FORM TI-12
8/94

WAPD-T-3117

CONF-970670--2

IRRECOVERABLE PRESSURE LOSS COEFFICIENTS FOR TWO ELBOWS IN SERIES WITH VARIOUS ORIENTATION ANGLES AND SEPARATION DISTANCES

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APR 28 1997
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DE-AC11-93PN38195

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ABSTRACT

Test data is described for two ninety degree elbows that are in series for a piping network. Both elbows had a radius of curvature of 1.2. Three relative angles and seven different separation distances were investigated. The overall irrecoverable pressure loss for the two elbows is characterized relative to the irrecoverable pressure loss for a single elbow. In addition to providing design guidance relative to the net irrecoverable pressure loss for multiple elbows, the data provides a data base for helping qualify computational fluid dynamics (CFD) computer codes used to predict the irrecoverable pressure loss in piping systems.

INTRODUCTION

In calculating the total pressure drop in coolant systems, the irrecoverable pressure drop in each fitting and component needs to be determined. It is this total pressure loss that establishes pumping power requirements for the system. Minimizing the errors associated with estimation of plant irrecoverable pressure drops, as well as reducing the pressure losses themselves, can lead to a reduction in required pumping power or an increased allocation of available pump pressure head to other system components, both of which result in reduced plant costs.

Prior to the testing to be described in Reference (a), the world's data base for piping elbows was limited and these were at relatively low Reynolds numbers ($<0.50 \times 10^6$). For example, less than a dozen data points were identified to exist for 45° elbows with a bend radius of curvature (r/D) less than 1.8, where irrecoverable loss effects start becoming significant. Data for 90° elbows was also found to be scarce with large inconsistencies between investigators. Because of the lack of reliable data for predicting piping irrecoverable pressure losses, testing was performed over a Reynolds number range of 10^5 to slightly more than 2.5×10^6. This is approximately a factor of five increase in the Reynolds number relative to the prior data base. Large variations from the measured data were found when comparisons of the new data were made to predictions proposed earlier by various handbooks and references. These comparisons were described earlier in Reference (a). Because of the large discrepancies for even a single elbow, studies were performed to extend the data base further to multiple elbow piping configurations with various relative angles (γ) of the elbows to each other and with various separation distances (L_S) between them. These parameters which were investigated for radius-to-diameter (r/D) elbows of 1.2 are defined by Figure 1. The earlier single elbow tests were performed with plastic elbows which were machined in two halves and then glued together (Reference (a)) whereas the multiple elbow tests used investment cast stainless steel elbows. Both were manufactured to tight tolerance specifications to minimize manufacturing uncertainties.

TESTING

Initially each of the two elbows was tested for comparison to earlier test phase results for a single elbow with the same bend radius. After this, the double elbows were tested using three different relative angles between the two test elbows. These are defined as $\gamma = 0, 90°$ and 180°. Seven different separation distances, L_s, between the elbows were studied. These were achieved by using separation pipes between the elbows as follows:

Separation Configuration	L_s/D
1	4
2	8
3	12
23 (= 2+3)	16
4	20
24 (= 2+4)	24
5	30

where the distance is given in pipe inside diameters (D = 1.689 inches). Two diameters of straight piping length were built into the elbow casting so that the minimum spacing (when the elbows touched) was the four diameters of separation given as the first configuration.

Figures 2, 3, and 4 show a typical loop arrangements for γ = 180°, 0°, and 90°, respectively. All seven separation distances were tested for each of the three relative angles.

Figure 5 shows the upstream and downstream tangent piping sections for the tests. Pressure measurements were recorded at tap positions noted as UA, UB, UC, UD and UE on the upstream tangent pipe and as DA, DB, DC, DD and DE on the downstream tangent pipe. The UA pressure tap was used as a reference tap and its value was subtracted from all other differential pressure measurements thru differential pressure cell measurements for each relative position. All taps were 0.046 inch inside diameter (ID) which were deburred by visual examination.

The upstream tangent piping, the downstream tangent piping, the separation pipes and the elbows had an average roughness of approximately 125 microinches. This results in a relative roughness (ϵ/D) of 2.32×10^{-4}. Figure 6 shows (as dashed line) the friction factor, f, based on this roughness (as a function of Reynolds number) used to predict the fluid friction pressure loss from the UA pressure tap upstream of the first elbow to pressure tap DE located near the exit of the downstream tangent pipe. The fully turbulent Moody friction factor (constant value of 0.01425) was used for Reynolds numbers greater than 3×10^5 and the smooth wall Moody friction factor was used for lower Reynolds numbers. This is similar to the variation in friction factor with Reynolds number depicted by the Nikuradse data (Reference (c)) for a surface roughness of the test section magnitude. The irrecoverable loss coefficient (K) for the particular test condition was then calculated from the relationship

$$\Delta P/(\rho V^2/2g_c) - f(L/D) = K$$

where

ΔP = Pressure loss measurement between the UA position upstream of the elbow and the furthest position downstream from the elbow, DE position, to allow maximum flow recovery. These positions were about 7 pipe diameters upstream and 37 pipe diameters downstream of the elbow for the respective ta

ρ = Fluid density

V = Fluid velocity

L = Distance between pressure measurements (excluding elbow turning length)

D = Inside pipe diameter

TEST RESULTS

Each of the two metal elbows used for the multiple elbow testing was separately tested to characterize its irrecoverable loss coefficient as a function of Reynolds number. The results for each elbow are shown on Figure 7 along with the plastic elbow data for the same r/D = 1.2 curvature elbow from the earlier tests (Reference (a)). The correlation developed in Reference (a), $K=1.49\ Re^{-0.145}$, is shown as a solid line and can be seen to provide good correlation for the metal elbows as well as for the plastic elbow for which it was originally developed. All the data for all three elbows falls within a ± 10% bound of the correlation as shown by Figure 7.

The average loss coefficient for the two bends (K_{avg}) was calculated for each test condition. This average loss coefficient for a particular multiple elbow test was then divided by the single elbow loss coefficient (K) from Figure 7 to obtain a ratio (R) or defined as

$$R = \frac{K_{avg}}{K}$$

which gives a measure of the pressure loss of each elbow for a particular series configuration versus what it is for a single elbow. Thus an R value of less than 1.0 indicates that the pressure loss for the two elbows is less than twice the value for single elbow at the same Reynolds number. Table I provides a summary of the R values for the U-bend configuration. The R values can be seen to be only weakly affected by Reynolds number for each separation distance and thus an average of the R's (for the five Reynolds number tested at each separation distance) is also given by Table I as R_{avg}. These R_{avg} values have been plotted on Figure 8 as a function of separation distance to characterize the elbow combination irrecoverable loss coefficient. Table II provides similar test data for the $\gamma=0°$ (Z-bend configuration) elbow combination. Table III provides the data for $\gamma = 90°$ (out of plane configuration) elbow combination. The R_{avg} values for the other two elbow combinations are also plotted on Figure 8.

SUMMARY OF RESULTS AND CONCLUSIONS

Figure 8 summarizes the relative irrecoverable loss coefficient performance for the two test elbows in series. Three different relative angles ($\gamma=0°$, 90° and 180°) and seven separation distances (from 4 to 30 pipe diameters) were investigated. For separation distances less than 20 diameters, the elbow pressure loss was found to be less than twice the pressure drop of a single elbow (which would be the normal design assumption), while at separation distances of 30 diameters, the pressure loss was about 15% greater. For zero separation distances, the data indicates that the irrecoverable pressure loss would be about one-third of that predicted by a standard design correlation in the Crane Handbook. All three relative angles can be seen to have a very similar variation in irrecoverable pressure loss coefficient with separation distance. These variations appear to be due to:

- For shorter separation distances, the swirl (in the form of counter-rotating vortices) developed by the first elbow feeds more directly into the second elbow without the same irrecoverable loss as developed by the first elbow.
- For longer separation distances, the flow experiences more friction pressure loss (from the combined axial and rotational flow velocities) between elbows and after the second elbow. The swirl intensity after the second elbow is more than after the first elbow because of the persisting residual swirl from the first elbow entering the second elbow. Upstream flow straighteners eliminate swirl from entering the first elbow.

Some of the potential applications for this data include:

- For piping designs often encountered, the interaction effects of upstream elbows makes the assumption of adding single elbow pressure losses conservative for separation distances less than 20 piping diameters. In fact, the Crane Handbook (Reference (c)) would indicate a loss coefficient of 0.713 for a 180° U-bend with ($L_s = 0$) at $Re = 1 \times 10^6$ whereas the this study indicates that the value should be about 0.24 which is about a factor of three reduction.

- The data provides a qualification data base for computational fluid dynamics (CFD) computer codes relative to predicting the irrecoverable pressure loss in piping systems.

REFERENCES

(a) R. D. Coffield, P. S. Brooks and R. B. Hammond, "Piping Elbow Irrecoverable Pressure Loss Coefficients for Moderately High Reynolds Numbers", FED-Vol. 211, pp. 19-24, 1995 ASME/JSME Fluids Engineering and Laser Anemometry Conference and Exhibition, Hilton Head, South Carolina, August 13-18, 1995.

(b) H. Schlichting, Boundary-Layer Theory, McGraw-Hill, 6th Edition, 1968.

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

TABLE I

RATIO OF AVERAGE IRRECOVERABLE LOSS COEFFICIENT (K_{avg}) FOR MULTIPLE ELBOWS TO THE IRRECOVERABLE LOSS COEFFICIENT FOR SINGLE ELBOW (K) [METAL ELBOWS WITH $r/D=1.2$ AND $\gamma=180°$ (U-BEND)]

	R = AVERAGE "K"/SINGLE ELBOW "K"						
REYNOLDS NUMBER (Re)	SEPARATION DISTANCE, (L_s/D)						
	4	8	12	16	20	24	30
221,517	0.734	0.791	0.890	0.938	1.049	1.088	1.135
328,647	0.729	0.779	0.842	0.924	1.013	1.059	1.122
551,160	0.685	0.755	0.814	0.870	0.998	1.027	1.105
871,908	0.677	0.749	0.840	0.897	1.038	1.073	1.161
1,082,552	0.668	0.775	0.832	0.887	1.037	1.088	1.153
	R_{avg} = 0.699	R_{avg} = 0.770	R_{avg} = 0.844	R_{avg} = 0.903	R_{avg} = 1.027	R_{avg} = 1.067	R_{avg} = 1.135

TABLE II

RATIO OF AVERAGE IRRECOVERABLE LOSS COEFFICIENT (K_{avg}) FOR MULTIPLE ELBOWS *TO THE IRRECOVERABLE LOSS COEFFICIENT FOR SINGLE ELBOW (K)* [METAL ELBOWS WITH r/D=1.2 AND $\gamma=0°$ (Z-BEND)]

	R = AVERAGE "K"/SINGLE ELBOW "K"						
REYNOLDS NUMBER (Re)	**SEPARATION DISTANCE, (L_s/D)**						
	4	**8**	**12**	**16**	**20**	**24**	**30**
221,517	0.748	0.837	0.932	0.980	1.078	1.117	1.156
328,647	0.733	0.794	0.884	0.975	1.032	1.053	1.134
551,160	0.714	0.770	0.847	0.918	1.024	1.030	1.120
871,908	0.722	0.811	0.878	0.939	1.068	1.078	1.162
1,082,552	0.717	0.790	0.877	0.921	1.063	1.093	1.157
	R_{avg} = 0.727	R_{avg} = 0.800	R_{avg} = 0.884	R_{avg} = 0.947	R_{avg} = 1.053	R_{avg} = 1.074	R_{avg} = 1.146

TABLE III

RATIO OF AVERAGE IRRECOVERABLE LOSS COEFFICIENT (K_{avg}) FOR MULTIPLE ELBOWS TO THE IRRECOVERABLE LOSS COEFFICIENT FOR SINGLE ELBOW (K) [METAL ELBOWS WITH $r/D=1.2$ AND $\gamma=90°$ (OUT OF PLANE)]

REYNOLDS NUMBER (Re)	R = AVERAGE "K"/SINGLE ELBOW "K"						
	SEPARATION DISTANCE, (L_s/D)						
	4	8	12	16	20	24	30
221,517	0.756	0.806	0.934	0.909	1.057	1.056	1.154
328,647	0.721	0.801	0.902	0.936	1.006	1.043	1.124
551,160	0.705	0.765	0.859	0.885	1.005	1.031	1.101
871,908	0.706	0.795	0.867	0.894	1.980	1.067	1.165
1,082,552	0.718	0.796	0.907	0.898	1.036	1.069	1.146
	R_{avg} = 0.721	R_{avg} = 0.793	R_{avg} = 0.894	R_{avg} = 0.909	R_{avg} = 1.017	R_{avg} = 1.056	R_{avg} = 1.138

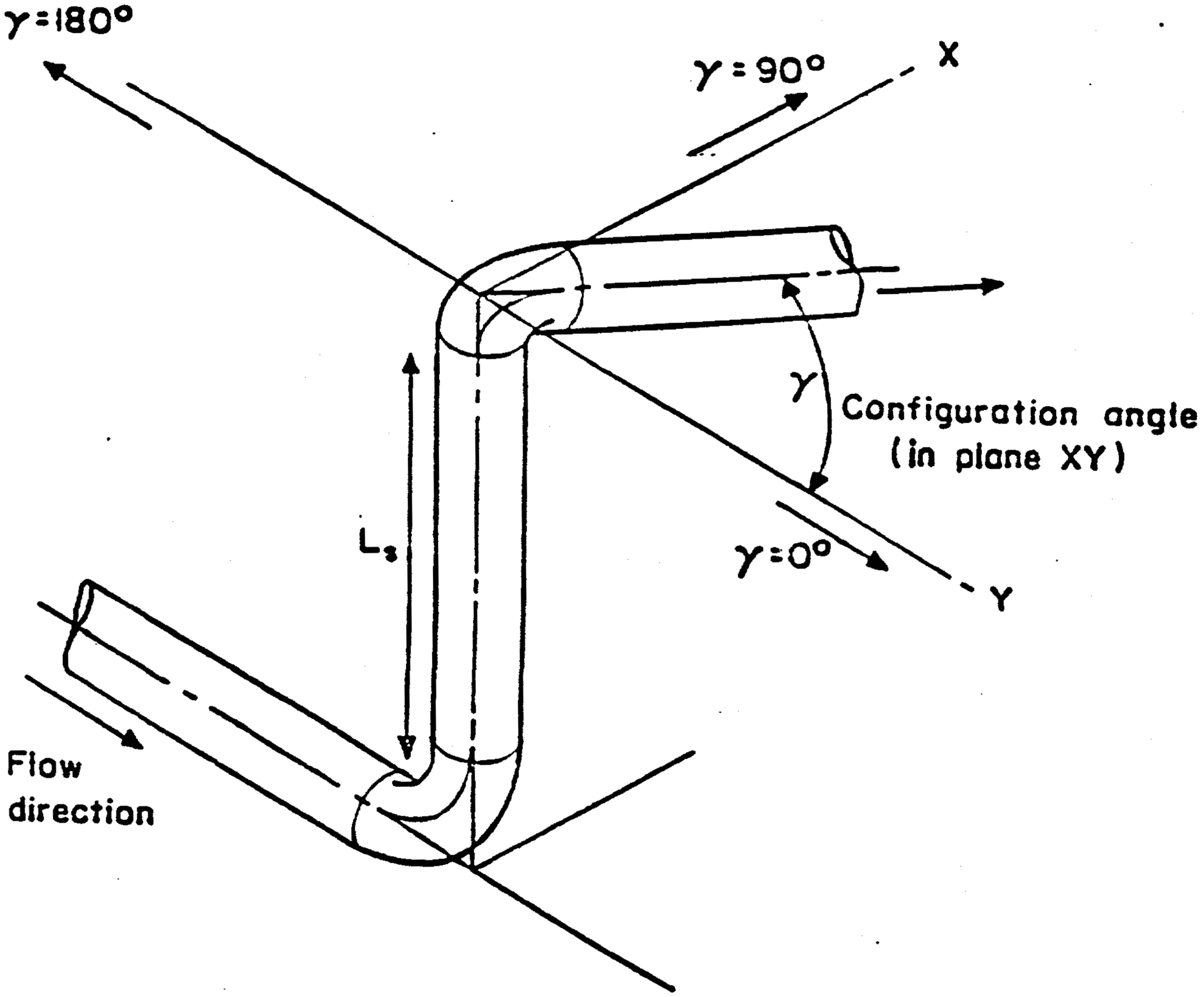


FIGURE 1: DEFINITION OF ELBOW ORIENTATION ANGLES

FIGURE 2: TYPICAL ARRANGEMENT FOR DOUBLE ELBOW TEST WITH $\gamma=180°$

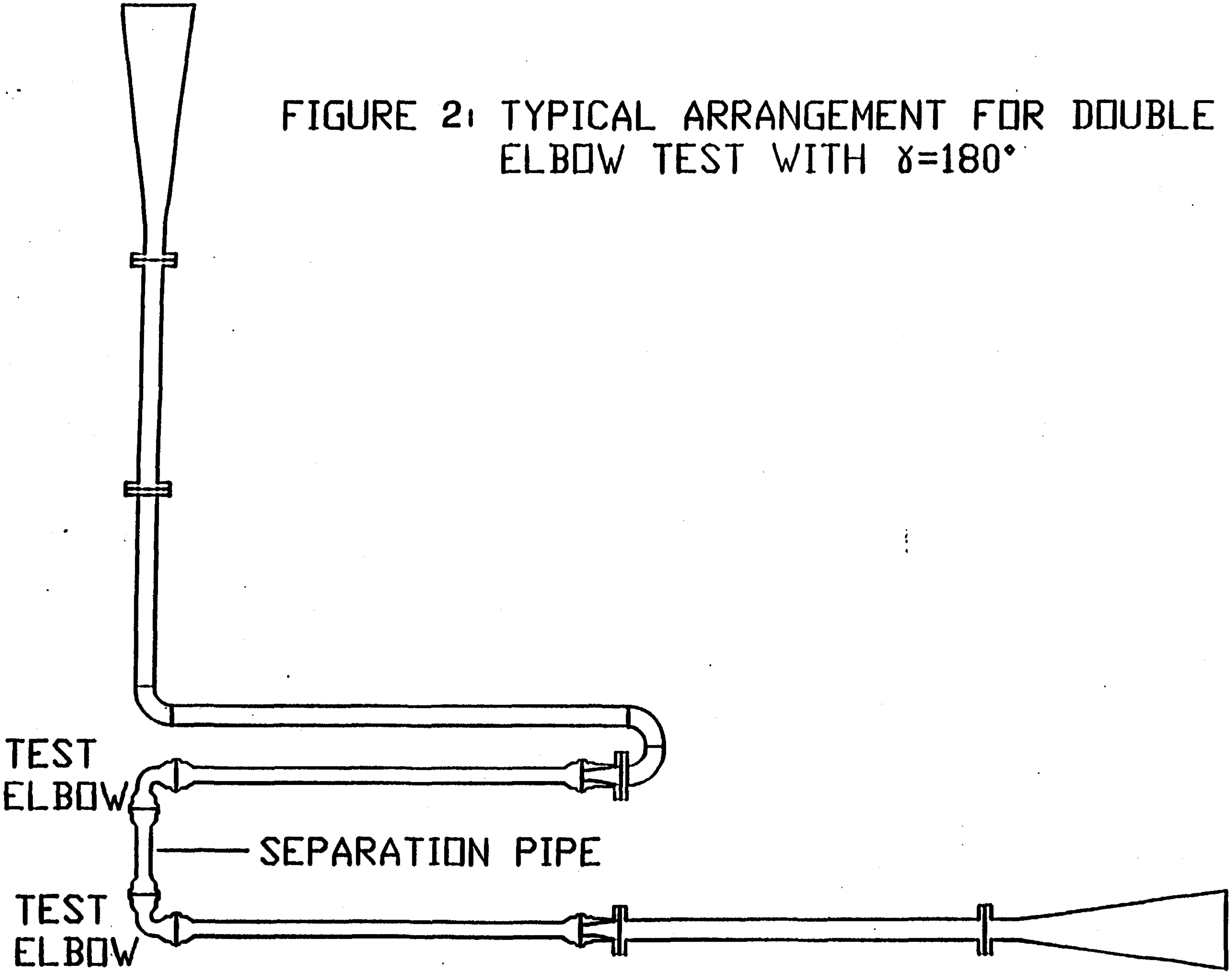


FIGURE 3: TYPICAL ARRANGEMENT FOR DOUBLE ELBOW TEST WITH $\delta=0°$

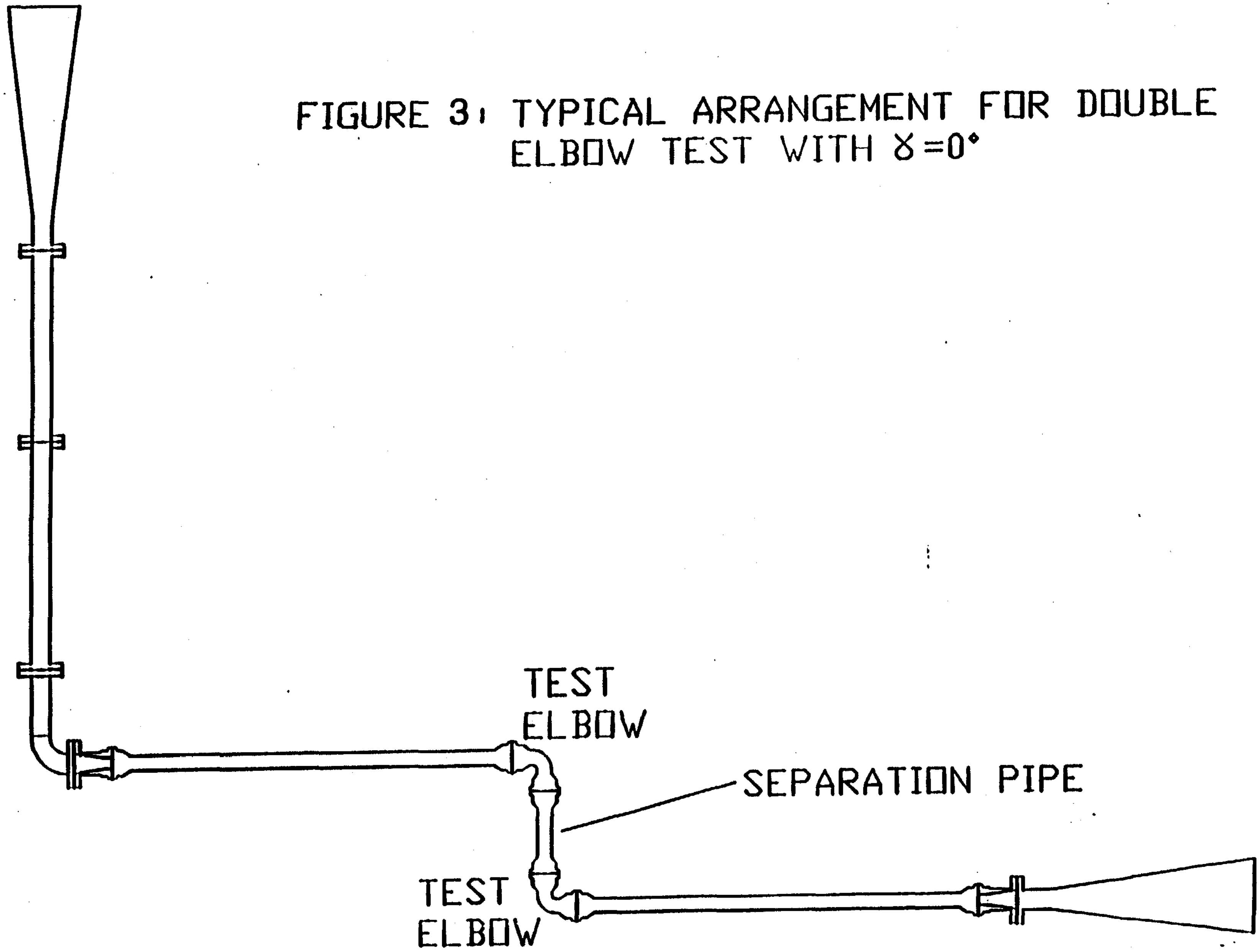
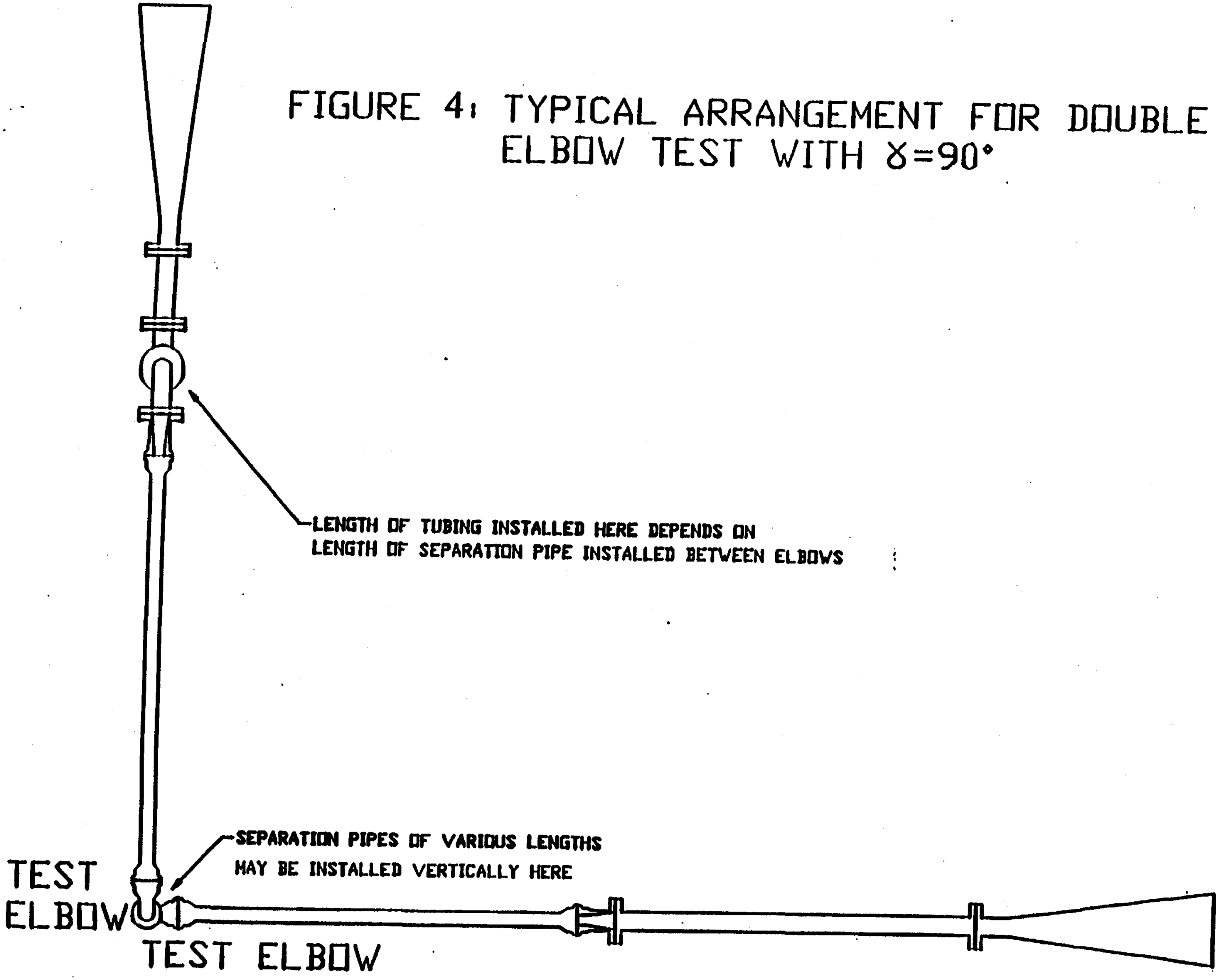
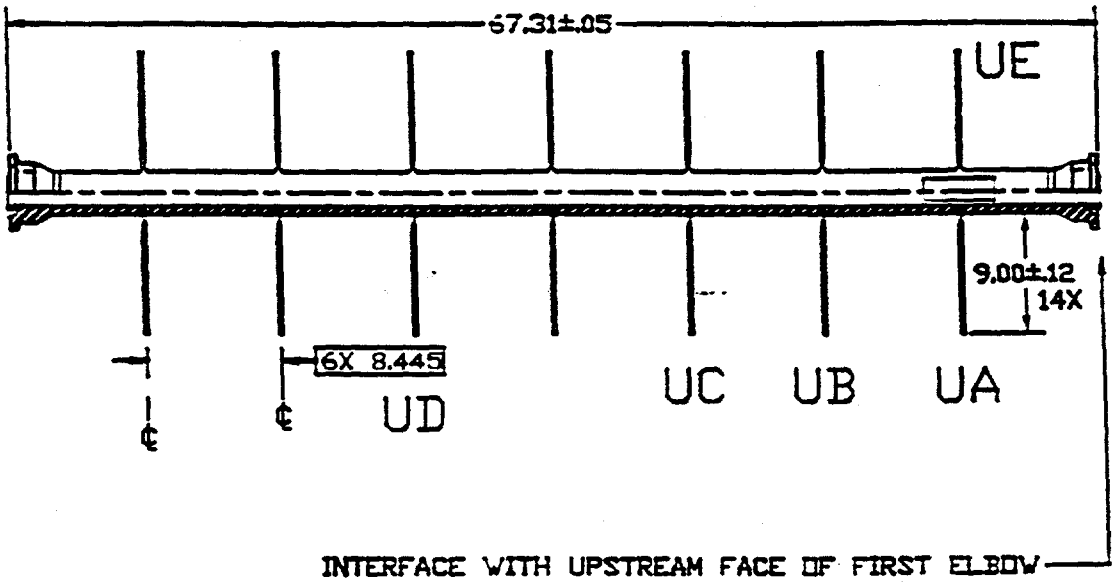


FIGURE 4: TYPICAL ARRANGEMENT FOR DOUBLE ELBOW TEST WITH $\gamma=90^\circ$



UPSTREAM TANGENT PIPE



DOWNSTREAM TANGENT PIPE

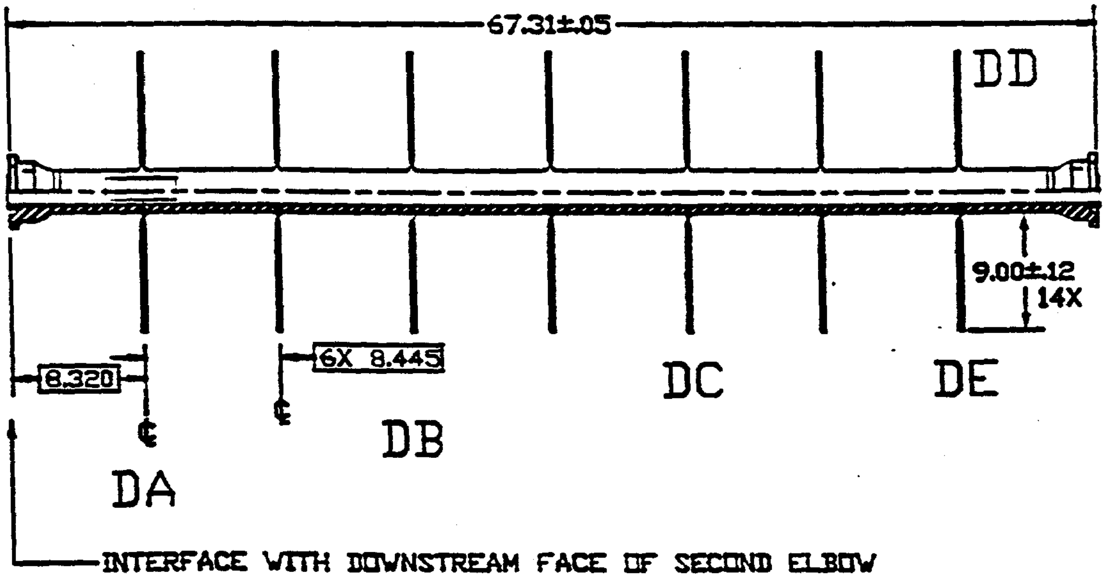


FIGURE 5: DEFINITION OF PRESSURE TAPS IN UPSTREAM AND DOWNSTREAM TANGENT PIPING

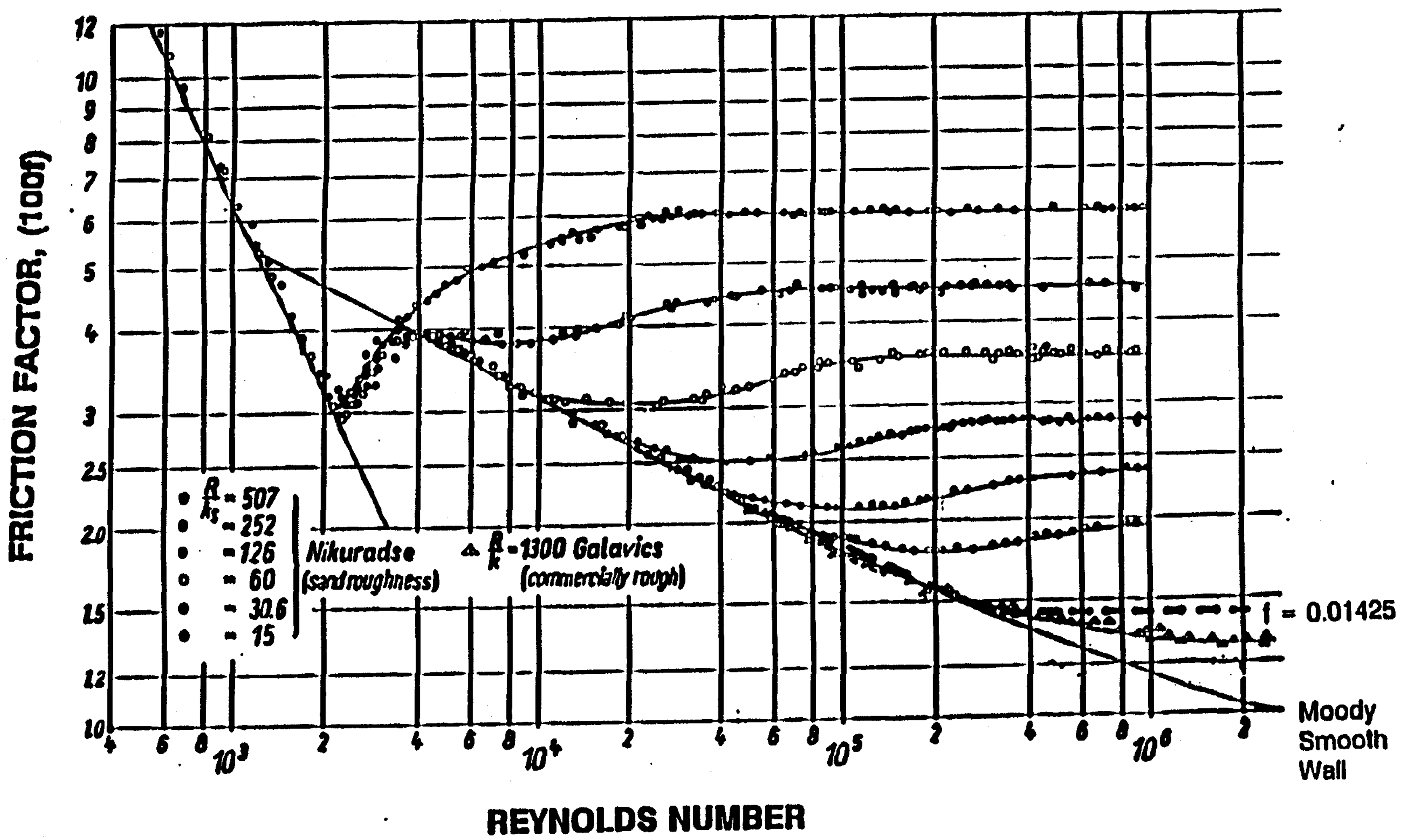


FIGURE 6: FRICTION FACTOR versus REYNOLDS NUMBER

Figure 7

Comparison of Single Elbow Test Data

r/D = 1.2, 90° Elbow

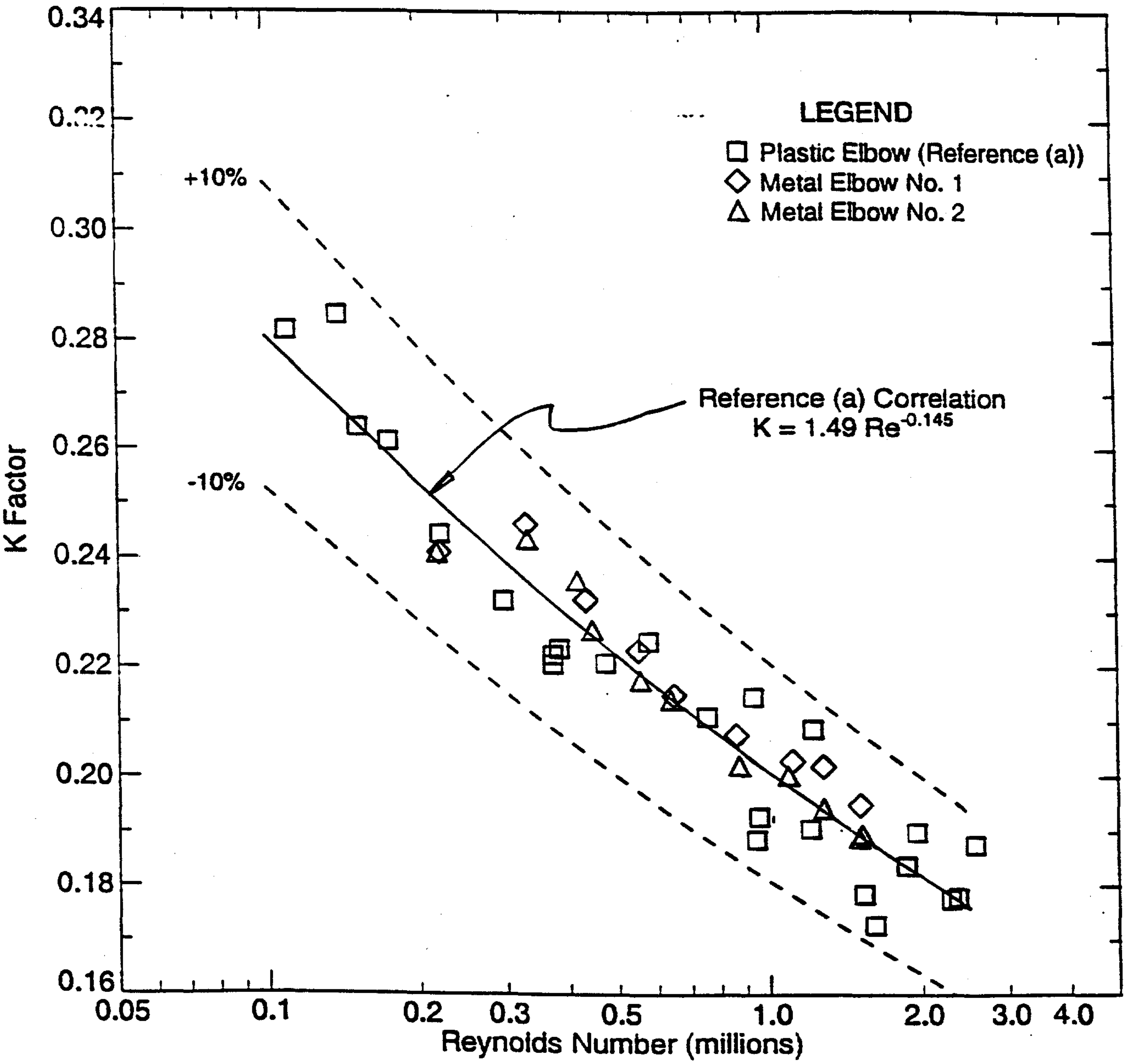


Figure 8

Correction Factors for Combined Bends
With Various Separation Distances and Relative Angles