Measurement Methods and Techniques for Pressure Losses in Pipe Fittings

Lingnan Lin, PhD **Marylia Duarte Batista** **Natascha Milesi Ferretti, PE**
Member ASHRAE

ABSTRACT

Pressure losses in pipe fittings are important design information for sizing pipelines and selecting pumps. Currently, there is no standard method of test for determining the pressure loss of pipe fittings. To assist future development of a standard method of test, this paper provides an overview of measurement methods and techniques for determining the pressure loss associated with pipe fittings. Principles as well as the advantages and disadvantages of each existing method are discussed. Instrumentation techniques are illustrated in detail, including guidelines and recommendations for the design or selection of pressure taps, impulse lines, pressure transducers, and flow meters. Finally, future research requirements and objectives for standardizing existing test methods are identified.

INTRODUCTION

Piping systems are commonly used for fluid distribution and heat exchange and are used in a variety of applications including plumbing, heating, ventilating, and air conditioning (HVAC), refrigeration, and chemical processes. The pressure losses within a piping system are of primary importance because they are directly related to sizing pipes, fittings, and pumps (if applicable). Incorrect sizing can impede achieving design flows, increase operating and installed cost, and reduce energy efficiency. For premise plumbing systems, i.e., part of the drinking water distribution system that extends beyond the service lines within buildings (NRC 2006), oversized pipes can result in great variation and increase of water age distribution and create conditions conducive to pathogen growth (NASEM 2019).

The pressure losses in a piping system consist of the frictional loss in pipes and additional losses caused by valves and fittings (i.e., components used to connect pipes to change direction, increase or decrease the pipe diameter, or merge or branch the pipe flow). Frictional losses in pipes, often referred to as "major losses", can be described by the Darcy–Weisbach equation, which uses a friction factor that can be determined from established methods such as the Moody Chart (Moody 1944) and Colebrook equation (Colebrook 1939). Pressure losses caused by valves and fittings are conventionally referred to as "minor losses", although they can be as significant as major losses in practice, especially in premise plumbing and HVAC systems. Since the theoretical analysis of flow through valves and fittings is too complex, minor losses are determined experimentally (Çengel and Cimbala 2006) and experimental data of minor losses are either provided by the manufacturer for a particular component or from the literature.

Lingnan Lin is a Research Scientist, **Marylia Duarte Batista** is a Research Associate, and **Natascha Milesi Ferretti** is a Mechanical Engineer in the Building Energy and Environment Division, National Institute of Standards and Technology, Gaithersburg, MD.

Representative values of minor losses can be found in technical handbooks, such as ASHRAE (2021), Crane (2013), and Hydraulic Institute (1990). However, considerable errors can be expected if one uses representative values from handbooks for practical engineering design, because minor losses are strongly dependent on the details of the geometry design of a valve or fitting, which varies significantly across manufacturers. In addition, most of the data in above mentioned handbooks originate from very old studies that are based on valves or fittings with obsolete material or geometry design. Therefore, it is always favorable to consult the manufacturer's data in the practical design of piping systems. Manufacturers' pressure loss data for valves are usually available (usually expressed as a flow coefficient) based on the application of standard methods of test, e.g., ANSI/ISA-S75.02 (1996). For pipe fittings, however, manufacturers' pressure loss data are generally not available due to the absence of a standard method of test.

Pressure losses of modern pipe fittings was identified as a prioritized research topic in a 2018 premise plumbing research workshop (Pickering et al. 2018), that was jointly organized by the National Institute of Standards and Technology (NIST), the U.S. Environmental Protection Agency, (EPA), and the Water Research Foundation (WRF). In a subsequent NIST report (Persily et al. 2020), the topic was documented as one of the fundamental research needs to "advance plumbing system design, operation and maintenance, as well as the standards, codes and guidelines that apply to these systems." In this light, in 2020, NIST funded a program to perform research on "Measurement Science for Bringing Premise Plumbing into the 21st Century". One goal is to establish standardized and precise means of characterizing pressure loss of modern plumbing fittings as a function of various parameters. In support of this goal, this paper reviews state-of-the-art methods and techniques for measurement of pressure losses in pipe fittings.

CLASSIFICATION OF PIPE FITTINGS

There are three main pipe fitting classifications: geometry, material of construction, and type of connection. Pipe fittings are primarily classified in terms of geometry because it is directly related to the function and purpose. Geometry is also the main factor influencing the flow characteristics and thereby the pressure losses in the pipe fitting. General geometrical classifications are branching, reducing, expanding, and deflecting (Crane 2013). Fittings such as tees, wyes, and crosses are branching fittings. Fittings that do not branch the flow are often referred to as flow-through fittings. Reducing or expanding fittings are those that change the cross-sectional area of the flow passage, such as reducers and bushings. Deflecting fittings are those changing the flow direction, such as ells and return bends. Additionally, there are fittings that are combinations of the foregoing general geometrical classifications, for example, reducing tees and ells. Unions and couplings are usually associated with insignificant pressure losses compared to the above types of fittings (Crane, 2013). However, some insert couplings or unions can cause considerable pressure loss.

Pipe fittings can also be classified according to material of construction and type of connection. Common pipe materials include steel, iron, copper, bronze, polyvinyl chloride (PVC), chlorinated polyvinyl chloride (CPVC), and cross-linked polyethylene (PEX). Common connection types include threaded, soldered, brazed, flared, compression, flanged, welded and fusion welded, solvent-welded, press-connect, push-connect, or insert fittings. For more information on materials and connections of pipe fittings, readers are referred to the Table 1 in ASHRAE Handbook (2021) – Fundamentals, Chapter 22.

METHODS TO DETERMINE PRESSURE LOSSES IN PIPE FITTINGS

The pressure loss caused by a pipe fitting is essentially the additional pressure drop that would not exist if the fitting were not present. This can be determined by measuring the pressure drop between a location upstream of the fitting and a location sufficiently far downstream (see **Figure 1**) to capture the effect of decaying eddies and then applying a correction to account for the frictional losses associated with the straight pipe between the pressure measurement locations. The pressure loss of the fitting is equal to the difference between the measured pressure difference and the frictional pressure loss of the straight piping. In cases where the downstream pipe diameter changes, the change of dynamic pressure also needs to be accounted for separately from the fitting. The frictional loss of the straight piping can be determined by a "calibration curve" that is established in pretests by measuring the pressure drop of the straight pipe (without the fitting) as a function of the flow rate.

Alternatively, the pressure loss of a fitting can be determined based on the hydraulic grade lines, which can be drawn by measuring the pressures at multiple locations along the flow through the fitting (see **Figure 2**). By analyzing the slopes of the hydraulic grade lines (i.e., the pressure gradients), the fully developed regions upstream and downstream of the fitting can be identified. The pressure loss due to the fitting can be obtained by projecting the linear hydraulic grade lines in fully developed regions to the upstream and downstream limits of the fitting and measuring the difference between them. Again, the dynamic pressure change must be accounted for in the case of fittings with downstream pipe diameter changes. Each method has advantages and involve different considerations. An apparent difference between them is the required number of axial pressure-tap locations. The first method requires only two tapping locations: one upstream and the other one downstream, whereas the second method requires many tapping locations distributed both upstream and downstream of the fitting. In this paper, the first method is referred to as the *two-tapping-location method*, and the second one as the *multi-tapping-location method*. Detailed principles, equations, and considerations for each method are illustrated as follows.

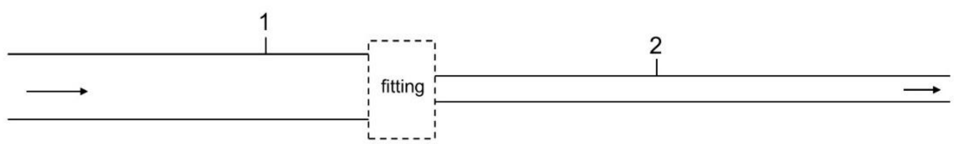

Figure 1. Control volume of an arbitrary pipe fitting connecting horizontal pipes.

Two-tapping-location method

Consider a control volume from a location upstream of the fitting (denoted by subscript 1) to a location sufficiently downstream (denoted by subscript 2), as shown in **Figure 1**, the Bernoulli equation is written as:

$$P_1 + \frac{1}{2}\rho V_1^2 = P_2 + \frac{1}{2}\rho V_2^2 + \Delta P_{L,\mathrm{t}} + \Delta P_{L,\mathrm{fr}_1} + \Delta P_{L,\mathrm{fr}_2} \tag{1}$$

where P is the pressure, ρ is the fluid density, V is the velocity, $\Delta P_{L,\mathrm{fr}}$ is the frictional loss of the piping between the fitting and the upstream (1)/downstream (2) location where the pressure is measured, and $\Delta P_{L,\mathrm{t}}$ is the pressure loss attributed to the fitting. Rearranging Eq. (1) yields:

$$\Delta P_{L,\mathrm{t}} = (P_1 - P_2) + \frac{1}{2}\rho(V_1^2 - V_2^2) - \Delta P_{L,\mathrm{fr}_1} - \Delta P_{L,\mathrm{fr}_2} \tag{2}$$

In Eq. (2), $(P_1 - P_2)$ is the static pressure drop, which is typically determined by a differential pressure measurement instead of absolute pressure measurements of individual P_1 and P_2; the term $\frac{1}{2}\rho(V_1^2 - V_2^2)$ is the change of dynamic pressure, where V_1 and V_2 are average velocities determined from flow measurements by the equation:

$$V = \frac{\dot{m}}{\rho A_c} \tag{3}$$

where $\dot{m}$ is the mass flow rate, A_c is the cross-sectional area of the piping. Note that $\dot{m}_1 = \dot{m}_2$ for flow-through fittings and $\dot{m}_1 \neq \dot{m}_2$ for branching fittings. $A_{c_1} \neq A_{c_2}$ for fittings with contraction or enlargement, otherwise $A_{c_1} = A_{c_2}$. The frictional loss terms $\Delta P_{L,\mathrm{fr}_1}$ and $\Delta P_{L,\mathrm{fr}_2}$ can be determined by the "calibration curve" that is established in pretests to compute the frictional pressure loss as a function of flow velocity or flow rate. The calibration curve is based on the Darcy–Weisbach equation:

$$\Delta P_{L,\mathrm{fr}} = f\frac{L}{D}\frac{\rho V^2}{2} \tag{4}$$

where f is the Darcy–Weisbach friction factor (or Darcy friction factor), D is the pipe diameter, L the pipe length for which $\Delta P_{L,\mathrm{fr}}$ is accounted. By measuring the $\Delta P_{L,\mathrm{fr}}$ of the straight piping for various V (or $\dot{m}$), a calibration curve of either $\Delta P_{L,\mathrm{fr}}$ as a function of V (or $\dot{m}$) or f as a function of the Reynolds number can be established. This curve can be subsequently used to compute $\Delta P_{L,\mathrm{fr}_1}$ and $\Delta P_{L,\mathrm{fr}_2}$ respectively from V_1 and V_2 (or directly from the measured $\dot{m}_1$ and $\dot{m}_2$).

The primary consideration of this method is to ensure the flow is fully developed at both the upstream and downstream pressure tapping locations (i.e., Locations 1 and 2 in **Figure 1**). While the majority of the pressure loss occurs locally within the fitting, some of it occurs in the upstream and downstream straight piping due to the propagated flow disturbances. The eddies induced in the fitting can continue to decay downstream and eventually be dissipated into heat while the flow returns to the fully developed condition. Therefore, Locations 1 and 2 should be adequately far upstream and downstream, respectively, to fully account for the additional irreversible losses that occur in the straight piping. Note that Locations 1 and 2 cannot be simply set as far as possible from the fitting, because that would cause the friction loss contribution to dominate the pressure drop, making the contribution of the fitting too small to be measured accurately. Table 1. Pressure tapping locations in selected studies using the two-tapping-location method*.

Literature	L_0 [$\times D_1$]	L_1 [$\times D_1$]	L_2 [$\times D_2$]	D_1 [mm (in.)]	D_2 [mm (in.)]	Fitting type
Itō and Imai (1973)	50	23	55	35	35 mm	gunmetal tees
Oka et al. (1996)	50	23	55	54	13 or 16 mm	brass tees
Rahmeyer (1999b, 1999a)	30 – 50	1 – 2	12 – 24	38.1 – 101.6 (1.5 – 4)	38.1 – 101.6 (1.5 – 4)	iron or steel ells, reducers, expansions, tees
Rahmeyer (2002)	n/a	1 – 2	6 – 10	304.8 or 406.4 (12 or 16)	304.8 or 406.4 (12 or 16)	steel tees
Rahmeyer (2003a, 2003b)	≥ 30	2	12	50.8 – 203.2 (2 – 8)	50.8 – 203.2 (2 – 8)	PVC ells, reducers, expansions, tees
Ding et al. (2005)	8.5	1.5	20	127 – 254 (5 – 10)	127 – 254 (5 – 10)	steel ells, reducers, expansions, tees
Oka and Itō (2005)	50	23	55	54	16	gunmetal tees

* L_0 denotes the distance between the upstream pressure tapping location and its inlet. L_1 and L_2 denote the distances between the fitting and the upstream and the downstream tapping locations, respectively. D_1 and D_2 denote the diameters of the upstream and the downstream piping, respectively.

Table 1 lists the pressure tapping locations in existing studies that used the two-tapping-location method and shows differences in the choices of pressure tapping locations. For example, among the tests for tees, Rahmeyer (1999b, 2002, 2003b) and Ding et al. (2005) placed the downstream tapping at less than 24 pipe diameters, whereas Itō and Imai (1973), Oka et al. (1996), and Oka and Itō (2005) placed the downstream tapping at 55 pipe diameters. Neither Rahmeyer (1999b, 2002b, 2003b) nor Ding et al. (2005) have provided detailed information on how these locations were selected. Oka and Itō (2005) referred to Serre et al. (1994) for their choice on the downstream tapping location.

Serre et al. (1994) demonstrated that 80 % to 90 % of the pressure loss for a tee occurs within 3 to 4 pipe diameters downstream the junction, while the remaining loss occurs at approximately 50 pipe diameters downstream regardless of the flow rate and the branch flow ratio. As for ells, on the other hand, Crawford et al. (2007) demonstrated that the downstream disturbances dispersed at approximately $40D$, $50D$, and $70D$ for ells with R/D of 10, 2.5, and 0.65, respectively, where R is the ell's curvature and D is the pipe diameter. In addition, a general statement was made by Miller (1990) that "more than 30 diameters are required before a steady friction gradient following components, such as bends, diffusers, and orifice plates." Since flow characteristics can vary significantly with the type of fittings and the detailed geometric design, the length required for re-establishing fully developed flow may vary accordingly. Therefore, further investigations are needed to understand the flow characteristics for various types of pipe fittings in order to establish a general method to determine pressure tapping locations.

The two-tapping-location method is the basic method for determining the pressure losses of fittings, and is introduced in fluid mechanics textbooks (e.g., Çengel and Cimbala, 2004) and industrial technical handbooks (e.g., Crane, 2013). Once the friction calibration curve and the two tapping locations have been determined, the pressure losses of fittings can be measured following the same procedure. This method does not require a case-by-case data analysis as required by the multi-tapping-location method and therefore may be more promising for standardized commercial and industrial uses. Future developments of this method should focus on uncertainty analysis in addition to systematic investigation of the abovementioned considerations.

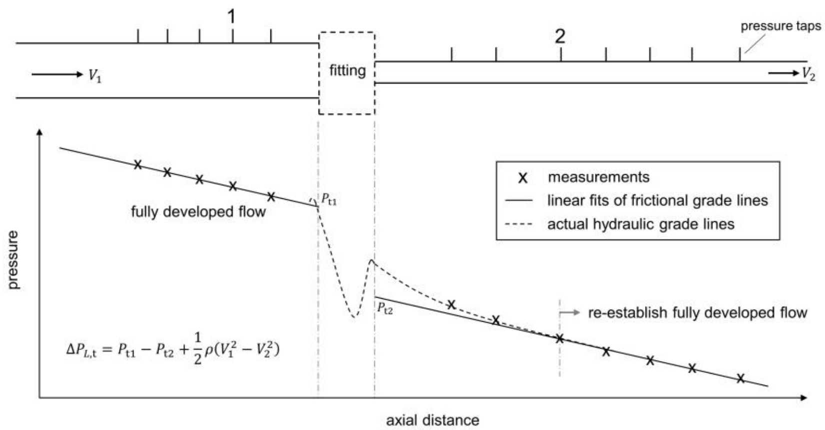

Figure 2. Schematic of the multi-tapping-location method

Multi-tapping-location method

Reconsidering the control volume shown in **Figure 1**, and assuming the flow is fully developed at Locations 1 and 2, the Bernoulli equation, Eq. (1), can be re-written as:

$$\Delta P_{L,\mathrm{t}} = \left(P_1 - \Delta P_{L,\mathrm{fr}_1}\right) - \left(P_2 + \Delta P_{L,\mathrm{fr}_2}\right) + \frac{1}{2}\rho(V_1^2 - V_2^2) \tag{5}$$

Comparing Eq. (5) with the corresponding hydraulic grade line (shown schematically in **Figure 2**), one can find that the term $\left(P_1 - \Delta P_{L,\mathrm{fr}_1}\right)$ equals the value of the upstream friction grade line at the inlet of the fitting (denoted as P_{t1}). Also, the term $\left(P_2 + \Delta P_{L,\mathrm{fr}_2}\right)$ equals the value of the downstream friction grade line at the outlet of the fitting (denoted as P_{t2}). In this light, one can measure the pressure at multiple locations along the flow, and compare the pressure gradient (i.e., the slope of the hydraulic grade line) at various locations. The upstream and downstream fully developed regions can then be identified by constant pressure gradients. The friction grade lines can be determined by best-fit regressions of the pressure measurements in the fully developed regions. Finally, P_{ft1} and P_{ft2} are obtained by extrapolating the upstream and downstream friction grade lines to the location of the fitting, which, in combination with $\frac{1}{2}\rho(V_1^2 - V_2^2)$ computed from flow measurements, can be used to compute $\Delta P_{L,\mathrm{t}}$. Note that local pressures along the pipe are typically measured by manometers or differential pressure transducers relative to a reference pipe location, because their full ranges are much smaller than those of barometers or absolute pressure transducers and thereby can give better measurement accuracy. Example studies using this method include Serre et al. (1994), Crawford et al. (2007), and Al-Tameemi and Ricco (2018).

A considerable source of uncertainty in $\Delta P_{L,\mathrm{t}}$ measurements using this procedure results from the curve-fitting and extrapolation from pressure measurements in fully developed regions. Using longer piping in the fully developed region and more pressure measurements for curve-fitting and extrapolation will reduce the uncertainty of $\Delta P_{L,\mathrm{t}}$. Therefore, it is recommended that the straight pipes connected to the fitting be as long as the experimental condition permits. However, it can take a considerably long distance for flow to recover from fittings like ells and tees. As a result, there may be situations where the flow does not recover to fully developed conditions. This problem was discussed by Serre et al. (1994) and they suggested fitting the downstream pressure measurements to an exponential function whose asymptote has a slope equal to the frictional pressure gradient (which may be determined from the upstream measurement). It is noteworthy that as the onset of the fully developed region varies with the flow condition as well as the geometry of the fitting, the selection of pressure measurements used for curve-fitting and extrapolation is typically judged on a case-by-case basis, which may present a barrier to standardize this method for industrial and commercial uses.

The advantage of this method is that it can be used to determine the pressure loss of the fitting by a single set of measurements without separate pretests, unlike the two-tapping-location method that requires pretests on straight piping to determine the friction loss. The use of multiple pressure tapping also aids in detecting errors due to the improper design or installation of taps and their position with respect to the pipe wall (Pigott 1949). Meanwhile, a pressure distribution of the flow through the fitting can be obtained, which provides important insights to the flow characteristics of the fitting. Note that the benefit of eliminating the need of pretests does not necessarily mean that this method is more accurate than the two-tapping-location method, because this method is subject to uncertainties that do not apply to the other method. The actual uncertainty for a measurement also depends on the design of experimental setup and the instrumentation, which must be considered case-by-case. Furthermore, more pressure taps means more cost and effort, which also needs to be taken into consideration.

General considerations

Regardless which method is used, the determination of pressure losses of pipe fittings primarily involves pressure and flow measurements. In addition, it is necessary to know the fluid density, pipe diameter and cross-sectional area, and the distance from each pressure tapping location to the fitting. The fluid density can be either measured directly or calculated from an equation of state using the absolute static pressure and temperature.

Since the pressure loss of a fitting is a function of the flow velocity, the measurements are typically performed for a range of velocities that would be applicable to the applications of interest. In general, the water velocities in HVAC and plumbing systems are between 0.6 m/s to 3 m/s (2 fps and 10 fps) (ASHRAE 2021). Some studies have tested for velocities up to 4.6 m/s (15 fps).

It should be noted that the foregoing methods apply not only to flow-through fittings (e.g., ells, reducers, expansions) but also to branching fittings (e.g., tees, wyes, crosses). For a branching fitting, the Bernoulli equation or hydraulic grade line is determined with respect to the flow to or from a specific branch, as is the computed pressure loss of the fitting. Branching fittings usually involve various flow directions and distributions. For each flow direction, the pressure loss of each branch can vary with the flow distribution, which is often characterized by the flow ratio, i.e., the ratio of volumetric flows of different branches to the fitting. Consequently, tests for branching fittings need to be done for different flow directions and flow ratios.

Data representation

Pressure losses of fittings are most commonly expressed in terms of the loss coefficient K_L (also called the resistance coefficient), defined as the ratio of the pressure loss caused by the fitting ($\Delta P_{L,\mathrm{t}}$) to the dynamic pressure ($\rho V^2/2$):

$$K_L = \frac{\Delta P_{L,\mathrm{t}}}{\rho V^2/2} \tag{6}$$

or the ratio of the head loss caused by the fitting ($h_L = \Delta P_L/\rho g$) to the velocity head ($V^2/(2g)$):

$$K_L = \frac{h_{L,\mathrm{t}}}{V^2/2g} \tag{7}$$

The loss coefficient, K_L, is a dimensionless parameter. Eq. (6) and (7) assume that the loss coefficient is independent of the Reynolds number that characterizes the flow condition, such that it is a constant for a given fitting. This is generally true for large Reynolds numbers where the flow is completely turbulent (Çengel and Cimbala 2004; Hooper 1981; Darby 1999). In reality, however, pressure loss coefficients of most pipe fittings can vary with the Reynolds number, especially for smaller Reynolds numbers (ASHRAE 2021). Therefore, it is often necessary to report the loss coefficient of a specific fitting with reference to the Reynolds number.

An alternative expression for pressure losses of fittings is in terms of the equivalent length L_{eq}:

$$L_{\mathrm{eq}} = \frac{D}{f} \cdot \frac{\Delta P_{L,\mathrm{t}}}{\rho V^2/2} = \frac{D}{f} \cdot K_L \tag{8}$$

where D is the diameter of the pipe connecting to the fitting and f is the friction factor. The equivalent length L_{eq} is defined such that the pressure loss caused by the fitting equals that caused by a straight pipe section with the length of L_{eq} under the same flow conditions. Thus, one can simply add L_{eq} to the actual length of straight pipes to account for the pressure loss caused by the fitting, then apply the total length to the Darcy–Weisbach equation to calculate the overall pressure drop of the pipeline. Although this approach is simple and easy to use, it has a drawback that the L_{eq} is not a constant for a given fitting, but depends on the Reynolds number and the value of f, which also depends on the Reynolds number as well as the pipe surface roughness. Additionally, it is important to use the same method (Moody Chart, Colebrook correlation, etc.) to determine f when calculating L_{eq} using Eq. (8) and when calculating overall pressure drops using the Darcy–Weisbach equation (Eq. (4)).

Other methods have been proposed to express the pressure losses of fittings and valves by incorporating more constants and parameters, such as the 2-K (Hooper 1981) and the 3-K (Darby 1999) methods. Since these methods are seldom used, and the vast majority of the available data are expressed in either K_L or L_{eq}, these methods are not discussed further.

PRESSURE AND FLOW MEASUREMENT TECHNIQUES

A modern liquid pressure measurement system typically consists of the following major components: pressure taps, impulse lines, and pressure transducers. A pressure tap is the basic device to indicate the static pressure at a pipe axial location, which usually takes the form of a small hole drilled into the pipe wall. Because downstream flow of fittings is often asymmetric and the pressure is not uniform around the pipe circumference, it is generally preferable to install four or more equally-spaced taps around the circumference at the same axial location and to connect these taps to provide a physically average pressure. The interconnected taps are sometimes referred to as "piezometer rings". Blake (1976) recommended a "Triple-T" arrangement of piezometer ring that can give a more accurate reading of the average pressure than conventional piezometer rings. This arrangement is also recommended by ISO 5167-1 (2003).

In practice, the pressure at the tap mouth can be higher than that at pipe boundary (i.e., true static pressure) as a result of the deflection of the pipe flow streamlines into the tap mouth. This deviation from the true static pressure is referred to as the velocity-induced error. Shaw (1960) showed that the velocity-induced error is a function of the local stress velocity and tap diameter. Smaller tap holes are subject to smaller velocity-induced error and therefore are generally more favorable. However, the hole size is limited by practical constraints such as the work quality and the need to avoid plugging. Departure from the recommended finish conditions (e.g., burrs, inclined hole, rounded edge) can lead to bias errors of - 0.5 % to 1.1 % of the dynamic pressure (Rayle 1949). ASME PTC 19.5 (2004) recommends a diameter between 4 mm (0.15 in.) and 10 mm (0.4 in.) for pressure taps used in venturi flow meters, and also recommends that the pressure taps be as small as possible when the fluids are clean and free from contaminant that can plug the holes. Smaller diameters have been used in research and special applications where accuracy is of paramount importance and the fluids can be kept clean. For example, Rahmeyer (1999a, 1999b) and Ding et al. (2005) used 1.59 mm (1/16-in.) holes for the pressure taps in their differential pressure measurements.

Impulse lines refer to the tubing as well as valves and fittings that connect the pressure taps to the pressure transducers to transfer the pressure signal. Generally, it is desirable to use impulse lines of the smallest possible diameter while considering blockage, trapped air, and capillary effects. Special attention should be paid to pulsating flow, which may be encountered in experimental systems driven by pumps. In this case, impulse lines should be as short as possible and avoid any change of bore size to prevent or minimize pulsation amplification. Comprehensive instructions and guidance on impulse lines have been provided by Reader-Harris and McNaught (2005) and ISO 2186 (2007).

Differential pressure transducers are the most commonly used device for pressure drop measurement, while manometers were primarily used in early studies. With the advance of sensor technology, modern differential pressure transducers are smaller and faster, and can be more sensitive, reliable, and precise than manometers. The primary considerations involved in selection of a differential pressure transducer are the magnitude of the pressure drop to be measured, as well as the range and accuracy of the device (ASME PTC 19.2, 2010). It is also recommended that pressure transducers be installed with valve manifolds to permit operation, calibration, and service of the pressure transducers without removing them (ISO 2018, 2007).

The flow rate is typically measured by flowmeters. Numerous types of flowmeters are available with a wide range of accuracy, capacity, and cost. The most common types are obstruction flowmeters (orifice, venturi, and nozzle meters), ultrasonic flowmeters, turbine meters, magnetic flowmeters, and coriolis flowmeters. Detailed flowmeter descriptions and guidelines can be found in ASME PTC 19.5 (2004). An alternative approach for flow rate measurement is to collect the fluid (typically water) in a weigh tank and record the collection time. In fact, this simple approach can be accurate (Çengel and Cimbala 2004), and it has been utilized in many studies, such as Rahmeyer (1999b, 2002, 2003b), Ding et al. (2005), Oka and Itō (2005).

CONCLUSIONS

The pressure loss occurs not only within the fitting, but also in varying lengths of pipe upstream and downstream of the fitting, depending on the fitting geometry and flow conditions. Therefore, experiments should be carefully designed to ensure that the pressure loss due to the fitting is fully captured, which is a major challenge in these measurements. There are two existing methods for measuring pressure losses of pipe fittings, i.e., the two-tapping-location method and the multi-tapping-location method. Each method has advantages and disadvantages. The multi-tapping-location method can provide detailed pressure distribution along the pipe; however, it requires more complicated instrumentation and data analysis. The two-tapping-location method is simpler and could be standardized more easily but relies on the correct selection of tapping locations. More work is needed to systematically analyze the uncertainties of the method and to establish a general method to determine pressure tapping locations. Finally, the accuracy of pressure loss measurement is dependent on correct design and installation of pressure taps and impulse lines as well as the accuracy of selected pressure transducers and flow meters.

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REFERENCES

Al-Tameemi, W. T. M., and P. Ricco. 2018. Pressure-Loss Coefficient of 90 deg Sharp-Angled Miter Elbows. *Journal of Fluids Engineering*, *140*(6):1–7.

ANSI/ISA-S75.02. 1996. Control Valve Capacity Test Procedures.

ASHRAE. 2021. Chapter 22 - Pipe Design. In *ASHRAE Handbook - Fundamentals*.

ASME PTC 19.2. 2010. Pressure Measurement.

ASME PTC 19.5. 2004. Flow Measurement.

Blake, K. A. 1976. The design of piezometer rings. *Journal of Fluid Mechanics*, *78*(2):415–428.

Çengel, Y. A., and J. M. Cimbala. 2006. *Fluid Mechanics - Fundamentals and Applications*. McGraw-Hill.

Colebrook, C. F. 1939. Turbulent Flow in pipes, with particular reference to the transition region between the smooth and rough pipe laws. *Journal of the Institution of Civil Engineers*, *11*(4):133–156.

Crane Co. 2013. *Flow of Fluids Through Valves, Fittings and Pipe. Technical Paper No. 410M Metric Version*.

Crawford, N. M., G. Cunningham, and S. W. T. Spence. 2007. An experimental investigation into the pressure drop for turbulent flowin 90° elbow bends. *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering*, *221*.

Darby, R. 1999. Correlate pressure drops through pipe fittings, *106*:127–130.

Ding, C. (Alex), L. Carlson, C. Ellis, and O. Mohseni. 2005. *Pressure Loss Coefficients of 6, 8 and 10-inch Steel Pipe Fittings (Final Report on ASHRAE Research Project No. 1116-TRP)*. Minneapolis.

Hooper, W. B. 1981. The two-K method predics head losses in pipe fittings. *Chemical Engineering*.

Hydraulic Institute. 1990. *Hydraulic Institute Engineering Data Book* (2nd ed.).

ISO 2186. 2007. Fluid flow in closed conduits — Connections for pressure signal transmissions between primary and secondary elements.

ISO 5167-1. 2003. Measurement of fluid flow by means of pressure differential devices inserted in circular cross-section conduits running full — Part 1: General principles and requirements.

Itō, H., Imai, K. 1973. Energy losses at 90° pipe junctions. *Journal of the Hydraulics Division*, *99*(9):1353–1368.

Miller, D. S. 1990. *Internal flow systems* (2nd ed.).

Moody, L. F. 1944. Friction factors for pipe flow. *Transactions of ASME*, *66*:671–684.

National Academies of Sciences, Engineering, and M. (NASEM). 2019. *Management of Legionella in Water Systems*. Washington, D.C.: National Academies Press.

National Research Council (NRC). 2006. *Drinking Water Distribution Systems Assessing and Reducing Risks*. Washington, D.C.: National Academies Press.

Oka, K., and H. Itō. 2005. Energy Losses at Tees With Large Area Ratios. *Journal of Fluids Engineering*, *127*(1):110–116.

Oka, K., T. Nozaki, and H. Itō. 1996. Energy Losses Due to Combination of Flow at Tees. *JSME International Journal*, *39*(3):489–498.

Persily, A., D. Yashar, N. Milesi Ferretti, T. Ullah, and W. Healy. 2020. *Measurement Science Research Needs for Premise Plumbing Systems*. *NIST Technical Note 2063*. Gaithersburg, MD.

Pigott, R. J. S. 1949. Pressure Losses in Tubing, Pipe, and Fittings. *Transactions of ASME*, 679–689.

Rahmeyer, W. J. 1999a. Pressure loss coefficients of pipe fittings for threaded and forged weld pipe tees. *ASHRAE Transactions*, *105*:355–385.

Rahmeyer, W. J. 1999b. Pressure loss coefficients of threaded and forged weld pipe fittings for ells, reducing ells, and pipe reducers. *ASHRAE Transactions*, *105*:334–354.

Rahmeyer, W. J. 2002. Pressure loss data for large pipe ells, reducers, and expansions. *ASHRAE Transactions*, *108*:360–369.

Rahmeyer, W. J. 2003a. Pressure Loss Data for PVC Pipe Elbows, Reducers, and Expansions. *ASHRAE Transactions*, 230–251.

Rahmeyer, W. J. 2003b. Pressure Loss Data for PVC Pipe Tees. *ASHRAE Transactions*, 252–271.

Rayle, R. E. 1949. *An Investigation of the Influence of Orifice Geometry on Static Pressure Measurements*. Massachusetts Institute of Technology.

Reader-Harris, M. J., and J. M. McNaught. 2005. *Best Practice Guide - Impulse Lines for Differential-Pressure Flowmeters*. East Kilbride, Glasgow, UK.

Serre, M., A. J. Odgaard, and R. A. Elder. 1994. Energy Loss at combining pipe junction. *Journal of Hydraulic Engineering*, *120*(7):808–830.

Shaw, R. 1960. The influence of hole dimensions on static pressure measurements. *Journal of Fluid Mechanics*, *7*(4):550–564.