

NIST Technical Note 2206

State-of-the-art Review on Measurement of Pressure Losses of Fluid Flow through Pipe Fittings

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Abstract

This report presents a state-of-the-art review of the measurement of pressure loss associated with pipe fittings. The mechanisms of pressure loss in pipes and fittings are discussed to facilitate understanding of these measurements and their challenges. Existing methods for measuring the pressure loss of pipe fittings are critically reviewed. Advantages and disadvantages of each method and other general considerations are discussed. The 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. The available pressure loss data of fluid flow through pipe fittings, published from 1926 to 2021, are reviewed. In general, most of the existing data are not representative of modern pipe fittings and flow conditions. Future research efforts are described to focus on developing a standard method of test and terminology and generating new representative data for modern pipe fittings.

Keywords

fitting; flow; measurement; pressure loss; pipe.

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1. Introduction

Piping systems are commonly used for fluid distribution and heat exchange in a variety of applications including plumbing, heating, ventilation, 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 increase of water age distribution and create conditions conducive to pathogen growth such as *Legionella* (NASEM 2019).

The pressure losses associated with 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, change flow 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 the 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. For valves, manufacturer-provided pressure loss data (usually expressed as a flow coefficient) are generally available based on the application of standard methods of test, e.g., ANSI/ISA-S75.02 (1996). For fittings, however, there is no standard method of test for pressure loss measurement, probably due to the increased flow complexity associated with various fittings. As a result, manufacturer-provided pressure loss data are generally not available. Currently, designers typically rely on data for fittings that are published in handbooks.

The most referenced handbooks for such data are published by ASHRAE (2021), Crane (2013), Idelchik (2007), Miller (1990), and Hydraulic Institute (1990). Unfortunately, most of the data in these books originate from very old studies that are based on valves or fittings with obsolete material or geometry design. For example, the data sources of these handbooks include a study from the Institute of Hydraulic Research done in 1942 (cited in Rahmeyer 1999a), a study by F. R. Freeman done in 1892 and described by Freeman (1941), and studies by Benedict et al. (1966) and Simpson (1968).

Hegberg (1995) reviewed the pressure loss data published in the 1993 version of ASHRAE Handbook – Fundamentals. He demonstrated that there was a significant variation in the published data and called for further research by ASHRAE. Around 2000, ASHRAE funded a few projects to test commercial pipe fittings and update the existing database. With ASHRAE support, Rahmeyer et al. published a series of papers between 1999 and 2003 on measurements of various commercial fittings, including ell, tees, reducers, and expansions made of malleable iron, wrought steel, and PVC. A full list of publications by Rahmeyer et al. are provided in Section 5. A subsequent ASHRAE-supported research project was carried

out by Ding et al. (2005) for wrought steel pipe fittings. These new data have been included in the 2021 version of ASHRAE Handbook – Fundamentals, Chapter 22.

There are many experimental investigations on pipe fittings or junctions that are not included in the above-mentioned handbooks, such as Bullen et al. (1987), Serre et al. (1994), Oka and Itō (2005), Sharp et al. (2010), Al-Tameemi and Ricco (2018), and Coombs (2019). Although some of the studied components are not commercial fittings, their data are important and may be used for validating the data in handbooks or for system design. Furthermore, the methodology used in these studies as well as their insights and findings are valuable to the development of a standardized 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 of the projects under this program is to develop the measurement science needed to establish standardized and precise means of characterizing pressure loss of modern plumbing fittings as a function of various parameters. As an initial effort toward this goal, a literature review was performed on pressure losses of pipe fittings. The review was not limited to premise plumbing fittings, but also covered other pipe fittings given their similarities as well as the general applicability of some of the available data.

This report presents the results of this state-of-the-art review on the measurement of pressure losses of pipe fittings. The objectives of this report are to facilitate the understanding of the pressure losses caused by pipe fittings, summarize the available measurement methods and techniques, review the available data, and identify the research needed to generate more representative data for modern pipe fittings and a standard method of test.

2. 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 the material of construction and the 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.

3. Mechanisms of Pressure Losses in Pipes and Fittings

For the flow through a piping system, a portion of the total pressure is irreversibly lost to overcome the hydraulic resistance forces. This pressure loss is accompanied by the conversion of mechanical energy into heat, which is called energy dissipation. Therefore, the pressure loss represents the energy dissipation over a given section of the piping system. One should not confuse the term pressure loss with the term pressure drop. The term pressure loss emphasizes that it is an irreversible loss of the total pressure (i.e., the sum of the static, dynamic, and hydrostatic pressures), whereas the term pressure drop simply refers to the static pressure difference between two locations of a flow.

Pressure losses in straight pipes are due to the energy dissipation by fluid friction (i.e., viscous dissipation). In laminar flow, the fluid friction is caused by viscous forces that hinder one layer of fluid moving relative to the other. In turbulent flow, the fluid friction is dominated by the turbulent effect that induces random and rapid fluctuations of swirling regions within the flowing fluid, i.e., eddies, which significantly intensifies the mixing of fluid and enhances the momentum exchange. As a result, turbulent flow is associated with much greater frictional pressure losses as compared to laminar flow.

Pipe fittings invariably change the configuration of the flow passage, for example, the flow direction or cross-section. As explained by Miller (1990), any deviation from smooth, straight flow can create regions with adverse pressure gradients, i.e., regions where the static pressure rises in the direction of the flow. The fluid in these regions is decelerated due to the adverse pressure gradients, and the deceleration process can induce intense turbulence, which involves significant energy dissipation. When part of the fluid stops moving, the flow is separated from the wall boundary and, usually, the main flow contracts for some distance downstream of the separation point and causes an area of recirculation flow. In the wake of flow separation, large scale mixing spreads through the main flow to even out the energy distribution at the expense of a drop in total pressure.

Flow separation and mixing are the main mechanisms that contribute to pressure losses in pipe fittings. Figure 1 shows the location of principal adverse gradients (denoted by “P”) and flow separation in several common fittings. It can be seen that a fitting can have one or more regions with adverse pressure gradients. Larger areas of flow separation are accompanied with more intense fluid mixing, and therefore, cause greater energy dissipation and pressure losses.

In addition to flow separation and mixing, another mechanism that causes considerable pressure losses is the secondary flow, which generally occurs when the flow direction is changed. In a deflecting fitting, e.g., an ell, the turning of flow results in centrifugal forces

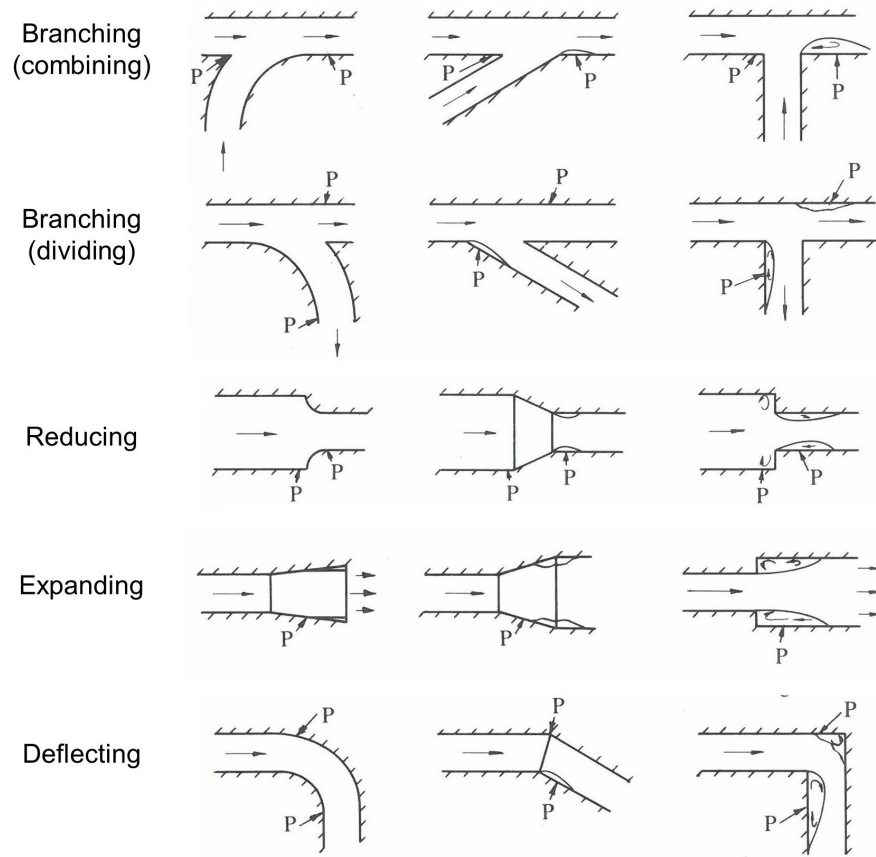


Figure 1. Location of principal adverse gradients (denoted as P) and flow separation in several common fittings. Arrows at the center of the pipes represent flow direction and curved arrows represent eddies. After Miller (1990).

that cause higher pressure at the outer wall and lower pressure at the inner wall. This situation sets up a pressure gradient across the flow and induces transverse secondary flows. The secondary flows are superimposed upon the main flow (parallel to the channel axis), resulting in a “double spiral” flow field with a pair of counter-rotating vortices (Dutta et al. 2016; Idelchik 2007), as schematically shown in Figure 2. The mixing of the main and secondary flows involves energy dissipation, which, together with the dissipation due to flow separation, contributes to most of the pressure losses of deflecting fittings such as ells.

It is important to note that although energy dissipation is primarily caused by flow separation mixing, and secondary flows that occur locally near the pipe fitting, some pressure losses can occur tens of diameters downstream of the fitting. This is because the large eddies generated within and near the fitting continue to cascade downstream and decay until they are eventually dissipated into heat and a fully developed flow is re-established. Therefore, when measuring pressure losses of pipe fittings, the pressure tap should be placed sufficiently far downstream to fully capture the pressure losses due to these decaying eddies.

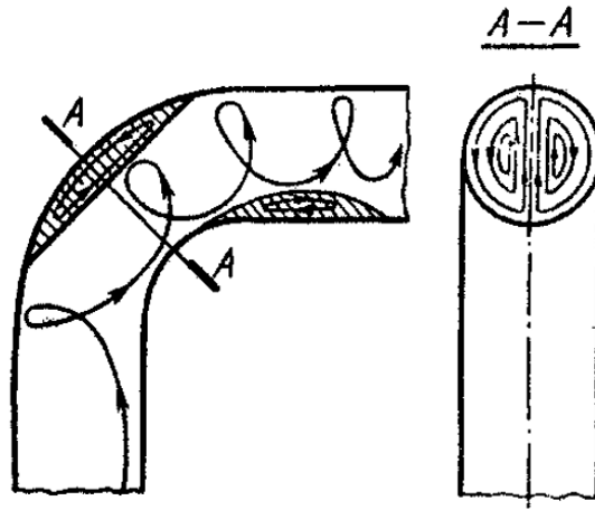


Figure 2. Schematic diagram of the double-spiral flow in an ell. After Idelchik (2007).

4. Measurement Methods and Techniques

4.1. Methods to determine pressure losses of pipe fittings

The pressure loss caused by a pipe fitting is essentially the additional pressure drop that would not exist if the fitting was not present. This can be determined by measuring the pressure drop between a location upstream of the fitting and a location sufficiently far downstream 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. 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.

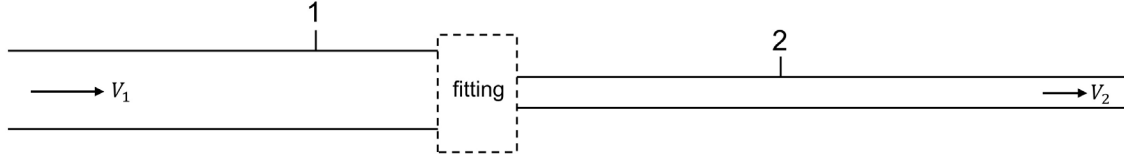


Figure 3. Control volume of an arbitrary pipe fitting connecting horizontal pipes.

4.1.1. 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 3, the Bernoulli equation is written as:

$$P_1 + \frac{1}{2}\rho V_1^2 = P_2 + \frac{1}{2}\rho V_2^2 + \Delta P_{L,t} + \Delta P_{L,fr1} + \Delta P_{L,fr2} \quad (1)$$

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

$$\Delta P_{L,t} = (P_1 - P_2) + \frac{1}{2}\rho(V_1^2 - V_2^2) - \Delta P_{L,fr1} - \Delta P_{L,fr2} \quad (2)$$

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:

$$V = \frac{\dot{m}}{\rho A_c} \quad (3)$$

where $\dot{m}$ is the mass flow rate, and 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. $A_{c1} \neq A_{c2}$ for fittings with contraction or enlargement, otherwise $A_{c1} = A_{c2}$. The frictional loss terms $\Delta P_{L,fr1}$ and $\Delta P_{L,fr2}$ 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:

$$\Delta P_{L,fr} = f \frac{L}{D} \frac{\rho V^2}{2} \quad (4)$$

where f is the Darcy–Weisbach friction factor (or Darcy friction factor), D is the pipe diameter, L the pipe length for which $\Delta P_{L,fr}$ is accounted. By measuring the $\Delta P_{L,fr}$ of the straight piping for various V (or $\dot{m}$), a calibration curve of either $\Delta P_{L,fr}$ 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 $\Delta P_{L,fr_1}$ and $\Delta P_{L,fr_2}$ from V_1 and V_2 , respectively (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). 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 (1999a, 1999b)	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 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 on the above-mentioned considerations.

4.1.2. Multi-tapping-location method

Figure 4 shows the schematic of the multi-tapping-location method. For an upstream Location 1 and a downstream Location 2 where the flow is fully developed at each location, the Bernoulli equation, Eq. (1), can be re-written as:

$$\Delta P_{L,t} = (P_1 - \Delta P_{L,fr_1}) - (P_2 + \Delta P_{L,fr_2}) + \frac{1}{2}\rho(V_1^2 - V_2^2) \quad (5)$$

Comparing Eq. (5) with the corresponding hydraulic grade line, one can find that the term $(P_1 - \Delta P_{L,fr_1})$ equals the value of the upstream friction grade line at the inlet of the fitting

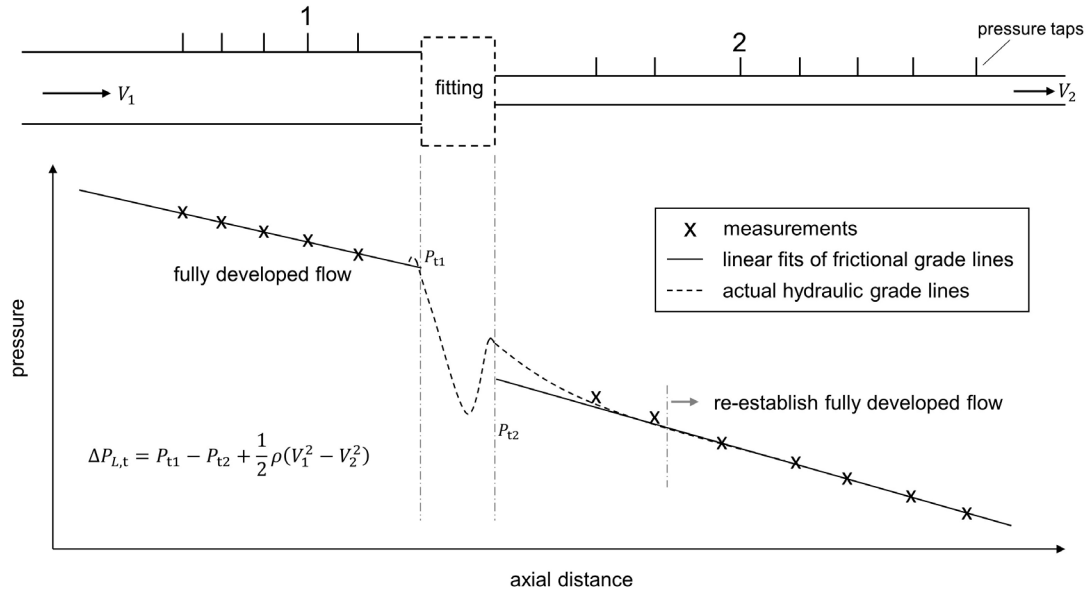


Figure 4. Schematic of the multi-tapping-location method.

(denoted as P_{t1}). Also, the term $(P_2 + \Delta P_{L,fr_2})$ 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_{t1} and P_{t2} 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 $\Delta P_{L,t}$.

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 $\Delta P_{L,t}$ 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 regions, more pressure measurements for curve-fitting, and extrapolation will reduce the uncertainty of $\Delta P_{L,t}$. 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 standardizing 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 mean greater cost and effort, which also must be taken into consideration.

4.1.3. General considerations

Regardless which method is used, the determination of pressure losses fluid flow through 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 building 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 both of the foregoing methods apply to flow-through fittings (e.g., elbows, reducers, expansions) and branching fittings (e.g., tees, wyes, crosses). For a branching fitting, the Bernoulli equation or hydraulic grade line is, 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. Figure 5 shows flow directions that may be encountered in tees and crosses. 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.

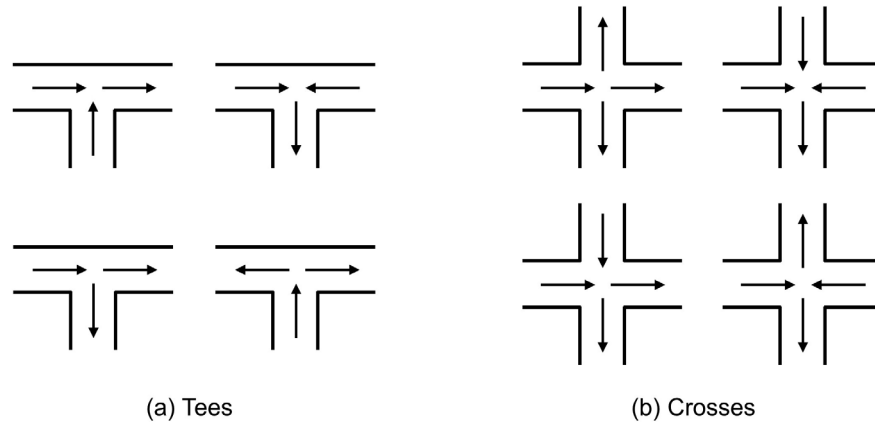


Figure 5. Possible flow directions in tees and crosses.

4.2. 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 ($\Delta P_{L,t}$) to the dynamic pressure ($\rho V^2/2$):

$$K_L = \frac{\Delta P_{L,t}}{\rho V^2/2} \quad (6)$$

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

$$K_L = \frac{h_{L,t}}{V^2/2g} \quad (7)$$

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} :

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

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.

4.3. 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 (see Figure 6). This arrangement is also recommended by ISO 5167-1 (2003).

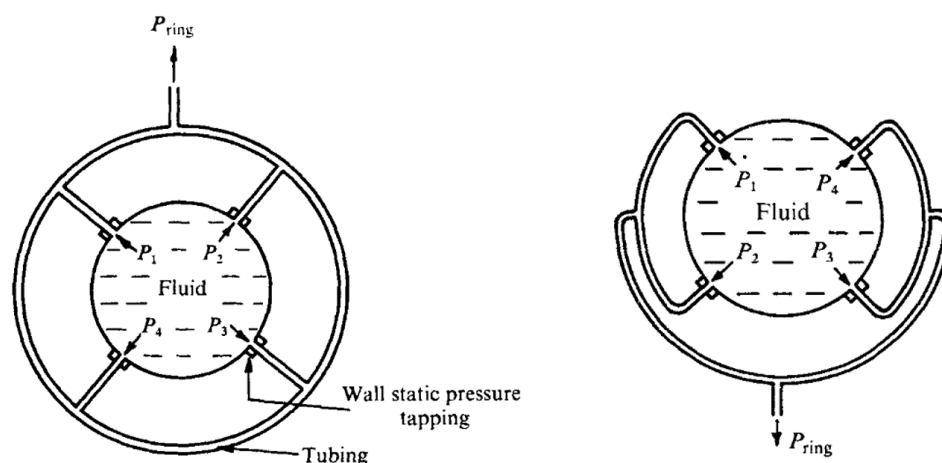


Figure 6. Conventional piezometer ring (left) and triple-T piezometer ring (right). From Blake (1976)

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).

With the advance of sensor technology, modern differential pressure transducers have become the most commonly used device for pressure drop measurement. This provides a significant benefit over manometers, manual instruments that were primarily used in early studies. 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).

5. Available Data

Measurements of pressure loss coefficients of pipe fittings or junctions have been published since the 1920s. Available sources, including well-known industry handbooks and relevant papers, are presented in this section. Subsection 5.1 consists of a chronological listing and description of the most cited handbooks that contain original or previously published pressure loss data. Subsection 5.2 includes data from relevant recent papers which have been cited in the most recent ASHRAE handbook (ASHRAE 2021). Subsection 5.3 summarizes other relevant papers that have not been as extensively cited, but still contain original data. Finally, subsection 5.4 consists of a comparison across the literature cited in the previous two sections, as well as a discussion of limitations of the studies and future research needs.

5.1. Data in handbooks

Handbooks on flow of fluids and hydraulic resistance usually contain data on pressure loss coefficients for pipes and fittings as tables and graphs to support plumbing sizing. The most widely referenced sources are Freeman (1941), Hydraulic Institute (1990), Miller (1990), Idelchik (2007), Crane (2013), and ASHRAE (2021). A summary of their data and findings is presented on the following paragraphs.

Freeman (1941) conducted investigations on pressure loss in fittings in 1892, but his work was only published by his family in 1941. He conducted work with 90° and 45° ells, drainage ells, return bends, tees, reducing tees, couplings, reducers, and enlargements for diameters ranging from 6.35 mm (1/4 in.) to 203.2 mm (8 in.). Freeman mostly tested pipe arrangements in which more than one fitting was placed apart from each other in series, however, it is not clear if and how the impact of the proximity between the fittings was assessed. To obtain the average loss of a single fitting, the total pressure loss was divided by the number of fittings used. His detailed results in tables and graphs show how pressure loss coefficients vary with fitting diameter, velocity, and the Reynolds number.

Hydraulic Institute (1990) includes tables and graphs with pressure loss coefficients for several types of pipes and fittings. For fittings such as screwed and flanged 45° and 90° ells, screwed and flanged tees, couplings, and unions, there are graphs of pressure loss coefficients as a function of diameter. Also, the source of the data is not clear. In addition, there is a table with estimated percentage variation of K_L for ells, bends, tees, and valves for screwed or flanged connections.

Miller (1990) contains a vast list of tables containing pressure loss coefficients for bends, contractions, expansions, and tees with branching and combining flow patterns. The effect of the internal geometry on K_L was discussed, and graphs were provided for estimating coefficients for different sizes. Equations and graphs were provided for correcting some coefficients for factors such as the Reynolds number and roughness. Miller (1990) demonstrated that negative pressure loss coefficients are possible for tees under some flow distributions. He also categorized the data into three classes. Class 1 corresponds to experimental data on pressure loss coefficients originating from other sources and that had been cross-checked, although the specific conditions of each experiment (e.g., geometry-related and inlet/outlet characteristics) limit their applicability to other cases. Class 2 includes data from other sources for which cross-checking was not possible, or data estimated from two or more sources that disagree with each other within the experimental accuracy. It also includes data from Class 1 that had been adapted to new conditions. Class 3 consists of data from less trustworthy sources or data from Class 1 and 2 that were adapted to conditions outside of the original application. Some results shown in this reference are from Miller's previous works, such as the one described in Miller (1971), but others are from different sources such as Gardel (1957a), Blaisdell and Manson (1963), and Itō and Imai (1973).

With its first English-translated edition published in 1966, Idelchik (2007) presents a large set of data on pressure loss coefficients as figures, graphs, and tables for varied area and diameter ratios of fittings such as ells, bends, wyes/tees. Idelchik indicated those pressure loss coefficients originated from either experimental or theoretical data obtained by equations. Although the references were listed and original data obtained by the author are present, it is difficult to associate specific data with its source. Similar to Miller (1990), Idelchik (2007) observed that mixing flow in tees can result in negative pressure loss coefficients.

The most recent edition of Crane Technical Paper 410 (SI version) was published in 2013, but the first edition of the technical paper dates from 1942. According to Michalos (2011), it has been the most utilized source in the U.S. to support determination of pressure losses in pipes and fittings. Crane (2013) data originated from tests conducted in their engineering laboratories, and from other published sources. In their laboratory, a test rig was built to test the flow of air, steam and water through 150 mm valves, ells, and tees. It appears that the results from their original work presented in this reference were limited to two graphs of pressure drop as a function of water velocity for water flow in valves and two graphs of steam flow for valves, for a 90° short radius elbow (for Schedule 40 pipe) and a cast-iron ell. There is an additional graph that shows how K_L obtained from several studies (including data from Crane tests) varied with inside diameter for a Schedule 40 pipe (30 diameters long), valves, and pipe bends. Appendix A of this reference contains a set of formulas to calculate K_L for valves and fittings (e.g., contractions and enlargements, tees and wyes, elbows, miter bends) as a function of friction factor, a constant value representing the equivalent ratio (L/D), among other parameters. A note recommends that the use of K_L provided from manufacturers should be prioritized when that information is available.

The ASHRAE Handbook – Fundamentals, ASHRAE (2021), contains data on pressure loss coefficients for several sizes and types of fittings in its Chapter 22. These data are from several sources, including other earlier handbooks and papers. Some of the sources include

the aforementioned handbooks by Freeman (1941), Crane Co. (although an early version from 1988), and Hydraulic Institute (1990), in addition to Rahmeyer (1999a, 1999b, 2002a, 2002b, 2003a, 2003b) and Ding (2005), which will be discussed in the next section.

5.2. Data in recent papers

Some papers and a report have been published from projects funded by ASHRAE aimed towards validating existing pressure loss data and obtaining values for conditions in which data are lacking. The first work described in this section is that of Rahmeyer (1999a, 1999b, 2002a, 2002b, 2003a, 2003b) and Rahmeyer and Dent (2002), performed at the Utah Water Research Laboratory (UWRL). In addition to Rahmeyer's work, other research projects were conducted at UWRL which resulted in two master's thesis (Coombs 2019; Dent 2000), and those are also described. Finally, the work of Ding et al. (2005) at St. Anthony Falls Laboratory is also characterized.

Rahmeyer (1999a, 1999b, 2002a, 2002b, 2003a, 2003b) and Rahmeyer and Dent (2002) published a series of papers that obtained pressure loss coefficients for ell, reducers, expansions, and tees from different manufacturers. Fittings used were of large diameters [i.e., 50.8 mm (2 in.) to 609.6 mm (24 in.)] connected to pipe runs through different types of connections (e.g., threaded, welded, and compression). Steel, iron, and Schedule 80 PVC fittings were tested, and velocities ranged from 0.3 m/s to 6 m/s. Because tees are more complex fittings due to the two-flow paths, pressure losses were determined for both branching and mixing flow patterns, with flow ratios varying from 0 % to 100 %.

The following conclusions were similar across most Rahmeyer's studies. A variation in pressure loss coefficients was observed for fittings with the same pipe diameter, material and connection type originated from different manufacturers, that ranged from 2 % to 161 % across studies. In addition, the type of connection between pipes and fittings had an impact on pressure loss coefficients in studies with iron and steel fittings, with threaded fittings leading to larger K_L . Finally, some ratios for mixing flows in tees resulted in negative pressure loss coefficients for all materials tested, which is due to a negative pressure created by the momentum of the large inlet flow.

However, some different conclusions were derived from these studies. Rahmeyer (1999a) found that K_L for iron and steel tees did not depend on velocity, but on flow distribution in mixing and branching flows. Rahmeyer (1999b) found that K_L for iron and steel ell, reducers, and expansions varied with pipe velocity, and thus with Reynolds number. Rahmeyer (2002a) tested different pipe configurations of iron and steel ell – two ell in a plane in U and Z shapes, a torsional configuration of two ell out of plane, and a swing configuration of three ell out of plane – located at different distances apart from each other. They found that at distances greater than or equal to 20 pipe diameters, ell did not interfere with each other and allowed for complete pressure recovery. On the contrary, distances of less than 20 pipe diameters led to overall lower pressure losses in closely spaced ell compared to losses in single fittings. When testing even larger ell, reducers and expansion fittings [304.8 mm (12 in.) to 609.6 mm (24 in.)], Rahmeyer (2002b) observed that pressure loss coefficients are approximately constant at high velocities, and that they decrease as fitting diameter increases. Although a similar observation on impact of diameter was observed in large tees, Rahmeyer and Dent (2002) noticed a much greater effect of the flow ratio on mixing and branching flows on K_L . Similar conclusions regarding impacts of

diameter and flow ratios were made for PVC ells, reducers, expansions, and tees in Rahmeyer (2003a, 2003b), however, K_L for PVC reducers decreased with velocity, while the opposite occurred for PVC expansions. In addition, no trend was observed for K_L with respect to diameter of PVC tees.

Following the work performed at UWRL, Dent (2000) conducted a similar study to Rahmeyer using wrought-steel ells, pipe expansions and reducers, and tees from different manufacturers, with diameters ranging from 254 mm (10 in.) to 609.6 mm (24 in.) and for water velocities of 0.6 m/s to 6.1 m/s. Tees were tested for mixing and branching flows, and flow ratios ranging from 0 % to 100 %. Although there was variation in pressure loss coefficients among manufacturers, they were considered small (maximum scatter across all vendors ranged from 9.44 % to 86.29 %). Overall, K_L did not vary much with pipe velocity, except for lower velocities for ells, and for some expansions and reducers, but it decreased with increases in diameter. However, as velocity increased, K_L leveled off rapidly. Pressure loss coefficients in tees were more impacted by flow distribution than velocity and diameter. Mixing tees also had negative values for some conditions.

The experimental work of Coombs (2019) at UWRL was conducted using a different type of segmented fitting called a mitered ell (Figure 7), although most of his data analysis came from Computational Fluid Dynamics (CFD) simulations for mitered and regular ells. CFD predictions were compared to both experimental and literature data. 90° and reducing steel mitered ells with diameters of 50.8 mm (2 in.), 76.2 mm (3 in.), 101.6 mm (4 in.) were tested for water velocities of 0.6 m/s to 6 m/s. The comparison between experimental, literature and modeled data suggested that pressure loss in the tested ells were dependent on the Reynolds number. However, since few diameters were tested for reducing and expanding mitered ells, more research is needed to evaluate the impact of that factor.

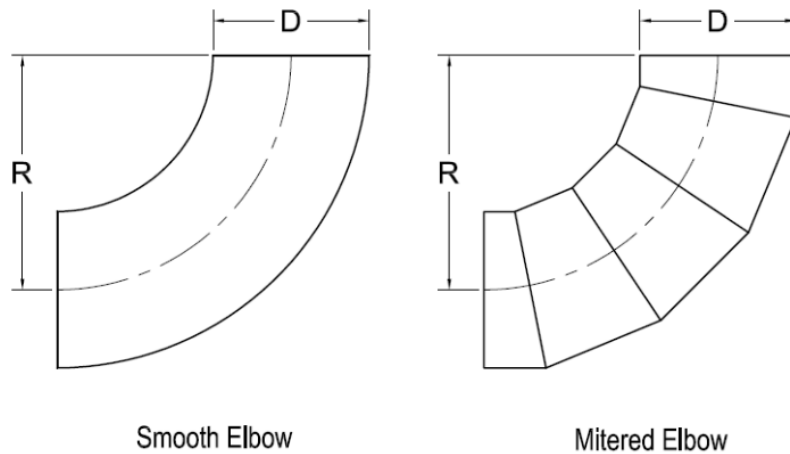


Figure 7. Schematics of a smooth and a mitered elbow. From Coombs (2019)

Ding et al. (2005) conducted a study aimed at determining pressure loss coefficients in wrought butt-welded steel ells, reducing and expansion ells, tees, reducing tees, concentric reducers, and expansions by different manufacturers. The diameters tested were 152.4 mm (6 in.), 203.2 mm (8 in.), and 254 mm (10 in.) for velocities of 0.6 m/s to 6 m/s. Tees were

run at both branching and mixing flows, with flow distributions varying from 25 % to 100 %. Although uncertainty analysis showed an overall error of less than 0.04 in determining pressure loss coefficients, this was still smaller than variations within manufacturers in most cases. For long ells, they found that fitting diameter caused K_L to increase as diameter decreased. For reducing and expanding ells, K_L was impacted by the percent reduction or expansion in the fitting. Negative K_L were also obtained for some tee flow distribution conditions, such as reported by Rahmeyer and Dent (2002) and Rahmeyer (2003b), in this case for mixing flow in tees and reducing tees for when the flow entering the branching line was less than 25 %. Finally, K_L did not vary significantly with upstream velocity for reducers and expansions, but more with diameter and percent reduction or expansion in area.

5.3. Other sources of data

In addition to the sources previously described, many other studies measured pressure losses in pipe fittings or junctions. More details on the range of factors considered by these and aforementioned publications are presented in Appendix of this report. Data on pressure loss coefficients in tees account for the majority of the available studies. Vogel (1926, 1928), Petermann (1929), Kinne (1931), Giesecke and Badgett (1931, 1932a, 1932b), Hoopes et al. (1948), McNown (1954), Gardel (1957a, 1957b), Blaisdell and Manson (1963), Iwanami et al. (1969), Iwanami and Suu (1969), Gardel and Rechsteiner (1970), Müller and Stratmann (1971), Itō and Imai (1973), Jeppson (1973), Reimann and Seeger (1986), Katsaounis (1987), Serre et al. (1994), Oka et al. (1996), Maia et al. (1998), Maia et al. (2000), Oka and Itō (2005), Costa et al. (2006), Crawford et al. (2007), and Klein (2021) conducted studies in branching and mixing 90° or oblique-angled tee fittings and junctions. Their work included testing of a variety of sizes, materials, and percentages of flow distributions. Giesecke (1926), Giesecke and Badgett (1932a), Itō (1960), Ruus (1970), Jeppson (1973), Iwasaki and Ojima (1996), Spedding et al. (2004), Crawford et al. (2007), Al-Tameemi and Ricco (2018), and Klein (2021) performed studies with 45° and/or 90° regular or mitered ells, also including a variety of sizes and materials. Benedict et al. (1966), Astarita and Greco (1968), and Bullen et al. (1987) tested reducer and expansion fittings, or contractions and enlargements in pipes. Sharp et al. (2009) tested cross junctions, Itō et al. (1984) tested 90° wyes, and Ruus (1970) tested 45°, 60°, and 90° wyes and manifolds. Keulegan and Beij (1937) and Beij (1938) were not conducted using pipe fittings, rather they studied curved pipes and pipe bends.

5.4. Limitations and research needs

Limitations of the existing studies are noted when comparing the cited literature. The surveyed pressure loss data of pipe fittings covers tees, ells, reducers, expansions, and crosses, published from 1926 to 2019. Most of the data are for pipe diameters greater than 25.4 mm (1 in.). Among the limited data for diameters of 25.4 mm (1 in.) and less, water was used as the test fluid in Giesecke (1926), Giesecke and Badgett (1931, 1932a, 1932b), Keulegan and Beij (1937), Hoopes et al. (1948), Astarita and Greco (1968), Iwanami et al. (1969), Al-Tameemi and Ricco (2018), and Klein (2021), while air was used as the test fluid in Crawford et al. (2007). The predominant piping material in the literature is metal, specifically steel, iron, and brass. The few studies on copper were conducted by Giesecke and Badgett (1932a) and most recently by Klein (2021). Literature on plastic pipes had only appeared occasionally since the 1960s. Blaisdell and Manson (1963), Ruus (1970), and Serre et al. (1994) used ‘transparent plastic pipe’; Jeppson (1973), Iwasaki and Ojima (1996), and

Spedding et al. (2004) used PVC; Benedict et al. (1966), Ruus (1970), Reimann and Seeger (1986), Maia et al. (1998), Maia et al. (2000), Costa et al. (2006), and Al-Tameemi and Ricco (2018) used acrylic. Klein (2021) was the only study found that tested and compared fittings made of a metal material (copper) with two different plastic materials (PEX and CPVC).

Despite the numerous measurements on pipe fittings or junctions that have been made for over a century, their applicability to modern pipe design is limited for the following reasons. First, the pressure loss of pipe fitting is a strong function of the fitting's internal geometry and surface roughness, and it can also vary with the pipe diameter and the Reynolds number. As the common material and geometry of pipe fittings have changed considerably over time, most of the data obtained from early studies are no longer representative of modern pipe fittings and flow conditions. There are very limited data for copper, PEX, CPVC, and PVC pipe fittings that are commonly used in modern domestic water piping applications. The data for small pipe fittings [i.e., ≤ 25.4 mm (1 in.)] are also very limited. In addition, the effects of fitting connections have rarely been investigated in the literature, despite the knowledge that they can also cause additional pressure losses (Rahmeyer, 1999b). Therefore, future measurements on pipe fittings are needed to fill these gaps. A recent survey of design engineers, plumbing contractors and building engineers by Omaghomi et al. (2022) found that 69 % of the respondents would like to see improved estimates of pressure losses in fixtures. Also, a high percentage of respondents mentioned there is a need for detailed estimates on pressure loss in modern piping and fittings made from CPVC (73 %), PEX (69 %), and copper (58 %).

Besides generating more data for modern pipe fittings, future research efforts should also focus on the standardization of a test method. It is always recommended to consult the manufacturer's data in the practical design of piping systems, considering the sensitivity of pressure loss characteristics of pipe fitting for a given design; the actual diameter may vary due to the variation in material and manufacturing. A standard method of test will allow pipe fitting manufacturers to provide their product catalogs and instructions with more accurate and repeatable data in a generalized manner. In order to prevent possible misuse of data, the manufacturer provided documents should include a full characterization of fitting dimensions and features (i.e., the material and type of connection), in addition to specifying the corresponding conditions (i.e., the Reynolds number).

Finally, we observed inconsistent terminology across the literature to describe pipe fittings. For instance, components that resemble tee fittings are sometimes referred as "right-angle pipe branches" (e.g., Vogel (1926, 1928)) or "90° pipe junctions" (e.g., Itō and Imai (1973) and Serre et al. (1994)), or even "tee junctions" (e.g., Katsaounis (1987), Reimann and Seeger (1986), Maia et al. (1998), and Maia et al. (2000)). It is not clear whether those terms are used to describe components that are fabricated differently than the existing modern fittings, or if they are synonyms of the same term. Such ambiguities should be eliminated in the future by developing a standard set of terminology and definitions for pipe fittings, which could be included in a standard method of test.

6. Conclusions

Pipe fittings cause pressure losses because they induce flow separation, fluid mixing, and secondary flows. 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.

Existing methods for measuring pressure losses of pipe fittings may be classified into two categories, i.e., the two-tapping-location method and the multi-tapping location method. Both methods have 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-method is simpler and may be easier to be standardized. More work is needed to systematically analyze the uncertainties of each method and to establish a general method to determine pressure tapping locations.

Available pressure loss data of pipe fittings published from 1926 to date were reviewed and summarized. Most existing data focus on iron and steel pipe fittings, whereas there are limited data for copper, PEX, and CPVC fittings, especially with diameters smaller than 25.4 mm (1 in.), which are commonly used in modern residential plumbing systems. Few studies have considered the effect of pipe connection, although it can also cause considerable pressure loss.

Inconsistent terminology has been used in the literature to describe pipe fittings. Therefore, in addition to filling the above research gaps, future works should focus on developing standard terminology as well as a standard method of test for pipe fittings.

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Appendix: Summary of literature with original pressure loss data of fluid flow through pipe fittings

Author (year)	Fluid	Fitting types*	Size [†] [mm (in.)]	Material	Connection type	Velocity range [m/s]	Re range [‡] [$\times 10^5$]	Temperature [°C]
Vogel (1926)	Water	Right-angle pipe branches (tees)	M: 43, B: 15, 25	Steel	n/a	n/a	0.04 – 9	n/a
Giesecke (1926)	Water	90° long radius, 90° short radius, 45° ells	25.4 – 76.2 (1 – 3)	n/a	Threaded	0.3 – 0.9	n/a	10.6 – 29.4
Vogel (1928)	Water	Right-angle pipe branches (tees)	M, B: 43	Steel	n/a	n/a	0.04 – 9	n/a
Petermann (1929)	Water	Sharp-, round-edged and conical transition 45° oblique-angled pipe branches (tees)	M: 43, B: 15, 25, 43	Red brass	Flanged	n/a	n/a	n/a
Giesecke and Badgett (1931)	Water	Tees	25.4 (1)	Cast iron	n/a	n/a	n/a	21.1
Kinne (1931)	Water	45°, 60°, 90° pipe branches (tees)	M: 43, B: 15, 25, 43	Red brass	Flanged	n/a	n/a	Ambient conditions
Giesecke and Badgett (1932a)	Water	Ells and tees	19.1, 25.4, 31.8, 38.1 ($\frac{3}{4}$, 1, 1 $\frac{1}{4}$, 1 $\frac{1}{2}$)	Copper	Couplings	0.4 – 2.2 [‡]	n/a	28.9
Giesecke and Badgett (1932b)	Water	Tees	25.4 (1)	Cast iron	n/a	n/a	n/a	n/a
Keulegan and Beij (1937)	Water	Smooth-walled, large-radius curved pipes	9.5 ($\frac{3}{8}$)	Drawn brass	Couplings	n/a	0.005 – 0.6	n/a
Beij (1938)	Water	90° pipe bends	101.6 (4)	Steel	Butted by friction clamps and bolts	n/a	0.2 – 4 [‡]	n/a
Freeman (1941)	Water	Ells, tees, reducing tees, couplings, reducers, and enlargements	6.35 – 203.2 ($\frac{1}{4}$ – 8)	Wrought iron, cast-iron	Screwed, flanged	0.08 – 8.5	0.008 – 11	14.7 – 24.7
Hoopes et al. (1948)	Water, oil	Tees	25.4 (1)	Galvanized malleable iron	Threaded	n/a	0.03 – 0.4 [‡]	n/a
McNown (1954)	Water	Combining and dividing manifold flows (sharp-edged tee junctions)	M: 50.8 (2), B: 12.7, 25.4 ($\frac{1}{2}$, 1)	Brass	n/a	n/a	n/a	n/a
Gardel (1957a, 1957b)	Water	45° to 135° tees	M: 150, B: 60, 100, 150	Cement	n/a	n/a	n/a	n/a
Itō (1960)	Water	Smooth pipe bends, 45°, 90° ells	34.65 – 45.36	Brass casting	Screwed (ells), flanged	n/a	0.1 – 4 [‡]	n/a
Blaisdell and Manson (1963)	Water	15° to 165° sharp-edged pipe junctions (tees)	M: 50.8 (2), B: 12.7 – 50.8 ($\frac{1}{2}$ – 2)	Transparent plastic	O-ring couplers	0.6, 1.5, 3, 4.6	0.2 – 2.9	23
Benedict et al. (1966)	Water, air	Enlargements, contractions	n/a	Acrylic	n/a	n/a	n/a	n/a
Astarita and Greco (1968)	Water, glycerol	Sharp-edged pipe contraction	Upstream: 9.8, Downstream: 3.94	n/a	n/a	n/a	0.0002 – 0.02 [‡]	n/a
Iwanami et al. (1969)	Water	Sharp-edged right-angled fitting (tees)	M: 21, B: 15, 21	Synthetic resin	n/a	n/a	0.005, 0.01, 0.02, 0.025	n/a
Iwanami and Suu (1969)	Flyash, sand slurry	Sharp-edged right-angled fitting (tees)	M: 53.2, B: 28, 42.1, 53.2	Drawn steel	n/a	1 – 6 [‡]	0.8 – 4.3 [‡]	20
Gardel and Rechsteiner (1970)	Water	45° to 135° tees	M: 150, B: 100, 125, 150	Asbestos cement	n/a	n/a	n/a	n/a
Ruus (1970)	Water	45°, 60°, 90° wyes, ells in manifold arrangement	95.3, 133.4, 148.6, 190.5 (3.75, 5.25, 5.85, 7.5)	Acrylic [‡]	Flanged	n/a	0.8 – 4	n/a
Miller (1971)	Air	90° tees	203.2, 304.8 (8, 12)	Plywood, acrylic [‡]	n/a	n/a	7.5 – 10	n/a
Müller and Stratmann (1971)	Air	35°, 45°, 55°, 65° branch pipes (tees)	M: 141, 163, B: 82	n/a	n/a	n/a	3.5 – 3.6 (flow ratios = 0 – 0.6)	n/a
Itō and Imai (1973)	Water	90° pipe junctions (tees)	35	Gunmetal casting	Flanged	n/a	n/a	n/a
Jeppson (1973)	Water	Ell, tee, reducing tee	101.6, 152.4 (4, 6)	PVC [‡]	Gasketed	0.17 – 5.0	0.15 – 4.4	n/a
Itō et al. (1984)	Water	90° wye	27.7	Gunmetal	Flanged, screwed	n/a	0.5, 1, 2	n/a

Author (year)	Fluid	Fitting types*	Size [†] [mm (in.)]	Material	Connection type	Velocity range [m/s]	Re range [‡] [$\times 10^5$]	Temperature [°C]
Reimann and Seeger (1986)	Air, water, steam	Tee junctions	50	Acrylic	n/a	n/a	n/a	n/a
Bullen et al. (1987)	Water	Pipe contraction	40 – 110	n/a	Flanged	n/a	0.4 – 2	n/a
Katsounis (1987)	Air, water	Tee junctions	M: 45, 203, B: 19, 82	n/a	n/a	Liquid: 0.2 – 1.4 Gas: 0.03 – 2	n/a	n/a
Serre et al. (1994)	Water	90° sharp-edged combining pipe junction (tee junctions)	M: 444, B: 63.5 – 203.2	Transparent plastic	n/a	n/a	n/a	n/a
Iwasaki and Ojima (1996)	Air	90° ell pipes	50, 75, 100, 150, 200, 250, 300	PVC	n/a	5.5 – 33	0.34 – 6.0	n/a
Oka et al. (1996)	Water	Sharp-edged combining tees	M: 54.03, B: 12.83, 15.97	Gunmetal casting	Flanged	n/a	0.24, 0.3	n/a
Maia et al. (1998), Maia et al. (2000)	Water	90° sharp-edged tee junction	n/a	Acrylic	n/a	n/a	0.05 – 0.32	15 – 20
Rahmeyer (1999)	Water	Ells, reducing ells, reducers	50.8, 101.6 (2, 4)	Malleable iron and wrought steel	Threaded, socket	0.3 – 3.7	n/a	12.8
Rahmeyer (1999)	Water	Tees	50.8, 101.6 (2, 4)	Malleable iron and wrought steel	Threaded, socket	0.6 – 3	n/a	12.8
Dent (2000)	Water	Ells, expansions/reducers, tees	254, 304.8, 406.4, 508, 609.6 (10, 12, 16, 20, 24)	Wrought steel	Butt-welded	0.6 – 6	n/a	Ambient conditions
Rahmeyer (2002)	Water	Close-coupled ells	50.8, 101.6 (2, 4)	Malleable iron and forged steel	Threaded, socket	0.3 – 6	n/a	12.8
Rahmeyer (2002)	Water	Ells, reducers, expansions	304.8, 406.4, 508, 609.6 (12, 16, 20, 24)	Wrought steel	Compression union	0.6 – 6	n/a	n/a
Rahmeyer and Dent (2002)	Water	Tees	304.8, 406.4 (12, 16)	Wrought steel	Compression union	1.2 – 3.7	n/a	12.8
Rahmeyer (2003)	Water	Fabricated injection-molded tees	50.8, 101.6, 152.4, 203.2 (2, 4, 6, 8)	Schedule 80 PVC	Socket, solvent weld	n/a	n/a	17.4 – 18.3
Rahmeyer (2003)	Water	Ells, reducers, expansions	50.8, 101.6, 152.4, 203.2 (2, 4, 6, 8)	Schedule 80 PVC	Socket and solvent weld	0.6 – 6	n/a	17.4 – 18.3
Spedding et al. (2004)	Air	90° ell bend	26	PVC	n/a	n/a	0.02 – 0.4 [‡]	n/a
Ding et al. (2005)	Water	90° long ells, reducing/expansion ells, tees, reducing tees, concentric reducers, expansions	152.4, 203.2, 254 (6, 8, 10)	Steel	Wrought butt-welded	0.6 – 6	n/a	n/a
Oka and Itō (2005)	Water	45°–135° sharp-edged tees	M: 54.03, B: 15.97	Gunmetal casting	Flanged	n/a	M: 0.3, B: 1	n/a
Costa et al. (2006)	Water	90° sharp-edged and round-edged tee junctions	30.1	Acrylic	n/a	n/a	0.05 – 0.32	n/a
Crawford et al. (2007)	Air	90° ell bends, 90° tee junction	25.4	Aluminum	n/a	n/a	0.20 – 1.3	21.9 – 26.9
Sharp et al. (2009)	Water	Cross junctions	279.4	Carbon steel	n/a	0.3 – 4	0.3 – 4.5	n/a
Crane (2013)	Water, steam	Valves, ells, tees	150	n/a	n/a	Water: 0.6 – 6 Steam: 0.05 – 0.2	n/a	n/a
Al-Tameemi and Ricco (2018)	Water, air	90° sharp-angled miter ells	11, 16, 21	Acrylic	Flanged	n/a	0.005 – 0.6	25
Coombs (2019)	Water	90° mitered ell, reducing mitered ell	50.8, 76.2, 101.6 (2, 3, 4)	Steel	Welded, flanged	0.6 – 6	n/a	n/a
Klein (2021)	Water	Ells, tees, couplings	3.2 – 25.4 ($\frac{1}{8}$ – 1)	Copper, PEX, CPVC	Push-to-connect, screwed, press, expansion	0.6 – 3	n/a	n/a

Notes:

* Original terminology used by the study authors, text in parenthesis indicates potential alternative terminology.

[†] M: main line; B: branch line

[‡] Factor was estimated based on information from the paper.