QUALIFICATION OF A METHOD TO CALCULATE THE IRRECOVERABLE
PRESSURE LOSS IN HIGH REYNOLDS NUMBER PIPING SYSTEMS

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Qualification of a Method to Calculate the Irrecoverable Pressure Loss in High Reynolds Number Piping Systems

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ABSTRACT

High Reynolds number test data has recently been reported for both single and multiple piping elbow design configurations at earlier ASME Fluid Engineering Division Conferences (see Section 1.0). The data of these studies ranged up to a Reynolds number of 42×10^6 which is significantly greater than that used to establish design correlations before the data was available. Many of the accepted design correlations, based on the lower Reynolds number data, date back as much as fifty years. The new data shows that these earlier correlations are extremely conservative for high Reynolds number applications. Based on the recent high Reynolds number information a new recommended method has been developed for calculating irrecoverable pressure losses in piping systems for design considerations such as establishing pump sizing requirements. This paper describes the recommended design approach and additional testing that has been performed as part of the qualification of the method. This qualification testing determined the irrecoverable pressure loss of a piping configuration that would typify a limiting piping section in a complicated piping network, i.e., multiple, tightly coupled, out-of-plane elbows in series under high Reynolds number flow conditions. The overall pressure loss measurements were then compared to predictions, which used the new methodology to assure that conservative estimates for the pressure loss (of the type used for pump sizing) were obtained. The recommended design methodology, the qualification testing and the comparison between the predictions and the test data are presented. A major conclusion of this study is that the recommended method for calculating irrecoverable pressure loss in piping systems is conservative yet significantly lower than predicted by early design correlations that were based on the extrapolation of low Reynolds number test data.

1.0 INTRODUCTION

In an effort to improve existing piping loss correlations used in high Reynolds number piping systems, testing was performed (References (a) and (b)) to measure the irrecoverable pressure losses in single and multiple short radius of curvature elbows for single-phase high Reynolds number flow. The purpose of the single elbow testing documented in Reference (a) was to accurately define the irrecoverable pressure loss coefficient at high Reynolds number for a design limiting short radius elbow with a radius to diameter (r/D) ratio of 1.2. To complement the Reference (a) testing, the Reference (b) testing was performed to define the interaction effects of multiple short radius of curvature elbows in series. Prior to this testing, piping pressure loss calculations were based on open literature databases which were extrapolated to high plant design Reynolds numbers from limited low Reynolds number data ($< 0.50 \times 10^6$). The Bettis single elbow testing showed that for test elbows with a r/D of 1.2, irrecoverable pressure loss coefficients measured at least a factor of two less than those predicted by the methods developed by Pigott in References (c) and (d). Figure 1.1 compares the test data loss coefficient (K factor) versus Reynolds number to the design methods used prior to that testing. The Bettis multiple elbow testing showed that if sufficient spacing existed between two elbows in series, their loss coefficients could be predicted using the methods developed in the single elbow testing; however, as the spacing between the two elbows was decreased, interaction effects were found to occur. For application to piping design pressure loss predictions, Figure 1.2 plots the ratio of average K factor for interacting elbows divided by the single elbow K factor (without interaction) versus separation distance from this testing.

The methodology developed from the single and multiple elbow testing first assigns a loss coefficient to each elbow in the system based on the Figure 1.1 data. Factors are then applied for radius of curvature based on data presented in References (c) and (d), bend angle based on data presented in Reference (e), and piping separation distance based on the Figure 1.2 data. An additional 20% is added to this resultant pressure loss to account for uncertainty. This test helps qualify this methodology for design application.

The first phase of the test determined the irrecoverable pressure loss coefficient for a multiple elbow arrangement. The second phase of the test was performed to determine the effect of the inlet flow field on the irrecoverable loss coefficient. All testing was performed over a Reynolds number range of approximately 2.3×10^6 to 34.3×10^6 .

FIGURE 1.1 – K FACTOR VERSUS REYNOLDS NUMBER FROM SINGLE ELBOW TESTING

FIGURE 1.2 – SEPARATION DISTANCE FACTOR DERIVED FROM MULTIPLE ELBOW TESTING

2.0 TEST CONFIGURATION

The test was conducted in the Bechtel Bettis Fluids and Mechanical Test Laboratory. The loop was configured to minimize resistance (thus maximizing loop flow) by removing the main loop control and check valves, and flow rate was varied by varying pump frequency. Figure 2.1 shows the loop configuration for the test. The section of pipe tested included three long radius of curvature elbows at close proximity. The test section piping (includes inlet pipe, elbows and outlet pipe) was fabricated from 8-inch commercial carbon steel pipe, and was polished to an average surface roughness of 10 microinches.

The test section piping was tied into the 16" loop piping with a custom reducer designed to minimize flow separation effects in the inlet piping. At the entrance to the test section inlet pipe (approximately 23 pipe diameters upstream of the first elbow), a flow straightener was installed to ensure a uniform flow field for pressure drop measurements. The flow straightener used 35 holes with approximately 0.904 inch inside diameter each. This design configuration was found in Reference (a) to provide a fully developed turbulent velocity profile for high Reynolds number applications. The first elbow was a 90° long radius elbow, followed by a 60° long radius elbow, and finally another 90° long radius elbow. The flow then entered a 21-foot long outlet pipe before returning to the 16-inch loop piping.

All piping connections in the test section used custom Grayloc connecting hubs. Both diametral and axial variations were maintained within ± 0.005 inches at these connections to minimize flow disturbances both upstream and downstream of the test elbows.

All pressure taps in the test section piping were 0.028 inches in diameter. Earlier high Reynolds number testing demonstrated that small imperfections on the pressure tap hole edge can cause either increased or decreased pressure readings if high velocity flow is deflected into or away from the tap hole. The tap holes in this test piping were first drilled to 0.024 inches in diameter. The piping was then sent to Fintech in Houston, Texas for mechanical polishing. Once the piping was returned, the holes were hand reamed in 0.002 inch increments to the final diameter of 0.028 inches. This process was shown by the vendor in a model piping section to produce the sharpest tap hole edges, prior to fabrication of the actual test piping. Pressure taps and designations are shown in Figure 2.2.

This test utilized commercial piping and elbows. As a result, some variation in inside diameter occurred in the test elbows due to the forming process. This variation in elbow inside diameter introduced small entrance and exit losses into the overall test section loss coefficient calculations. Therefore, all test section piping was measured (outside diameter and wall thickness) prior to testing in an effort to use the most accurate calculations for both pipe friction and loss coefficient. Table 2.1 documents these measurements.

Flow was measured using the loop venturi. A 16 inch flow straightener of the same 35 hole design was installed upstream of the venturi, and the venturi was calibrated at Alden Research Laboratory, Inc. with the flow straightener installed.

Prior to testing, the test section piping was passivated at 550°F for 10 days. This process formed a prototypical layer of magnetite on the surface. The magnetite helps minimize other types of oxidation, which could cause surface pitting. Loop downtime (no flow) was minimized over the duration of the test, and post-test inspection of the piping showed a uniform layer of magnetite.

For the second phase of the test, the 8-inch flow straightener was removed from the test loop and replaced with a spacer. The removal of the flow straightener altered the flow field at the inlet of the first elbow. Overall differential pressure measurements were again taken to assess the effect of the flow field on the irrecoverable loss coefficient.

Reynolds number was varied by varying test temperature and loop flow rate. Test temperatures ranged from approximately 120°F to 590°F.

The test instrumentation was configured to provide the following accuracies for measured test parameters:

Measured Parameter	Accuracy
Flow rate (combined uncertainties including differential pressure reading, temperature reading, and venturi flow coefficients)	±1%
Differential pressures greater than 0.21 psid	±1.7%
Water Temperature (with thermocouple calibration data incorporated)	±2 °F
Loop Pressure	±20 psi

The carbon steel test section piping inside diameter was corrected for thermal expansion effects with the relationship:

$$D_{\text{elevated-temperature}} = D_{\text{measured}} (1 + \alpha(T_{\text{elevated}} - T_{\text{measured}}))$$

where;
 D_{measured} = measured inside diameter
 T_{elevated} = test temperature
 $T_{\text{measured}} = 70^{\circ}\text{F}$
 α = thermal expansion coefficient

The following values were used for the carbon steel thermal expansion coefficient (Reference (k)).

Temperature (°F)	$\alpha \times 10^{-6}$ (in/in/°F)
70	6.07
200	6.38
300	6.60
400	6.82
500	7.02
600	7.23

Similarly, test piping length was corrected for thermal expansion effects with the relationship:

$$L_{\text{elevated-temperature}} = L_{\text{measured}} (1 + \alpha(T_{\text{elevated}} - T_{\text{measured}}))$$

where;
 L_{measured} = measured length
 T_{elevated} = test temperature
 $T_{\text{measured}} = 70^{\circ}\text{F}$
 α = thermal expansion coefficient

FIGURE 2.1 - TEST LOOP ARRANGEMENT

FIGURE 2.2 – TEST SECTION PIPING PRESSURE TAP LOCATION AND DESIGNATIONS

TABLE 2.1 – AS BUILT DIMENSIONS OF TEST SECTION PIPING

Description of Dimension	As-Built Dimension (all dimensions taken at 70°F)
Inlet Spool Piece Inside Diameter (D_{ISP})	6.978 in.
Average Inside Diameter of Straight Pipe Sections ($D_{pipe-avg}$)	6.984 in.
Distance between pressure taps UE-UA and UJ-UF (L_{taps})	72.000 in.
Total Length of Straight Pipe between pressure taps UA and DF/DN (L_{pipe})	321.39 in.
Total Length of Straight Pipe between pressure taps UF and DH/DP (L_{pipe})	345.39 in.
Elbow 1 Inside Diameter ($D_{elbow-1}$)	6.704 in.
Elbow 2 Inside Diameter ($D_{elbow-2}$)	6.696 in.
Elbow 3 Inside Diameter ($D_{elbow-3}$)	6.704 in.
Average Elbow Inside Diameter ($D_{elbow-avg}$) (average ID of Elbow 1, 2, and 3 at bend)	6.701 in.
Inside Diameter of Pipe Upstream of Elbow 1 ($D_{pipe-up-1}$)	7.009 in.
Inside Diameter of Pipe Upstream of Elbow 2 ($D_{pipe-up-2}$)	7.004 in.
Inside Diameter of Pipe Upstream of Elbow 3 ($D_{pipe-up-3}$)	7.001 in.
Transition angle from upstream pipe diameter to elbow 1 inside diameter (θ_{ent-1})	5.76° (calculated)
Transition angle from elbow 1 inside diameter to downstream pipe inside diameter (θ_{exit-1})	6.04° (calculated)
Transition angle from upstream pipe diameter to elbow 2 inside diameter (θ_{ent-2})	7.46° (calculated)
Transition angle from elbow 2 inside diameter to downstream pipe inside diameter (θ_{exit-2})	3.30° (calculated)
Transition angle from upstream pipe diameter to elbow 3 inside diameter (θ_{ent-3})	5.02° (calculated)
Transition angle from elbow 3 inside diameter to downstream pipe inside diameter (θ_{exit-3})	5.65° (calculated)
Total Elbow Arc Length ($L_{elbow-arc}$) (sum of three elbow arc lengths)	50.265 in.
Inside Diameter of Pipe Downstream of Elbow 1 ($D_{pipe-down-1}$)	7.012 in.
Inside Diameter of Pipe Downstream of Elbow 2 ($D_{pipe-down-2}$)	6.944 in.
Inside Diameter of Pipe Downstream of Elbow 3 ($D_{pipe-down-3}$)	6.960 in.

3.0 DIFFERENTIAL PRESSURE MEASUREMENTS

Figure 2.2 identifies the pressure tap designations used in the test. Pipe friction factor was derived from inlet pipe differential pressures UA/UE, UA/UC, and UF/UE. The irrecoverable loss coefficient was derived from test section overall differential pressure UA/DF, UA/DN, UF/DH and UF/DP. Taps UA and UF were considered reference taps. Elbow form loss calculations which utilized the UF tap used friction derived from UF differential pressure measurements. Similarly, elbow form loss calculations which utilized the UA tap used friction derived from UA differential pressure measurements. For each data run, both friction and loss coefficient were determined from differential pressures taken during that run.

Differential pressure (DP) cells with the following ranges were used:

DP Measurement	DP Cell Models	Calibrated Ranges (High/Low)
UC/UA	3051CD1	+0.55 to -0.1 psid
	3051CD2	+4.0 to -0.1 psid
UE/UA	3051CD1	+0.55 to -0.1 psid
	3051CD2	+4.0 to -0.1 psid
UE/UF	3051CD1	+0.55 to -0.1 psid
	3051CD2	+4.0 to -0.1 psid
UF/DH	3051CD1	+0.2 to -0.7 psid
	3051CD2	+2.0 to -2.0 psid
	3051CD3	+9.5 to -2.0 psid
	3051CD4	+34.0 to -2.0 psid
UF/DP	3051CD1	+0.2 to -0.7 psid
	3051CD2	+2.0 to -2.0 psid
	3051CD3	+9.5 to -2.0 psid
	3051CD4	+34.0 to -2.0 psid
UA/DF	3051CD1	+0.2 to -0.7 psid
	3051CD2	+2.0 to -2.0 psid
	3051CD3	+9.5 to -2.0 psid
	3051CD4	+34.0 to -2.0 psid
UA/DN	3051CD1	+0.2 to -0.7 psid
	3051CD2	+2.0 to -2.0 psid
	3051CD3	+9.5 to -2.0 psid
	3051CD4	+34.0 to -2.0 psid

Due to large elevational differences between upstream and downstream taps, cells had to be ranged to accommodate the density differences at all test run temperatures. At the start of each data series, zero readings were obtained. Readings were recorded every 5 seconds for a 120 second period. The data acquisition system was programmed to read the differential pressure from the most accurate cell in the bank of cells. Readings over the 120 second period were averaged and standard deviations were calculated.

4.0 SURFACE ROUGHNESS

For fully turbulent flow, the friction factor is a function of the Reynolds number and the relative roughness (RR) of the pipe. The relative roughness of the test section piping can be determined from Reference (a) by the following relationship:

$$RR = \frac{\varepsilon}{D} = \frac{\pi R_a}{D}$$

where;

$$\begin{aligned} R_a &= \text{Pipe surface roughness average (inches)} \\ D &= \text{Pipe inside diameter (inches)} \end{aligned}$$

Pipe wall roughness is usually considered to be either uniform or nonuniform in the axial direction. For nonuniform surface roughness as found in commercial pipes, the Moody curve (Reference (f)) can be used to determine friction factor. In the Moody relationship, friction factor monotonically decreases with increasing Reynolds number. For uniform surface roughness, the friction factor of the fluid with the wall can increase with increasing Reynolds number as shown by Nikuradse (Reference (g)). This is due to the laminar sublayer becoming less than the height of the surface asperities, which enhance the formation of vortices and a general increase in pressure loss due to the increased form drag which develops. This transition as discussed in Reference (g) occurs mathematically when

$$\pi R_a \sqrt{f/8} * U / \nu > 5, \text{ where;}$$

$$\begin{aligned} R_a &= \text{Pipe roughness average} \\ f &= \text{Pipe friction factor} \\ U &= \text{Fluid velocity} \\ \nu &= \text{Kinematic viscosity} \end{aligned}$$

The test piping was fabricated from standard commercial pipe, and was polished by mechanical means to an average of 10 microinches. Surface roughness measurements were made by the polishing vendor and ranged from 7 to 14 microinches. Prior to data taking, the test piping was passivated for 10 days. It was not practical to measure the surface roughness after passivation, but prior to data taking. At the completion of the test, the pipe surface roughness was measured using a surface roughness measurement gage. The readings ranged from 13 to 23 microinches, which is still extremely smooth. This small change in surface roughness is attributed to the formation of magnetite coating on the surface.

Figure 5.2 shows the average test data friction factor versus Reynolds number. In the test data, an increase in friction with Reynolds number can be seen occurring at approximately 17×10^6 Reynolds number. This transition would suggest a pipe roughness average of approximately 22 microinches from the above relationship. Figure 5.2 compares test data friction factor to the Nikuradse correlation as defined by Reference (h), as well as the Moody friction relationship for a roughness average of 22 microinches. The test data indicates that the pipe roughness was closer to that measured at the end of the test, suggesting that the passivation process and continued test operation increased the pipe roughness from that which was measured at fabrication.

5.0 DETERMINATION OF FRICTION FACTOR FROM DIFFERENTIAL PRESSURE MEASUREMENTS

Because of the fully developed turbulent flow field in the inlet pipe, its pressure gradient can be used to determine friction factor. This method utilizes multiple differential pressure measurements along the length of a pipe to determine friction losses. Beginning with the general equation for pressure drop;

$$\Delta P = \frac{fL\rho V^2}{2Dg_c}, \text{ and manipulating it to } \frac{2\Delta P g_c}{\rho V^2} = f \left(\frac{L}{D} \right), \text{ friction is equivalent to the slope of the line determined from plotting } \frac{2\Delta P g_c}{\rho V^2} \text{ (pressure ratio) versus } \frac{L}{D}.$$

The test data friction factor shown in Figure 5.2 was derived from differential pressure measurements UA/UE, UA/UC and UF/UE. Pressure ratio versus L/D for taps UA/UE and UA/UC were plotted and curve fit for all data points. Since only two differential pressure measurements were used for each friction factor calculation, the curve fit through the two data points was compared to a curve fit through the data points and forced through zero. The resulting friction factors were in agreement to within $\pm 3\%$. Figure 5.1 provides examples of pressure ratio versus L/D for the UA/UE and UA/UC measurements.

Measurements taken between the UF/UE taps were also used to derive friction factor using the above methods. In this case, only one differential pressure measurement was used, and a curve fit through this point and zero was used to determine friction.

The friction data presented in Figure 5.2 is the average of all the friction data taken from the UA and UF taps. Figure 5.2 compares the test data to two classical friction factor correlations for a pipe roughness average of 22 microinches, which is consistent with the pipe roughness measured at the end of the test. The Nikuradse curve is used for pipe with uniform surface roughness (axially), while the Moody curve is used for commercial pipe where the pipe is not as uniformly rough. In general, the test data performance characteristics are similar to those predicted by both the Nikuradse and Moody correlations.

The averaged friction data presented in Figure 5.2 tends to be lower than that from earlier Loop 6 testing presented in Reference (a) and perfectly smooth Princeton piping presented in Reference (i). This difference can likely be accounted for in data uncertainty. However, for the purposes of this test, the use of lower friction factors is conservative in that they result in higher elbow form losses, since pipe and elbow friction account for approximately 83% of the total loss.

FIGURE 5.1a – PRESSURE RATIO VS. L/D FOR UA/UE AND UA/UC MEASUREMENTS

FIGURE 5.1b – PRESSURE RATIO VS. L/D FOR UA/UE AND UA/UC MEASUREMENTS

FIGURE 5.1c – PRESSURE RATIO VS. L/D FOR UA/UE AND UA/UC MEASUREMENTS

FIGURE 5.2 – FRICTION FACTOR VERSUS INLET PIPE REYNOLDS NUMBER

6.0 DETERMINATION OF ELBOW FORM LOSS FROM DIFFERENTIAL PRESSURE MEASUREMENTS

To determine the total irrecoverable loss coefficient in the test section, differential pressure was measured across the test section from upstream of the first elbow, to greater than 32 pipe diameters downstream of the last elbow. This overall differential pressure was used to calculate the total irrecoverable loss coefficient (K_{factor}) by the following equation:

$$K_{factor} = \frac{35788366.6 \Delta P g_c D_{elbow-avg}^4}{\rho Q^2}$$

where;

ΔP	=	DP measured between taps UA/DF, UA/DN, UF/DH and UF/DP.
ρ	=	Density
g_c	=	Conversion constant.
Q	=	Loop volumetric flow rate.
$D_{elbow-avg}$	=	The average elbow inside diameter defined in Table 2.1, adjusted for thermal expansion.

Pressure taps DH and DP were located at the same axial position (approximately 36 pipe diameters downstream of the last elbow), but were on diametrically opposite sides of the pipe. Similarly, pressure taps DF and DN were located at the same axial position (approximately 32 pipe diameters downstream of the last elbow), but were on diametrically opposite sides of the pipe.

In the test section, the total irrecoverable loss coefficient includes losses due to friction in the straight pipe and elbows, form losses in the elbows, as well as entrance and exit losses in the elbows due to a reduction in inside diameter. Friction losses in the straight pipe and elbows can be calculated from the following equations:

$$K_{elbow-friction} = f \left(\frac{L_{elbow-arc}}{D_{elbow-avg}} \right)$$

$$K_{pipe-friction} = f \left(\frac{L_{pipe}}{D_{pipe-avg}} \right) \left(\frac{D_{elbow-avg}^4}{D_{pipe-avg}^4} \right)$$

In the above equations, friction factor (f) is derived from differential pressure measurements in the test section inlet pipe and the methods described in Section 5.0. The differential pressures used to determine friction were measured at the same time as the differential pressure measurements used to determine the overall K_{factor} . The length and diameter values in the above equations are defined in Table 2.1.

Due to the forming process of commercial grade elbows, a reduction in the elbow inside diameter occurs beyond that in the same schedule straight pipe. The test section elbows were measured prior to the start of the test in an effort to characterize the inside geometry. These measured values are presented in Table 2.1. The losses associated with these changes in diameter can be estimated using the following relationships defined in Appendix A of Reference (j) for gradual contractions and enlargements:

$$K_{Elbow1-entrance} = K_{Elbow2-entrance} = K_{Elbow3-entrance} = .8 \sin \frac{\theta_{entrance-1,2,3}}{2} \left(1 - \left(\frac{D_{elbow-1,2,3}}{D_{pipe-up-1,2,3}} \right)^2 \right)$$

$$K_{Elbow1-exit} = K_{Elbow2-exit} = K_{Elbow3-exit} = 2.6 \sin \frac{\theta_{exit-1,2,3}}{2} \left(1 - \left(\frac{D_{elbow-1,2,3}}{D_{pipe-down-1,2,3}} \right)^2 \right)^2$$

A total (three elbow) form loss is then calculated from the following equation:

$$K_{form} = K_{factor} - K_{pipe-friction} - K_{elbow-friction} - K_{Elbow1-entrance} - K_{Elbow1-exit} - K_{Elbow2-entrance} - K_{Elbow2-exit} - K_{Elbow3-entrance} - K_{Elbow3-exit}$$

The test data showed that the combined pipe and elbow friction losses accounted for an average of 83% of the total system loss. Elbow form losses accounted for an average of 14% of the total loss, while the entrance and exit losses accounted for an average of 3% of the total system loss. With entrance and exit losses accounting for such a small percentage of the overall system loss, and their values based on approximations, a conservative approach of including these losses as part of the overall K_{form} was assumed. Figure 6.1 shows the average K_{form} as a function of elbow Reynolds number. The K_{form} presented in Figure 6.1 includes both the total three elbow form loss as well as the losses approximated from entrance and exit effects. The test results are compared to the form losses predicted by the recommended methods for the tested piping configuration. The recommended methods, which are based on the elbow testing documented in References (a) and (b), apply a $\pm 20\%$ uncertainty. An uncertainty of $\pm 25\%$, which is described in detail in Section 8.0, is applied to the test data in Figure 6.1. The upper bound of the test data is shown to fall below the lower bound of the prediction above approximately 4.8×10^6 Reynolds number, which is below typical piping design limiting conditions used to establish component pressure loss requirements.

FIGURE 6.1 – AVERAGE TOTAL K_{form} VERSUS ELBOW REYNOLDS NUMBER

7.0 DETERMINATION OF LOSS COEFFICIENT FROM DIFFERENTIAL PRESSURE AFTER REMOVAL OF FLOW STRAIGHTENER

In order to assess the effect of flow field on the overall K_{form} , the 8-inch flow straightener was removed from the loop and replaced with a spacer that had an equivalent inside diameter as the inlet pipe. Inlet pipe differential pressures previously used to establish friction factor (UA/UE and UA/UC) were examined to confirm the change in flow field (i.e., flow field was no longer uniform).

Since a uniform flow field no longer existed in the inlet pipe, the friction factor could not be determined from inlet pipe differential pressure measurements for these test runs. Friction factor data from the uniform inlet flow conditions of having a flow straightener was used since this would correspond to a designer using either the Moody or Nikuradse friction factor for their pressure loss predictions. Overall test section differential pressures UA/DF and UA/DN were used to determine K_{form} using the same methodology as described in Section 6.0. Figure 7.1 plots the new K_{form} versus elbow Reynolds number for the modified inlet flow field. The test data shows that the elbow form loss was not significantly changed as a result of the altered inlet flow field, particularly at higher Reynolds numbers where design limiting conditions (e.g., pumping power requirements) are established.

FIGURE 7.1 - K_{form} VERSUS ELBOW REYNOLDS NUMBER WITH FLOW STRAIGHTENER REMOVED

8.0 UNCERTAINTY ANALYSIS

The form loss across the three elbows was calculated from the following equation:

$$K_{form} = \frac{1152385405 \Delta P_1 D_{elbow_avg}^4}{\rho Q^2} - \frac{1152385405 \Delta P_2 D_{lsp}^5 L_{elbow_arc}}{\rho Q^2 L_{taps} D_{elbow_avg}} - \frac{1152385405 \Delta P_2 D_{lsp}^5 L_{pipe} D_{elbow_avg}^4}{\rho Q^2 L_{taps} D_{pipe_avg}^5}$$

where;

ΔP_1	=	Differential pressure measured across the test section
D_{elbow_avg}	=	Per Table 2.1
ρ	=	Fluid density
Q	=	Loop volumetric flow rate
ΔP_2	=	Differential pressure in the inlet pipe used for friction factor
D_{lsp}	=	Per Table 2.1
L_{elbow_arc}	=	Per Table 2.1
L_{taps}	=	Per Table 2.1
L_{pipe}	=	Per Table 2.1
D_{pipe_avg}	=	Per Table 2.1

The total uncertainty of the form loss measurement was calculated by:

$$U_K = \sqrt{\sigma_K^2 + \beta_K^2}$$

where the σ_K term (standard deviation) is primarily based on the uncertainty of the instruments used for the measurements, and the second term β_K (bias) is based on the uncertainty in the physical test assembly conditions. The standard deviation of the form loss coefficient is determined from:

$$\sigma_K = \sqrt{\sum \left(\frac{\partial K}{\partial X} \sigma_X \right)^2}$$

where, $X = \Delta P_1, \Delta P_2, \rho, Q, D_{lsp}, D_{elbow_avg}, D_{pipe_avg}, L_{elbow_arc}, L_{taps}, L_{pipe}$

Bias uncertainty is the more difficult component to estimate because its component variation sources are not measurable during testing. The bias uncertainty is intended to bound the variation sources involved in the physical test assembly, not the measurement uncertainties. These include physical characteristics such as burrs/surface imperfections and local surface roughness effects. Since only one test assembly was built, the bias uncertainty could be considered as the variation that would be found between repeated builds of the same test assembly. The bias uncertainty of the form loss coefficient is determined from:

$$\beta_K = \sqrt{\sum \left(\frac{\partial K}{\partial X} \beta_X \right)^2}$$

where, $X = \Delta P_1, \Delta P_2, \rho, Q, D_{lsp}, D_{elbow_avg}, D_{pipe_avg}, L_{elbow_arc}, L_{taps}, L_{pipe}$

Using this approach resulted in a maximum uncertainty (U_k) range of the form loss coefficient measurement to be $\pm 25\%$ based on a 2σ level of confidence.

9.0 SUMMARY AND CONCLUSIONS

The test supports the overall qualification of the methodology described in Section 1.0, and recommended for calculating irrecoverable pressure loss in high Reynolds number piping systems. The methodology developed from the single and multiple elbow testing remains conservative when applied to a design limiting piping section. At high Reynolds numbers the predicted pressure losses are about a factor of two less than would be calculated with correlations that had been developed from low Reynolds number data. The test also demonstrated that modification of the flow field entering the first elbow did not have a significant effect on the overall irrecoverable loss coefficient, based on comparisons of the data with and without a flow straightener being used upstream of the test section.

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- (j) Crane Technical Paper No. 410 (1988), Flow of Fluids Through Valves, Fittings, and Pipe, published by Crane Co.
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