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Experimental determination and computational fluid dynamics predictions of pressure loss in close-coupled elbows (RP-1682)

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An experimental program was implemented to study pressure losses in HVAC duct systems associated with 305 mm (12 in.) diameter close-coupled round five-gore elbows. The goal of this program was to experimentally verify a computational fluid dynamics model to accurately predict pressure losses in order to design duct systems more effectively. The results of this study showed that the loss coefficient increased as a function of separation distance between the elbows in a Z-configuration and decreased in a U-configuration. For both 305 mm (12 in.) and 203 mm (8 in.) diameter elbows, power law expressions correlating the combination loss coefficient data as a function of intermediate length for close-coupled elbows arranged in a Z-configuration or a U-configuration were presented. Computational fluid dynamics modeling with enhanced wall treatment using the $k-\varepsilon$ method was generally able to correctly predict elbow loss coefficients with an error of less than 15%.

Introduction

Previously, Salehi et al. (2016) reported friction factor values for the flow of air in a round, galvanized steel straight spiral duct. In addition, loss coefficient data for a single five-gore 90° elbow and two close-coupled five-gore elbows were presented. The tests were performed on ducts/fittings having a nominal diameter of 203 mm (8 in.). Likewise a comparison of computational fluid dynamics (CFD) turbulence models in predicting pressure drop for each of the configurations was performed. This was achieved by conducting a critical comparison between turbulence models, including the $k-\varepsilon$ and $k-\omega$ models, as well as the Reynolds Stress Model

(RSM) to establish their capabilities and limitations in predicting such flows. It was demonstrated that two-equation turbulence models predicted incorrect trends when applied to flow in U- and Z-configuration ducts. However, the RSM with enhanced wall treatment was generally able to correctly predict elbow loss coefficients with less than 15% of error. Per Salehi et al. (2016), a prediction uncertainty of $\pm 15\%$ obtained using CFD techniques is consistent with random measurement errors anticipated from experimental methods.

Other experimental and CFD studies related to pressure loss in close-coupled fittings have been reported in the literature; several of the more pertinent are herein discussed. Sepsey and Knotts (1972) performed an experimental investigation of upstream and downstream branch loss coefficients for round cross-section close-coupled tees possessing different branch spacing. Generally, the upstream loss coefficients, whether for branches on the same or opposite sides of the main duct, showed little effect due to branch spacing. However, the downstream loss coefficients decreased with increased branch spacing. Rahmeyer (2002) measured pressure loss for the flow of water in round close-coupled ells arranged in either a U-, Z-, torsional-, or swing-configuration. It was claimed that for all close-coupled test configurations, a spacing of less than 20 pipe diameters between the ells resulted a loss coefficient that was lower than the equivalent uncoupled el, whereas separation distances greater than 20 diameters yielded the same loss coefficient as an uncoupled fitting. Similarly Mylaram and Idem (2005) measured pressure loss for airflow in several types of round

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elbows arranged in either a U- or a Z-configuration. They concluded that the loss coefficient for a close-coupled combination exceeded the value of twice the loss coefficient for a single elbow in almost all cases, although in many instances the effect of close-coupling was not dramatic. Gan and Riffat (1995) performed a CFD and experimental study of two close-coupled round elbows arranged in a U-configuration. They contended that the separation distance between the elbows had little influence on the loss coefficient, although the overall pressure loss increased due to the presence of the additional straight ducts between the elbows. Mumma et al. (1997) attempted to compare pressure loss in rectangular elbows (both hard and easy bend) from measurements to those obtained by CFD methods for several practical arrangements downstream of an air handler. Their CFD predictions implied that for close-coupled elbows the total pressure loss was approximately 27% higher than would be obtained by simply summing the pressure loss for noncoupled fittings. Sami and Cui (2004) employed a CFD model to study pressure losses in two round close-coupled elbows arranged as a U-, Z-, or T-shape, and three round close-coupled elbows configured in an S-shape. In each instance the three-dimensional Reynolds-averaged Navier–Stokes (RANS) equations were solved. It was concluded that the shear stress transport (SST) turbulence model yielded better comparison with the limited experimental data from the literature than did the standard $k-\epsilon$ model. For separation distances less than 20 pipe diameters, it was predicted that the pressure loss coefficient was lower than that of a single equivalent elbow, and that for separation distances greater than 20 diameters there was no discernable effect of coupling the elbows.

The present article provides additional zero-length pressure loss coefficient data for close-coupled five-gore 90° elbows having a nominal diameter of 305 mm (12 in.); these data were not reported in Salehi et al. (2016). In every instance the turning radii of the elbows was again fixed at $r/D = 1.5$; refer to Figure 1. The purpose of the testing was to provide additional data to corroborate CFD modeling predictions, and to further establish whether the CFD methods recommended in Salehi et al. (2016) and RP-1682 (2016a) can predict results that are accurate to within 15% of experimentally determined loss coefficients. Two close-coupling configurations were studied in the present experiments, i.e.,

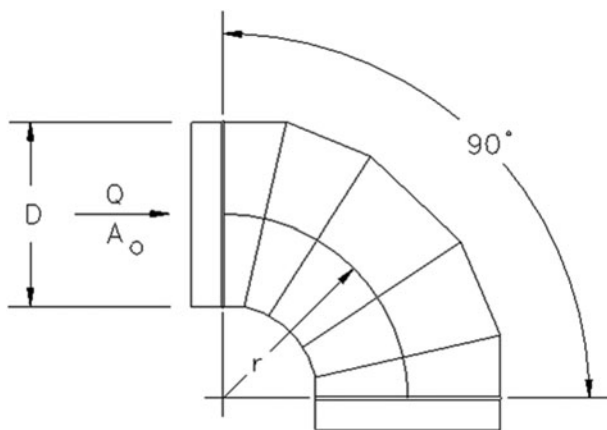


Fig. 1. 90° five gore elbow $r/D = 1.5$.

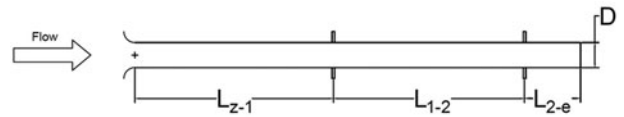


Fig. 2. Test setup to measure tare pressure loss.

cases where the close-coupled test apparatus constituted either a Z-shape or a U-shape. In every instance the duct length (L_{int}/D) separating the center-points of the elbows was systematically increased, starting from the situation where the two elbows were butted together in close proximity.

Experimental program

A series of experiments was performed to measure the friction factor in a straight duct, and the loss coefficient of both a single five-gore elbow and two close-coupled five-gore elbows. Complete details of the experimental apparatus and test procedure are provided in RP-1682 (2016b). The volume flow rate through the test section was measured using calibrated flow nozzles mounted in a chamber. The measurements of pressure drop and volumetric flow rate through the ducts and fittings were performed in accordance with ASHRAE Standard 120–2015 (2015). The elbow pressure loss experiments were preceded by a series of tests designed to evaluate the friction factor of straight ducts. A bellmouth was mounted at the entrance of the ducts to ensure uniform inlet flow. Pressure taps soldered to the ducts were employed to measure the pressure drop at specific distances prescribed in Standard 120–2015. In order to establish the baseline loss coefficient for a single elbow, the straight duct setup was modified by inserting an elbow and measuring the pressure drop across the single fitting. The setup shown in Figure 2 was used to measure the friction factor and relative roughness of the duct connected to the elbows. Similarly, Figure 3 depicts the setup that was employed to determine loss coefficient for a single elbow. Two close-coupling configurations were studied in the present experiments, i.e., either a Z-shape or a U-shape. In each case the straight duct length inserted between the upstream elbow and the downstream elbow was systematically varied; refer to RP-1682 (2016b) for further details. The test setup used for the experimental determination of the loss coefficient of two close-coupled elbows in a Z-configuration is illustrated in Figure 4. Likewise the setup employed to measure the loss

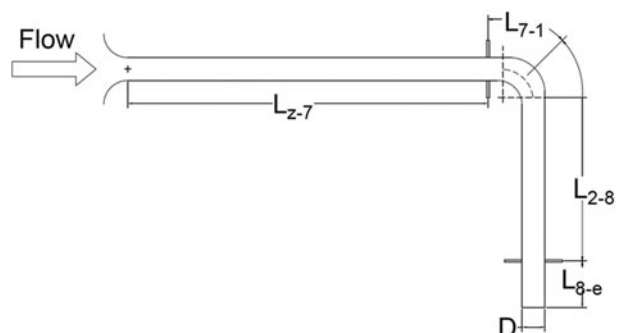


Fig. 3. Test setup to measure single elbow loss coefficient.

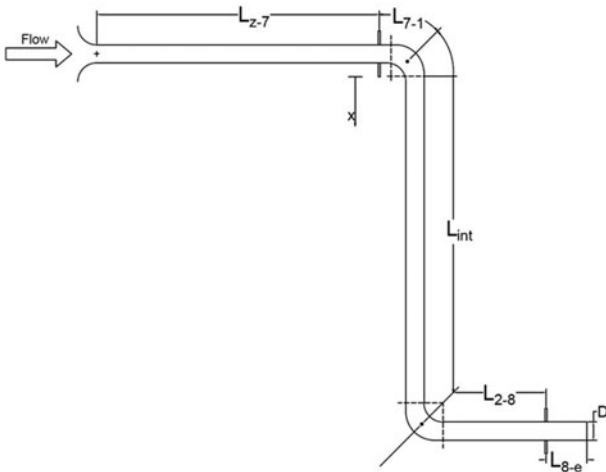


Fig. 4. Test setup to measure close-coupled elbow loss coefficient (Z-configuration).

coefficient of two close-coupled elbows in a U-configuration is portrayed in Figure 5.

Data reduction

The elbow pressure loss coefficient for a single elbow is defined as the ratio of the total pressure loss through the elbow to that of velocity pressure, and is expressed as:

$$C = \frac{\Delta p_{t,1-2}}{p_{v8}} \tag{1}$$

The velocity pressure is a function of the measured average velocity in the duct:

$$p_{v8} = \frac{1}{2} \rho \bar{V}_8^2 \tag{2}$$

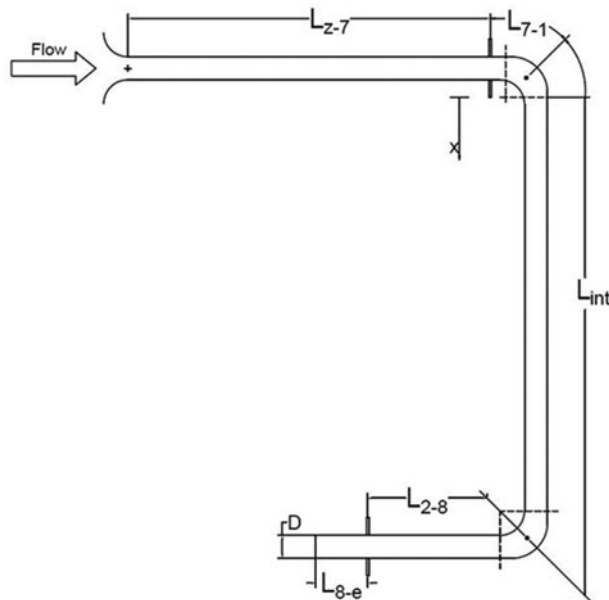


Fig. 5. Test setup to measure close-coupled elbow loss coefficient (U-configuration).

Referring to Standard 120–2015, the total pressure loss across an equal area elbow can be determined as follows:

$$\Delta p_{t,1-2} = \Delta p_{s,7-8} - (L_{7-1} + L_{2-8}) \left(\frac{\Delta p_f}{L} \right) \tag{3}$$

The subscripts in this equation refer to the planes indicated in Figure 3. The terms L_{7-1} and L_{2-8} represent the distance between the upstream taps and the center-point of the elbow, and center-point of the elbow to the downstream pressure taps, respectively. The tare pressure friction loss per unit length $\frac{\Delta p_f}{L}$ is calculated by Equation 4:

$$\frac{\Delta p_f}{L} = \frac{p_{v1} \cdot f}{D_1} \tag{4}$$

In the case of experiments conducted on two close-coupled elbows, the loss coefficient was determined using Equation 1. However, in that instance, the total pressure loss through two elbows was calculated using:

$$\Delta p_{t,1-2} = \Delta p_{s,7-8} - (L_{7-1} + L_{2-8} + L_{int}) \left(\frac{\Delta p_f}{L} \right) \tag{5}$$

The quantity L_{int} refers to the measured distance from center-point to center-point of the two close-coupled elbows; refer to Figure 4. The friction pressure loss $\frac{\Delta p_f}{L}$ was determined from Equation 4. The quantity $L_{int} \cdot \frac{\Delta p_f}{L}$ accounts for the additional loss due to the intermediate length.

The total pressure losses were measured experimentally at each flow rate for all setups, and the least squares method was employed in order to obtain an overall loss coefficient. The Darcy equation can be written as:

$$\Delta p_{t,1-2} = C \cdot p_{v8} \tag{6}$$

In the previous equation, the tare friction pressure loss has been subtracted from the overall pressure loss across the fitting thus yielding a zero-length loss coefficient; refer to Equation 5 for example. The slope of the curve $\Delta p_{t,1-2}$ plotted against p_{v8} is interpreted as the loss coefficient for either a single elbow or two close-coupled elbows.

Determination of the airflow rate in the test apparatus required the measurement of the pressure loss across the nozzle board, the static pressure of the plenum chamber, and the temperature inside the plenum chamber. Additional equations necessary to evaluate such quantities as the friction factor or the velocity pressure can be found in Standard 120–2015. The density of air in the test section was calculated by means of the correlations presented in Standard 120–2015 based on measurements of the ambient dry- and wet-bulb temperature and barometric pressure, and the test section temperature and average static pressure.

The tare pressure loss measurements were subjected to an uncertainty analysis based on the method of Kline and McClintock (1953), as prescribed by ASHRAE Guideline 2–2005 (2005) for random variations of the measured quantities. In every instance the measurement uncertainty estimates were

performed with a 95% confidence level. When a quantity to be measured depends on more than one independent variable it is necessary to characterize how the measurement error for each variable combines to produce the net error in the final result. Consider a dependent variable u that depends on “ n ” independent variables x_i , such that:

$$u = f(x_1, x_2, \dots, x_n). \tag{7}$$

If allowance is made for the fact that random errors tend to compensate (being both positive and negative) the root-sum-square error in the measured parameter δu_r is estimated as:

$$\delta u_r = \pm \left[\sum_{i=1}^n \left(\frac{\partial f}{\partial x_i} \delta x_i \right)^2 \right]^{1/2}. \tag{8}$$

In this instance δx_i denotes the measurement uncertainty of each independent variable. In many cases Equation 8 has the following form:

$$u = K x_1^{a_1} x_2^{a_2} \dots x_n^{a_n}, \tag{9}$$

where the quantity K is a constant and a_n are constant exponents. In that case it can readily be shown that the fractional root-sum-square error in the dependent variable can be expressed as:

$$\left(\frac{\delta u}{u} \right)_r = \pm \left[\sum_{i=1}^n \left(a_i \frac{\delta x_i}{x_i} \right)^2 \right]^{1/2}. \tag{10}$$

An error propagation analysis was performed on the straight duct tare pressure loss measurements performed in this test program. Therein, Equation 10 was used to estimate the measurement uncertainties of the straight duct test section Reynolds numbers and friction factors. The dimensional measurements in the experiments were assumed to have an accuracy of $\pm 1\%$. In some instances, the measurement uncertainty of a parameter exceeded the basic scale readability of a particular instrument. For example, that occurred when random fluctuations in the system static pressure were present, and those fluctuations exceeded the scale readability of the manometer; refer to Table 1. The flow nozzle coefficient uncertainty in every instance was assumed to be $\pm 1\%$.

The least squares method was used to calculate the combination loss coefficient $2C$ for each close-coupled elbow test condition. Therein, the following procedure was employed to estimate the experimental uncertainty associated with the measurements. The square of the standard error of the y-data about the fit S_{yx}^2 was determined by:

$$S_{yx}^2 = \frac{1}{N-1} \sum_{i=1}^N (\Delta p_{t,1-2} - 2C \cdot p_{v8})^2. \tag{11}$$

In this instance the quantity N refers to the number of data points measured for each test case. The loss coefficient was evaluated from the slope of the total pressure loss versus

Table 1. Uncertainties in measured parameters.

Dry-bulb temperature	0.6°C (1°F)
Wet-bulb temperature	0.6°C (1°F)
Plenum chamber temperature	0.6°C (1°F)
Test section temperature	0.6° (1°F)
Plenum chamber static pressure	25 Pa (0.1 in. wg)
Pressure loss across nozzle chamber	5 Pa (0.02 in. wg)
Test section static pressure	2.5 Pa (0.01 in. wg)
Barometric pressure	0.25 mm Hg (0.01 in. Hg)

velocity pressure curve for each data set. Therefore, the number of degrees of freedom was defined such that $\nu = N - 1$, i.e., it was based on the number of data points for each data set minus the number of coefficients determined from the data set. The sum of the squared deviations of x about the mean value S_{xx} was defined as:

$$S_{xx}^2 = \sum_{i=1}^N (p_{v8} - \bar{p}_{v8})^2. \tag{12}$$

The mean value of the velocity pressure was evaluated as:

$$\bar{p}_{v8} = \frac{1}{N} \sum_{i=1}^N p_{v8}. \tag{13}$$

Hence, the uncertainty of the close-coupled fitting loss coefficient was calculated using:

$$\Delta 2C = \pm t_{a/2, N-1} \frac{S_{yx}}{S_{xx}}. \tag{14}$$

The quantity $t_{a/2, N-1}$ is the Student’s t -statistic with $N-1$ degrees of freedom, and $a = 1 - c$ is the assumed level of confidence. In this study it was assumed that $c = 0.95$, i.e., a confidence level of 95% was considered. For single elbow tests, the loss coefficient uncertainty calculation were performed identically; however, in those cases, the single elbow loss coefficient C was employed in Equation 11.

CFD modeling

In Salehi et al. (2016) zero-length pressure loss coefficients for 203 mm (8 in.) diameter five-gore elbows were predicted using the $k-\epsilon$ and $k-\omega$ models, as well as the RSM, and these predictions were compared to experimental data. The cases that were considered included a single elbow, as well as two close-coupled elbows arranged in either a Z- or a U-configuration. It was shown that two-equation turbulence models, except the $k-\epsilon$ model, predicted incorrect trends when applied to flow in U- and Z-configuration ducts. However, the $k-\epsilon$ and the RSMs with enhanced wall treatment were generally able to

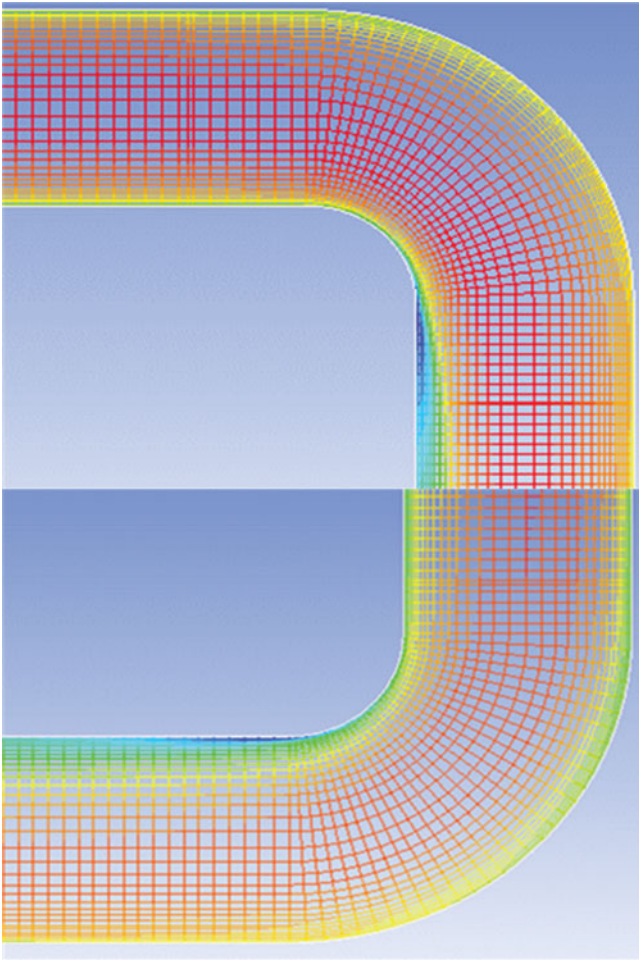


Fig. 6. Numerical grid for 304.8 mm (12.0 in.) diameter double elbow U-configuration $L_{\text{int}} = 3.78$ m (12.40 ft).

correctly predict elbow loss coefficients with an error of less than 15%.

In the current article, the standard $k-\varepsilon$ method incorporated in the CFD code FLUENT was employed to predict the zero-length loss coefficient of 305 mm (12 in.) diameter five-gore single elbows, and two close-coupled elbows arranged in a Z- or U-configuration. Each case was modeled using a quadrilateral structured grid and enhanced near-wall treatment. For enhanced near-wall treatment, the dimensionless wall distance y^+ for the first cell next to a wall was set between 1 and 3. To resolve the near-wall viscous region, at least 10 grid points were placed in the boundary layer near all walls. For each case considered in this study the turbulence models employed a grid size of 60×200 in the entrance region, 60×22 in the curved regions, and 60×160 in the exit region. The surface roughness of the duct and fittings was treated as a prescribed input quantity. In every instance a grid refinement study was performed to verify grid independence. For example, the numerical grid for the 305 mm (12 in.) diameter duct arranged in a U-configuration with a separation distance $L_{\text{int}}/D = 12.40$ is shown in Figure 6. A structured grid was used, with a finer mesh near walls and an aspect ratio that did not exceed 10. The flow initiation method used in all

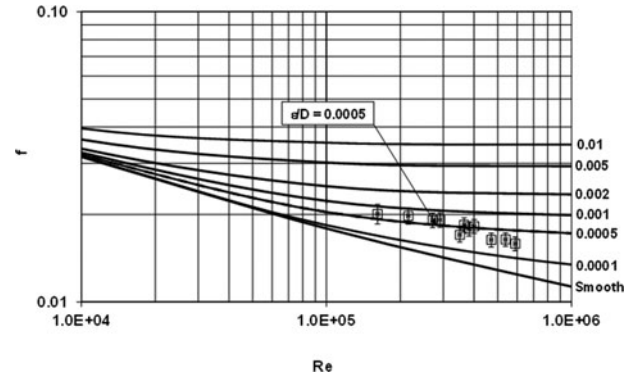


Fig. 7. 305 mm (12.0 in.) diameter straight duct moody diagram.

CFD cases was the velocity specification method at the inlet. The boundary conditions used were velocity inlet boundary conditions to define the velocity and scalar properties of the flow at the inlet and pressure outlet boundary conditions were used to define the static pressure at flow exit to insure better rate of convergence when backflow occurs during iteration. Complete details regarding the CFD model are provided in Salehi et al. (2016) and RP-1682 (2016a).

Results

Experimental measurements

In this study pressure loss measurements were performed on 305 mm (12 in.) diameter straight ducts in order to evaluate the tare pressure loss. The Darcy friction factor was calculated for each flow rate and plotted against the Reynolds number on a Moody diagram; refer to Figure 7. The Colebrook equation was employed to determine the relative roughness value using the least squares method. To a close approximation, the friction factor data for a 305 mm (12 in.) galvanized steel spiral duct suggested that the relative roughness $\varepsilon/D = 0.0005$. The tare pressure loss was calculated using the Colebrook equation, in conjunction with Equation 4. The error bars were evaluated per Equation 10.

The total pressure loss across the elbow(s) was calculated using Equation 3 for a single elbow, or Equation 5 for two close-coupled elbows, and plotted as a function of the velocity pressure through the elbow(s), thereby obtaining the zero-length loss coefficient for each elbow combination. The results of pressure loss measurements on a 305 mm (12 in.) diameter straight duct and single/close-coupled elbows are summarized in Tables 2 through 5, which also provide test setup dimensions per Standard 120. For a single 305 mm (12 in.) diameter five-gore elbow with $r/D = 1.5$ the loss coefficient measured in this experimental program was $C = 0.12$. The corresponding loss coefficient from the ASHRAE Duct Fitting Database (2015) is $C = 0.18$. Uncertainty estimates as calculated using Equation 14 for the experimental determination of elbow loss coefficients, i.e., either ΔC or $\Delta 2C$, are likewise tabulated.

When two close-coupled 305 mm (12 in.) diameter five-gore elbows were butted together in a Z-configuration the

Table 2. 305 mm (12.0 in.) diameter straight duct tare pressure loss testing.

L_{z-1} m (ft)	L_{1-2} m (ft)	L_{2-e} m (ft)	D mm (in.)	ϵ/D
5.80 (19.04)	9.00 (29.54)	2.37 (7.79)	305 (12.0)	0.0005

Table 3. 305 mm (12.0 in.) diameter single elbow pressure loss testing.

L_{z-7} m (ft)	L_{7-1} m (ft)	L_{2-8} m (ft)	L_{8-e} m (ft)	C	ΔC
5.80 (19.02)	0.69 (2.26)	4.12 (13.53)	1.76 (5.76)	0.115	0.025

loss coefficient of the combination exceeded that for 2C of a single elbow, for those cases where $L_{int}/D < 12$. As the separation distance between the center-points of the two elbows was increased the combination loss coefficient for the close-coupled pair arranged in a Z-configuration progressively decreased. In contrast, for two close-coupled elbows butted together in a U-configuration the loss coefficient of the combination was less than that 2C for a single elbow, when $L_{int}/D < 12$. As the separation distance between the elbow center-points was increased the combination loss coefficient for the two close-coupled elbows arranged in a U-configuration progressively increased. In either case it was observed that the combination loss coefficients 2C for the Z-configuration and the U-configuration tests converged to similar values after a separation distance (L_{int}/D) of approximately 12. Experimentally determined values of close-coupled zero-length loss coefficients are plotted as a

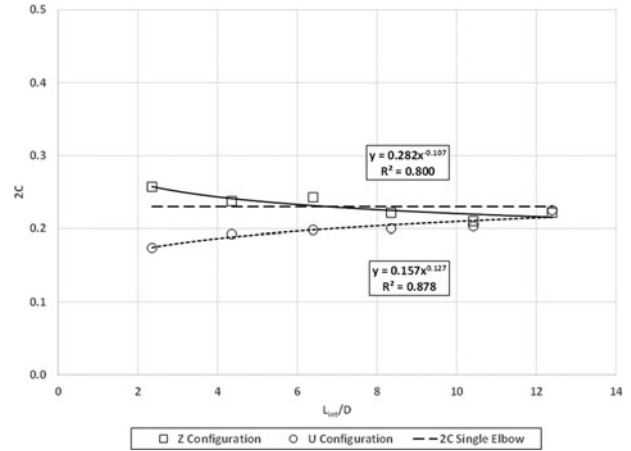


Fig. 8. 305 mm (12.0 in.) diameter double elbow pressure loss test results.

function of separation distance between the center-points in Figure 8.

These observations were quantified by fitting Power Law curves to the 2C data for 305 mm (12 in.) diameter close-coupled elbows arranged in both a Z-configuration or a U-configuration as a function of (L_{int}/D). It was found that the Power Law equation and coefficient of determination for 305 mm (12 in.) diameter close-coupled elbows arranged in a Z-configuration could be expressed as:

$$2C = 0.282 (L_{int}/D)^{-0.107}; R^2 = 0.800. \quad (15)$$

The quantity R^2 refers to the resulting coefficient of determination. Similarly, for 305 mm (12 in.) diameter close-coupled elbows arranged in a U-configuration the curve-fit equation and associated coefficient of determination was

Table 4. 305 mm (12.0 in.) diameter double elbow pressure loss testing: Z-configuration.

L_{z-7} m (ft)	L_{7-1} m (ft)	L_{2-8} m (ft)	L_{8-e} m (ft)	L_{int} m (ft)	L_{int}/D	2C	$\Delta 2C$
5.80 (19.02)	0.69 (2.26)	4.11 (13.47)	2.37 (7.79)	0.72 (2.36)	2.36	0.257	0.061
				1.33 (4.36)	4.36	0.237	0.062
				1.95 (6.40)	6.40	0.243	0.062
				2.55 (8.36)	8.36	0.221	0.063
				3.18 (10.42)	10.42	0.210	0.065
				3.78 (12.40)	12.40	0.222	0.063

Table 5. 305 mm (12.0 in.) diameter double elbow pressure loss testing: U-configuration.

L_{z-7} m (ft)	L_{7-1} m (ft)	L_{2-8} m (ft)	L_{8-e} m (ft)	L_{int} m (ft)	L_{int}/D	2C	$\Delta 2C$
5.80 (19.02)	0.69 (2.26)	4.11 (13.47)	2.37 (7.79)	0.72 (2.36)	2.36	0.174	0.059
				1.33 (4.36)	4.36	0.192	0.062
				1.95 (6.40)	6.40	0.198	0.064
				2.55 (8.36)	8.36	0.200	0.064
				3.18 (10.42)	10.42	0.203	0.064
				3.78 (12.40)	12.40	0.225	0.064

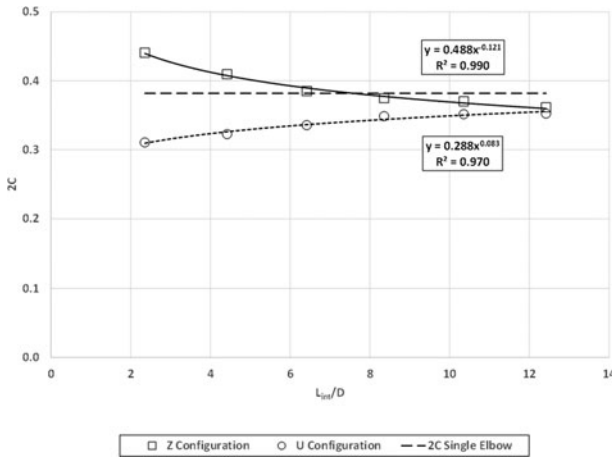


Fig. 9. 203 mm (8.0 in.) diameter double elbow pressure loss test results.

determined to be:

$$2C = 0.157 (L_{int}/D)^{0.127}; R^2 = 0.878. \quad (16)$$

For comparison purposes, Figure 9 illustrates zero-length loss coefficient data taken from RP-1682 (2016b) for 203 mm (8 in.) diameter close-coupled elbows in terms of separation distance between the center-points. For close-coupled elbows arranged in a Z-configuration, it was found that:

$$2C = 0.488 (L_{int}/D)^{-0.121}; R^2 = 0.990. \quad (17)$$

Likewise, for 203 mm (8 in.) diameter close-coupled elbows arranged in a U-configuration the resulting curve-fit expression and corresponding coefficient of determination was given by:

$$2C = 0.288 (L_{int}/D)^{0.083}; R^2 = 0.970. \quad (18)$$

Separate curve-fit expressions were generated for each elbow geometry, since no single correlation describing close-coupled loss coefficient variation as a function of separation distance was deemed to be adequate for the cases considered in RP-1682 (2016b).

CFD model predictions

In the present study extensive CFD predictions of zero-length pressure loss coefficients for two close-coupled five-gore 90° elbows having a nominal diameter of 305 mm (12 in.) and $r/D = 1.5$ were compared to experimental data. Several representative cases are herein discussed; for brevity not all cases from the present study are included but they are available in RP-1682 (2016a).

Figure 10 illustrates the pressure loss coefficient data obtained for two 305 mm (12 in.) diameter five-gore 90° close-coupled galvanized steel elbows with a dimensionless turning radius $r/D = 1.5$ that were arranged in a U-configuration. In this instance the distance between the center-points of each

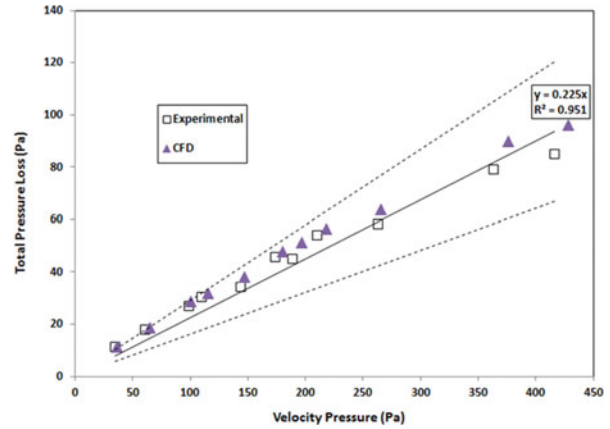


Fig. 10. Comparison of total pressure loss versus velocity pressure for 304.8 mm (12.0 in.) diameter double elbow U-configuration $L_{int} = 3.78$ m (12.40 ft).

elbow corresponds to $L_{int} = 3.78$ m (12.40 ft). For this case the measured total pressure loss versus velocity pressures is also compared to the values predicted using the $k-\epsilon$ method, as described previously. The dashed lines represent the expected uncertainty in the measured loss coefficient data, as calculated using Equation 14. The numerical convergence of this solution in terms of scaled residuals is depicted in Figure 11. The average number of iterations for such cases typically required about 1300 iterations. Contours of the corresponding static pressure (Pa) are shown in Figure 12. The effect of the two elbows on the static pressure is clearly shown, where the static pressure is increasing at the outer radii and decreasing at the inner radii. The opposite is predicted for the dynamic pressure (refer to Figure 13), where the dynamic pressure is decreasing at the outer radii and increasing at the inner radii. The error in the loss coefficient prediction is defined as follows: $Error = (Experimental - CFD) / Experimental$. This error is provided in Table 6 for the case of two close-coupled 305 mm (12 in.) diameter five-gore 90° galvanized steel elbows with a dimensionless turning radius $r/D = 1.5$ arranged in a U-configuration. In this instance the maximum error is about 10%.

Figure 14 shows the comparison between experimental and $k-\epsilon$ CFD total pressure loss versus velocity pressure

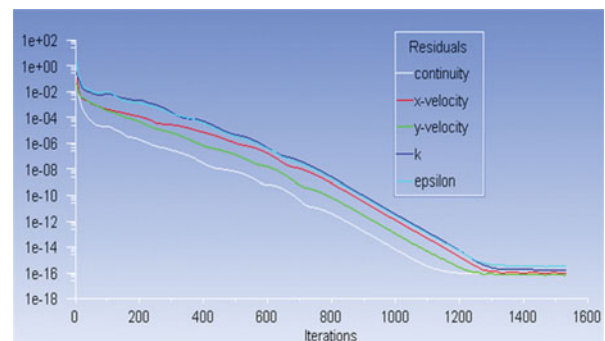


Fig. 11. Scaled residuals for 304.8 mm (12.0 in.) diameter double elbow U-configuration $L_{int} = 3.48$ m (12.40 ft).

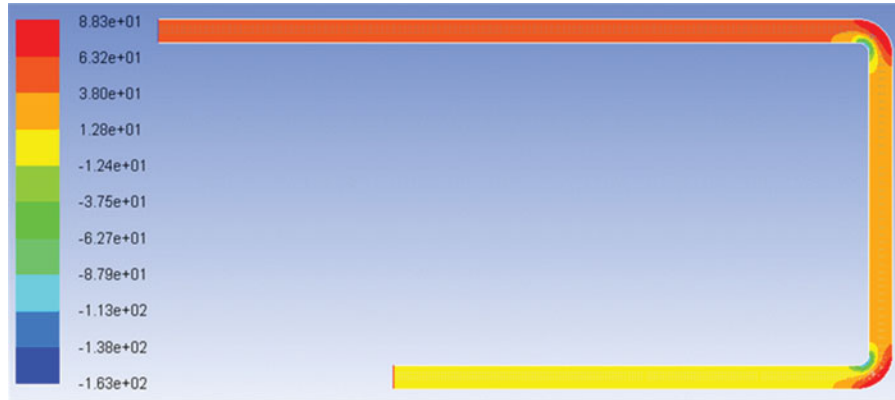


Fig. 12. Contours of static pressure (in Pa) for 304.8 mm (12.0 in.) diameter double elbow U-configuration $L_{int} = 3.48$ m (12.40 ft).

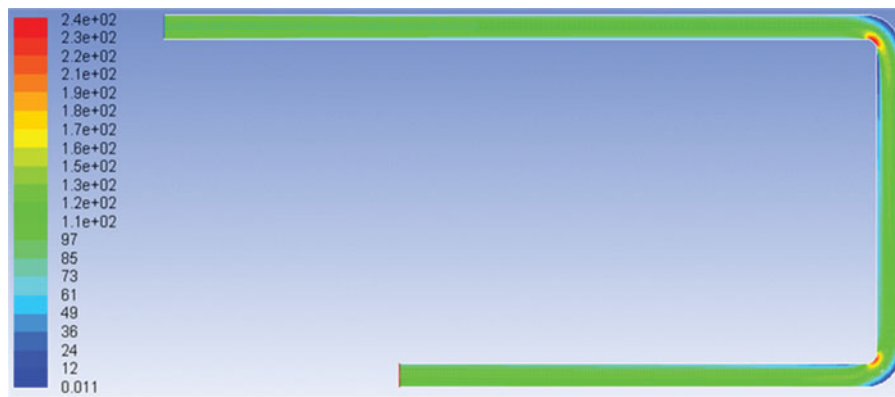


Fig. 13. Contours of dynamic pressure (in Pa) for 304.8 mm (12.0 in.) diameter. Double elbow U-configuration $L_{int} = 3.48$ m (12.40 ft).

for two 305 mm (12 in.) diameter close-coupled elbows five-gore 90° close-coupled galvanized steel elbows with a dimensionless turning radius $r/D = 1.5$ that were arranged in a Z-configuration. In this instance the distance between the center-points of each elbow corresponds to $L_{int} = 3.78$ m (12.40 ft). The maximum error for this case is approximately 8%, as shown in Table 7.

Table 6. Error for 308.4 mm (12.0 in.) diameter double elbow loss coefficient: U-Configuration $L_{int} = 3.78$ m (12.40 ft).

P_{v8}	Re_8	$\Delta p_{f,7-8}$ (Pa/m)	$\Delta p_{t,1-2}$ (Pa)	2C	Error (%)
146.9	304,346	8.6	38.0	0.259	-8.88
265.5	411,320	15.4	64.0	0.241	-9.42
428.0	516,918	24.1	96.0	0.224	-9.76
197.0	347,458	11.2	51.0	0.259	-8.21
376.0	481,710	21.1	90.0	0.239	-9.89
64.3	197,017	3.8	19.8	0.292	-0.73
115.0	264,535	6.6	31.7	0.276	0.04
180.6	332,431	10.3	47.7	0.264	-0.30
217.7	365,916	12.4	56.4	0.259	-0.72
36.2	149,418	2.1	11.4	0.315	3.06
99.9	250,579	6.0	28.5	0.285	-3.44

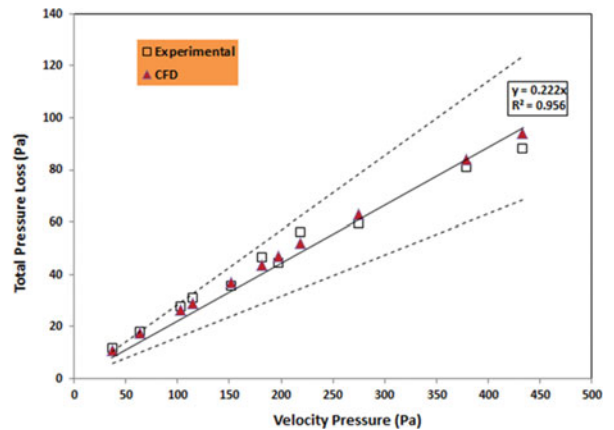


Fig. 14. Comparison of total pressure loss versus velocity pressure for 304.8 mm (12.0 in.) diameter double elbow Z-configuration $L_{int} = 3.78$ m (12.40 ft).

Discussion

In this test program, all measurements and data reduction were performed in conformity with Standard 120–2015. Tare pressure loss measurements are carefully designed to be performed under hydrodynamically fully developed conditions.

Table 7. Error for 304.8 mm (12.0 in.) diameter double elbow loss coefficient: Z-configuration $L_{\text{int}} = 3.78$ m (12.40 ft).

p_{v8}	Re_8	$\Delta p_{r,7-8}$ (Pa/m)	$\Delta p_{i,1-2}$ (Pa)	2C	Error (%)
151.7	330,599	9.0	37.0	0.244	-3.12
274.9	442,178	16.0	63.0	0.229	-5.91
433.4	553,526	25.0	94.0	0.217	-6.54
197.7	374,064	11.6	47.0	0.238	-5.89
378.8	515,830	21.9	84.0	0.222	-3.71
63.5	212,150	3.9	17.5	0.275	1.89
114.8	284,791	6.9	29.0	0.253	6.76
181.0	356,390	10.7	43.5	0.240	6.57
219.0	390,952	12.9	52.0	0.237	7.65
36.6	160,217	2.1	10.8	0.294	8.22
103.1	270,303	6.2	26.5	0.257	4.31

Likewise, the standard requires that flow in the duct upstream of a fitting duct must be fully developed. The use of fully developed pressure loss data to perform tare pressure corrections inevitably introduces some unavoidable errors to the determination of fitting loss coefficients. Regions where the flow is not fully developed would exhibit a different pressure gradient at that location than that predicted by the tare pressure correction mandated in Standard 120–2015. Consequently, this would contribute to uncertainty in the reported loss coefficient data, and consequently to the resulting correlations.

Conclusions

In order to quantify the effects that close-coupling has on elbow loss coefficients, tests were first performed on a single elbow where there was a sufficient length of duct upstream to ensure that the flow entering the test fitting was fully developed. For a single 305 mm (12 in.) diameter five-gore elbow with $r/D = 1.5$ the loss coefficient measured in this study was $C = 0.12$, whereas the corresponding loss coefficient from the ASHRAE Duct Fitting Database (2015) is $C = 0.18$. Hence, the single elbow loss coefficient obtained herein is lower than the value reported previously in the literature for that particular case. However, it was observed in the current test program that for 305 mm (12 in.) diameter close-coupled elbows arranged in either a Z-configuration or a U-configuration the combination loss coefficients $2C$ measured in the limit of $(L_{\text{int}}/D) \geq 12$ conformed closely to the value of $2C$ for a single elbow (within the expected uncertainty of the measurements). Conversely, referring to data presented in RP-1682 (2016b) for 203 mm (8 in.) diameter close-coupled elbows arranged both in Z- or U-configurations, the close-coupled loss coefficients $2C$ measured for separation distances $(L_{\text{int}}/D) \geq 12$ asymptotically approached values that were less than would be expected for large separation distances. These disparities exceeded the difference that would be anticipated from random measurement errors.

The principal results of the experimental portion of this study were Power Law expressions correlating zero-length loss coefficient data for close-coupled five-gore elbows having a diameter of 305 mm (12 in.), arranged in either a Z-configuration or a U-configuration as a function of (L_{int}/D) . These results were likewise contrasted with zero-length loss coefficient data taken from RP-1682 (2016b) for 203 mm (8 in.) diameter close-coupled elbows. These correlations are provided as Equation 15 through 18, respectively. In every instance the coefficients of determination exceeded 0.80, indicating suitable correlation.

Regarding the use of CFD methods to analyze airflow in complicated duct systems, as discussed further in Salehi et al. (2016), it was found that the Reynolds-averaged approach can generally be adopted for practical engineering calculations. It is not recommended to use the realizable $k-\varepsilon$ model for duct flow simulation because it produces nonphysical turbulent viscosities. This is due to the fact that the $k-\varepsilon$ model includes the effects of mean rotation in the definition of the turbulent viscosity. Likewise it is not recommended to use $k-\varepsilon$ turbulence models for duct flow simulations, because these models incorporate modifications for low-Reynolds-number effects, compressibility, and shear flow spreading. In many instances, the RSM may not always yield results that are clearly superior to the simpler models in all classes of flows. However, use of the RSM is a must when the flow features of interest are the result of anisotropy in the Reynolds stresses, such as the stress-induced secondary flows in ducts.

In the current study, it was determined that the use of the $k-\varepsilon$ model with wall function wall treatment yields predictions of pressure losses in duct systems that are within 15% of experimental data. The use of a structured grid with at least 31 grid points in the radial direction and an aspect ratio not exceeding 10 in the longitudinal direction is recommended. It is noted that a finer mesh is needed for high Reynolds numbers. Likewise, it was determined that double precision calculations should be employed in all calculations. For small values of L_{int} , the use of a finer numerical grid is suggested to resolve the secondary flows and to capture the effect of the turns. Furthermore, the wall roughness is a required input to turbulence models, and must be known beforehand in order to obtain accurate prediction of zero-length close-coupled elbow loss coefficients.

Nomenclature

- C = elbow pressure loss coefficient, dimensionless
- c = confidence level, dimensionless
- D = duct diameter, m (ft)
- f = friction factor, dimensionless
- L = length of ductwork between specified planes, m (ft)
- L_{int} = intermediate duct length, m (ft)
- N = number of data points, dimensionless

- n = number of independent variables, dimensionless
 p_v = velocity pressure, Pa (in. wg)
 p_t = total pressure, Pa (in. wg)
 p_s = static pressure, Pa (in. wg)
 \bar{p}_v = mean velocity pressure, Pa (in. wg)
 Δp_f = duct pressure loss, Pa (in. wg)
 Δp_s = static pressure loss, Pa (in. wg)
 Δp_t = total pressure loss, Pa (in. wg)
 Re = Reynolds number, dimensionless
 R^2 = coefficient of determination, dimensionless
 r = radius, m (ft)
 S_{xx}^2 = squared deviation of x-data, Pa² (in. wg²)
 S_{yx}^2 = square of the standard error of y-data, Pa² (in. wg²)
 $t_{\alpha/2, N-1}$ = t-statistic, dimensionless
 V = velocity, m/s (ft/s)
 \bar{V} = mean air velocity, m/s (ft/s)

Greek symbols

- ε = relative surface roughness, m (ft)
 ρ = density, $\frac{\text{kg}}{\text{m}^3}$ ($\frac{\text{lbm}}{\text{ft}^3}$)

Subscripts

- e = exit plane
 r = root-sum-square
 x = plane 1, 2, ..., n , as applicable
 z = upstream plane

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