal. The size of the restriction can vary and is referred to as the beta ratio. In general, the smaller the beta ratio value (the greater the physical restriction of the DP meter), the less susceptible they are to disturbances. The “Achilles heel” of the orifice plate is the location of the measuring taps. Even if the primary element interacts with the entire flow field, the pressure tap is only in one location along the pipe wall. Asymmetry and swirl can easily affect pressure measurements at one radial location versus another location. This is the reason DP meter, and orifice plate in particular, have long straight run requirements for accurate flow readings.

Attempts have been made to take multiple tap locations and average them for a single measurement value. These are known as annular rings and they are considered ineffective in solving measurement errors.

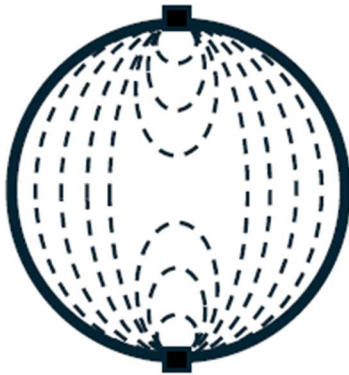


Figure 14



Figure 15

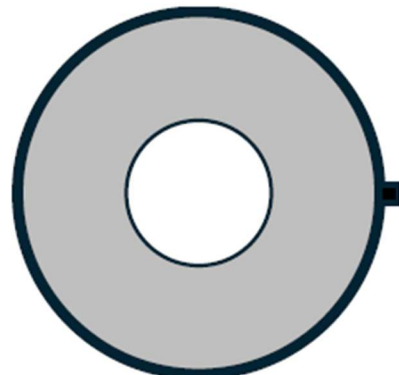


Figure 16

Redirect meters are the last category of flow meters. These meters control the flow direction completely and therefore are unaffected by disturbances such as asymmetry and swirl. Coriolis and positive displacement meters are two examples of redirect meters.

Coriolis meters will normally split the flow into two streams and redirect the flow along a curved path, see Figure 17. This interaction and complete control of the flow direction negated any disturbances upstream from asymmetry or swirl.

Positive displacement (PD) meters isolate small volumes of the fluid and move them through the meter, see Figure 18. Each isolated volume is precisely known and then counted to measure total volume and flowrate. The method of isolating these volumes varies greatly from lobes to gears, nutating discs, helical screws and vanes. Again the fluid is completely controlled by the meter mechanically and therefore PD meters are insensitive to upstream disturbances as well.



Figure 17

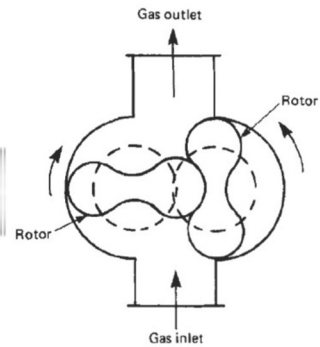


Figure 18

Effects of flow disturbances

Flow disturbances can cause inaccuracies in flow measurement and now the reader has the tools to categorize flowmeters into how much a meter is affected by them. The inaccuracies of common flow meter types are well documented but the scope of this paper does not allow an in depth review. However, below are some example results and the type of errors that are possible with flow disturbances on various technologies.

Mattingly and Yehⁱⁱ completed an exhaustive NIST study on flow meter installation effects. They studied both orifice plate and turbine meters. Figure 19 shows three orifice plates of three beta ratios at various distances from a single elbow. Figure 20 shows the same for double elbows out-of-plane.

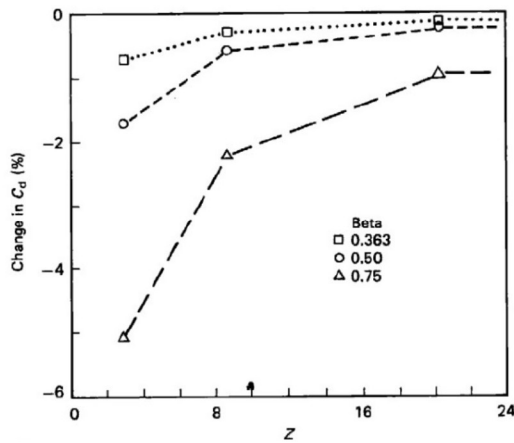


Figure 19

Single elbow effects on orifice

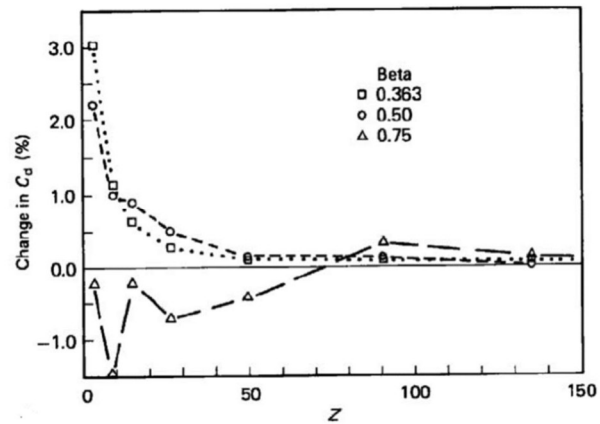


Figure 20

Double elbow effects on orifice

Figure 21 shows the effect on a turbine meter of single elbow and double elbows out of plane upstream at various distances.

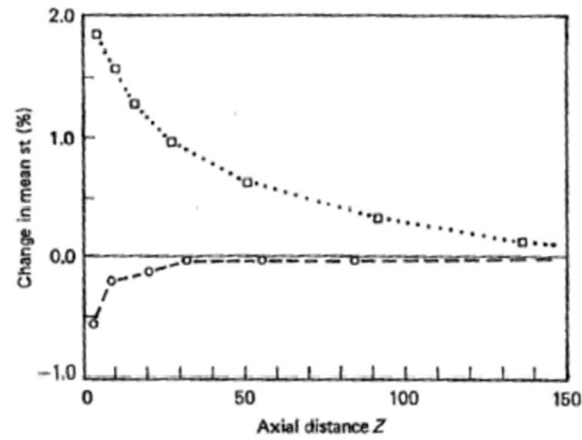


Figure 21

Figure 22 shows data from Kelner on the effects of double elbows upstream of a multipath (bounce-path) ultrasonic meter at 20D.

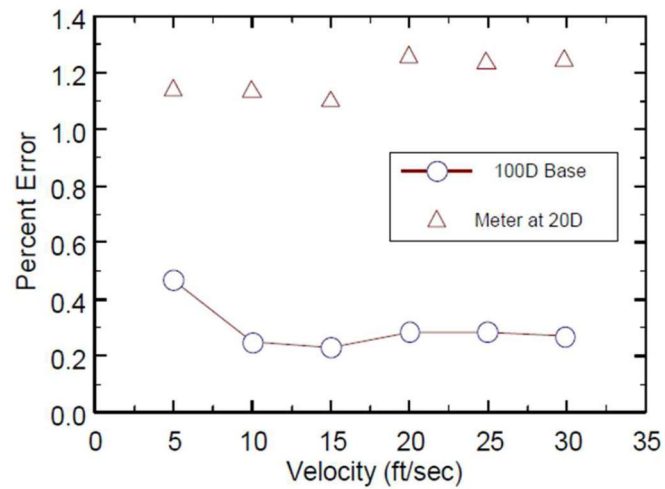


Figure 22

ⁱ Kelner, Eric, Flow Meter Installation Effects, Presented at the Appalachian Gas Measurement Short Course, 2012

ⁱⁱ Mattingly, George and Yeh, TT, Effects of pipe elbows and tube bundles on selected types of flowmeters, Flow Measurement Instrumentation, Vol 2, January 1991