Reference Manual
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Rosemount 485 Annubar® Primary Flow Element Flow Test Data Book

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Table of Contents

SECTION 1
Annubar Technology

SECTION 2
How the Annubar Works

SECTION 3
Flow Coefficient Reynolds Number Independence

SECTION 4
Annubar Flow Theory

SECTION 5
Test Facilities and Procedures

SECTION 6
References

Rosemount 485 Annubar Primary Flow Element Flow Test Data Book

NOTICE

Read this manual before working with the product. For personal and system safety, and for optimum product performance, make sure to thoroughly understand the contents before installing, using, or maintaining this product.

Customer Central
1-800-999-9307 (7:00 a.m. to 7:00 P.M. CST)

National Response Center
1-800-654-7768 (24 hours a day)
Equipment service needs

International
1-(952) 906-8888

⚠CAUTION

The products described in this document are NOT designed for nuclear-qualified applications.

Using non-nuclear qualified products in applications that require nuclear-qualified hardware or products may cause inaccurate readings.

For information on Rosemount nuclear-qualified products, contact an Emerson Process Management Sales Representative.

May be protected by one or more of the following U.S. Patent Nos. 4633713, 4717159, 5710370, 5773726, 5969266, 6321166, and 6470755. Other foreign patents issued and pending.

CE Fisher-Rosemount satisfies all obligations coming from legislation to harmonize product requirements in the European Union

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Section 1 Annubar Technology

The Rosemount 485 Annubar primary flow element maintains the traditional strengths of Averaging Pitot Tubes (APTs) with improved performance. The strengths of the Rosemount 485 Annubar include:

- Low permanent pressure loss
- A flow coefficient independence of Reynolds number
- Simple installation, including a gear drive insertion and retraction device
- The highest signal to noise ratio of any APT
- ±0.75% accuracy
- Integral temperature measurement
- Direct transmitter mounting capability

ROSEMOUNT 485 ANNUBAR PRIMARY FLOW ELEMENT

The Rosemount 485 Annubar primary flow element is the fifth generation Annubar. This design is comprised of three separate tubes that are drawn to produce a unique geometrical shape that produces a high and low pressure signal and contains an integral thermowell. The geometry change to the sensor required testing to establish a characterization curve and to determine a new flow coefficient.

Testing

Tests performed on the 485 Annubar primary flow element are divided into five major categories:

- Research and development testing
- Mechanical and structural testing
- In-house performance testing
- Independent laboratory testing
- On-site performance testing

All categories are on-going and continue to be a part of the current Rosemount test program for the 485 Annubar primary flow element.

Research and Development Testing

Extensive research was conducted to identify a sensor shape that would create a large differential pressure (DP) signal with minimal signal noise. Once the ideal shape T-shape was identified, tests were conducted to validate the improvements of the new primary flow element.

Parameters such as the impact of using a frontal slot design instead of discrete sensing ports to measure the impact pressure, aspect ratios, and surface texture were tested and optimized.

Mechanical and Structural Testing

Rosemount performed mechanical and structural testing for:

- Material hardness
- Moments of inertia
- Fatigue life
- Fluid loading due to lift and drag forces
- Static bend tests
- Allowable stress limits
- Failure analysis
- Vibration

Material and structural testing at:

- Hauser Laboratories
- MicroMotion Laboratory
- Eden Prairie Flow Laboratory

In-House Performance Testing

Hundreds of flow tests were performed in the Rosemount flow laboratory in 2" to 12" pipeline, using independently certified magnetic meters as primary reference meters. Baseline K-values, signal noise, cavitation, high and low Reynolds number limitations, methods of installations, static modeling, and straight-run requirements are just a few of the in-house performance tests that were performed on the Rosemount 485 Annubar primary.

Independent Laboratory Testing

Rosemount 485 Annubar primary flow element models were tested at three independent laboratories:

- Alden Research Laboratory (ARL)
- Colorado Engineering Experiment Station, Inc. (CEESI)
- Southwest Research Institute (SwRI)

Certified flow-data sheets were supplied from each of these facilities in pipelines ranging from 2" to 24" over a wide range of Reynolds numbers. A representative sample of independent tests conducted at Rosemount and independent laboratories are Section 5: Test Facilities and Procedures.

On-Site Performance Tests

Rosemount has a field service department that performs on-site performance tests and in-line calibrations for customers with unique installations or applications.

Rosemount 485 Flow Element Test Advantages

Rosemount test procedures incorporate the following criteria and advantages:

- Flow test data were collected over a flow turndown range of 10:1 in most cases
- All coefficients are ±0.75% of the published K-value of a particular primary flow element.

Section 2 How the Annubar Works

OVERVIEW

The Rosemount 485 is a device used to measure the flow of a liquid, gas or steam fluid that flows through a pipe. It enables flow measurement by creating a differential pressure (DP) that is proportional to the square of the velocity of the fluid in the pipe, in accordance with Bernoulli's theorem. This DP is measured and converted into a flow rate using a secondary device, such as a DP pressure transmitter.

The flow is related to DP through the following relationship.

Equation 2-1 $$Q \alpha K \sqrt{DP}$$

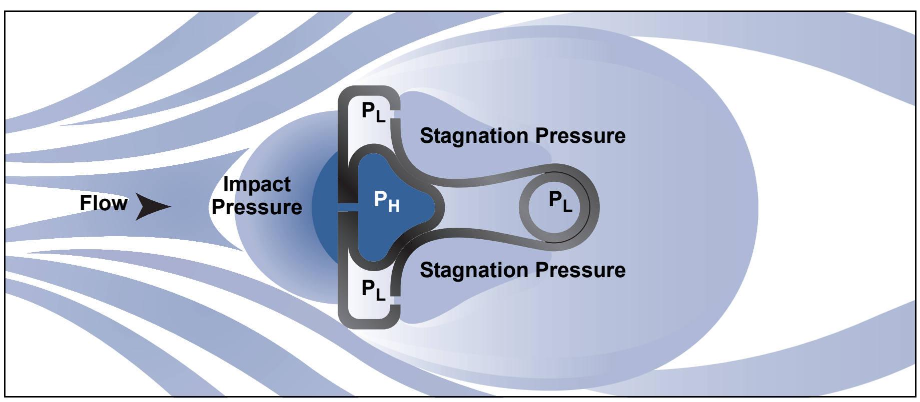
where:

Q = Flow Rate
K = Annubar Flow Coefficient
DP = Differential Pressure

For a more complete discussion on the flow equation, refer to Section 4: Annubar Flow Theory.

The Annubar generates a DP by creating blockage in the pipe and acting as an obstruction to the fluid. The velocity of the fluid is decreased and stalled as it reaches the front surface the Annubar sensor, creating the impact/high pressure. The Rosemount 485 Annubar senses the impact pressure by utilizing a frontal slot design, which opens into the high pressure chamber. This high pressure chamber connects directly into the DP transmitter for measurement.

Figure 2-2. Cross Section of the Rosemount 485 Annubar in a Flow Stream



As the fluid continues around the Annubar sensor, it creates a lower velocity profile on the backside of the sensor, creating the low/suction pressure downstream of the 485 Annubar. Individual ports, located on the backside of the Annubar sensor measure this low pressure. Working on the same principle as the high pressure, an average low pressure is maintained in the low pressure chamber that connects directly into the transmitter for measurement.

The resultant differential pressure is the difference between the impact (high) pressure reading and the suction (low) pressure reading as seen below.

Equation 2-3 $DP = P_H - P_L$

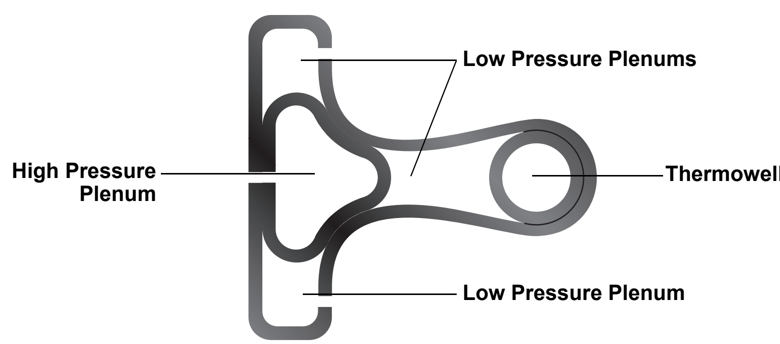
where:
PH = High Pressure
PL = Low Pressure

DESIGN AND PERFORMANCE

Rosemount 485 Annubar Sensor Design

The 485 Annubar is T-shaped in design and is constructed in three scaled sizes for use in a wide range of pipe diameters. Its design includes a single high-pressure plenum, three common low-pressure plenums, and an integral thermowell.

Figure 2-4. Cross-Section of the Rosemount 485 Annubar



Differential Pressure (DP) Signal

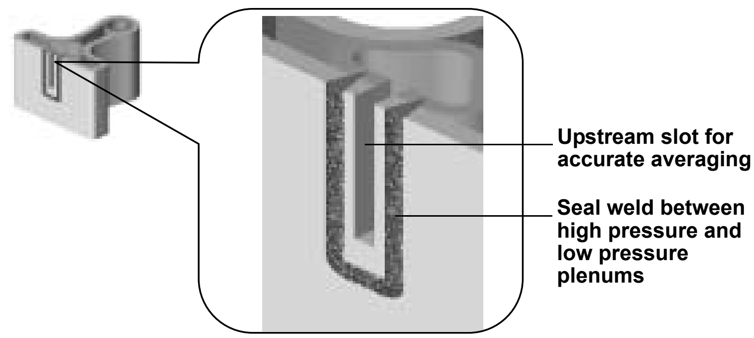
The T-shaped design of the 485 Annubar generates more differential pressure than any APT. The flat upstream surface of the sensor is perpendicular to the direction of flow, which results in a high and very stable drag coefficient. Since the flow coefficient, or k factor (see Equation 2-1), is a function of the drag coefficient, this produces a large, repeatable and predictable DP signal for a given velocity.

The magnitude of the DP signal is directly related to measurement accuracy and the amount of primary element turndown, particularly at lower flow rates. One traditional limitation of APT technology is that accuracy degrades at lower flow rates as a result of the minimal DP produced. The Rosemount 485 extends the lower range limit that an APT can measure and maintain performance as a result of the additional DP generated.

Impact (High) Pressure Measurement

As mentioned in the “Overview” on page 2-1, the Rosemount 485 Annubar measures the impact (high) pressure with a frontal slot design. The laser cut slots extend across the entire front surface of the sensor to maximize the amount of the velocity flow profile measured and increase the accuracy of the measurement. Multiple slots are used to maintain the structural integrity of the bar. A seal weld is visible around the perimeter of the slots and is used to seal the high pressure chamber from the low pressure chamber to prevent any leakage potential. Testing revealed that the raised surface of the weld does not have any effect on performance so it is not removed.

Figure 2-5. Rosemount 485 Frontal Slot Design



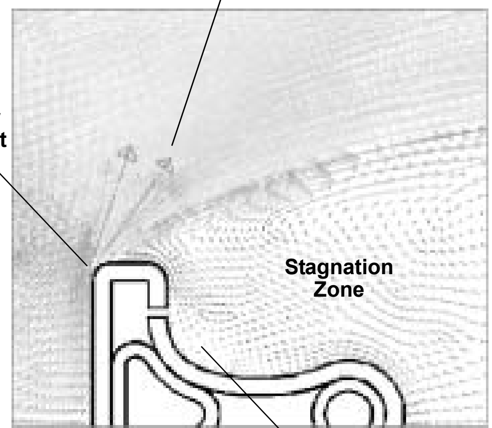
The patented slot design replaces sensing ports used by traditional APTs. This slot “integrates” the velocity flow profile and improves the accuracy of the measurement. By “integrating” the flow profile, a consistent series of data is recorded across the pipe diameter instead of limited samples taken at a few discreet points. By increasing the number of samples taken across the pipe of the actual flow rate, the accuracy of the measurement is improved.

Suction (Low) Pressure Measurement

The Rosemount 485 Annubar measures the suction (low) pressure with sensing ports located in stagnation zones on the backside of the sensor. As the fluid comes into contact with the 485 Annubar sensor and separates from the front edges, the velocity and turbulence level of the fluid in the area directly behind the sensor is greatly decreased. The low velocity and turbulence level in this stagnation zone significantly reduces any pressure variation in this region. Individual sensing ports are drilled in this location to detect the suction (low) pressure.

The number of ports located on the backside of a given sensor is a function of pipe size and mathematically determined by the same Chebyshev principles of previous Annubar designs.

Figure 2-6. Velocity Graph



Surface Texture

As the flow over any surface in the flow stream is increased, the character of the fluid flow near that surface goes through a transition. At a certain critical flow rate, the level of turbulence in this region, termed the boundary layer, increases sharply. This increase in turbulence in the boundary layer on the front surface of the 485 Annubar causes a marked change in the separation of the flow at the edge, which in turn affects the accuracy of the differential pressure signal. The transition from the non-turbulent (laminar) to a turbulent boundary layer condition is an inescapable fact described by the principles of fluid dynamics. However, it has been found that altering the roughness or texture of the surface adjacent to the boundary layer can control the flow at which that transition takes place.

The front surface of the 485 Annubar sensor is tailored to the customer's flow application. In high flow applications (where the maximum expected flow exceeds one million Reynolds number), the surface is textured to increase the level of turbulence at a given flow rate. This ensures that the transition from laminar to turbulent flow in the boundary layer occurs at flows below (and outside) the customer's measurement range. For lower flow applications, the surface is left smooth to maintain a laminar boundary layer forcing the transition to occur above the maximum flow that will be seen in the application.

Section 3 Flow Coefficient Reynolds Number Independence

FLOW COEFFICIENT OVERVIEW

The flow coefficient (K–factor) is the ratio of the actual flow rate to the calculated (theoretical) flow rate. The accuracy of the Rosemount 485 Annubar relates directly to the flow coefficient. The flow coefficient is empirically determined by testing a representative sample of flowmeters to establish the relationship between flowrate and the DP induced across the primary element.

This sampling of flow coefficients is generally plotted as a function of key flow-meter variables. For averaging pitot tubes, flow coefficients are plotted against the meter's pipe blockage.

Curve-fitting techniques are used to generate an equation that best fits the sampling of flow coefficients. This curve-fit equation becomes the basis for a manufacturer's published flow coefficients. These published flow coefficients are used for flowmeters in nearly all untested conditions.

Rosemount has supplemented the flow coefficient equations discussed above with the blockage equation derived in Section 4 of this document. This blockage equation defines a relationship between flow coefficient and blockage that substantiates the results of empirical testing. Extensive APT testing conducted by Rosemount over the past 35 years support the theoretical equation.

BENEFITS

The K-factor of an Annubar is a function of the blockage the probe presents to the flow stream. The flow coefficient of many other primary elements is a function of Reynolds number. This characteristic of Annubar performance offers significant benefits over other primary elements.

K-factor independence can be attributed to a constant separation point at the tips of the primary flow element's T-shape and to the probe's ability to take a proper average. Thus:

- It allows measurement of a wide range of Reynolds numbers without a correction factor for changing Reynolds numbers.
- Any variations in the K-factor with changing Reynolds number are due to scatter and fall within ±0.75% of the published K-value.

The K-to-blockage theoretical link demonstrates a higher degree of confidence in Rosemount 485 Annubar K-factors than shown by flowmeters that use only an empirical database to determine flow coefficients. Rosemount is the first company to identify and use theoretical equations linking self-averaging pitot-tube flow coefficients to pipe blockage.

ROSEMOUNT 485 ANNUBAR REYNOLDS NUMBER RANGES

For a Rosemount 485 Annubar to operate accurately, the flowing media must travel at a velocity sufficient to separate from the edges of the T shape.

Drag coefficients, lift coefficients, separation points, and pressure distributions around bluff bodies are best described by “rod” Reynolds numbers. There is a minimum rod Reynolds number at which the flowing fluid will not properly separate from the edges of the T shape. The rod Reynolds number can be calculated using Equation 3-1.

Equation 3-1 $$R_d = \frac{d \bullet V \bullet \rho}{\mu}$$

where:
d = Probe Width (feet or meters)
V = Velocity of fluid (ft/sec or meters/second)
ρ = Density of fluid (lbm/ft^3 or kg/m^3)
μ = Viscosity of fluid (lbm/ft-sec or kg/meter-sec)

Minimum rod Reynolds numbers for the Rosemount 485 Annubar can be found in Table 3-1.

Table 3-1. Rod Reynolds Number Lower Limits

Sensor Size	Minimum Rod Reynolds Number (R_d)	Probe Width (d)	
		feet	meters
1	6500	0.049167	0.014986
2	12500	0.088333	0.026924
3	25000	0.16125	0.049149

Section 4 Annubar Flow Theory

Annubar flow equations are built on basic hydraulic principles. The theoretical link to these concepts increases confidence in an Annubar measurement when compared to other measurements that are based solely on empirical data.

NOMENCLATURE

The following symbols are used in the derivation of the flow equation and the blockage equation:

A = cross sectional area of the pipe

B = blockage ratio = $\frac{\text{cross-sectional area of sensor}}{\text{cross-sectional area of pipe}}$

C_1 = integration constant

C_2 = integration constant

f(B) = function of blockage

Δh_B = differential pressure caused by blockage

Δh_S = differential pressure caused by shape of sensor

Δh = total differential pressure = $\Delta h_B + \Delta h_S$

g_c = gravitational constant

K_A = flow coefficient = $\frac{\text{Actual Flow Rate } (Q_A)}{\text{Theoretical Flow Rate } (Q_{th})}$

P = fluid pressure

Q_a = actual flow rate

Q_{th} = theoretical flow rate

V = average fluid velocity

ρ = fluid density

z = height above an arbitrary datum plane

Unless noted otherwise, subscript 1 denotes an upstream condition and subscript 2 denotes a downstream or throat condition.

FLOW EQUATION DERIVATION

The flow equation relates the DP induced across a primary element to the velocity of the fluid in the pipe. As with other differential-pressure flowmeters, Rosemount 485 Annubar equations are based on the Bernoulli equation:

Equation 4-1

$$\frac{V_1^2}{2g_c} + \frac{P_1}{\rho_1} + g_c z_1 = \frac{V_2^2}{2g_c} + \frac{P_2}{\rho_2} + g_c z_2$$

For incompressible fluids $\rho_1 = \rho_2$. Changes in elevation around a primary element are negligible so $z_1 = z_2$.

Also, assume the velocity just within the mouth of the impact-sensing ports is zero, ($V_1 = 0$). While minor circulation may occur within the high pressure chamber of the Rosemount 485 Annubar, this flow is extremely small and may be considered negligible.

Solving for V_2 yields:

Equation 4-2

$$V_2 = \sqrt{2g_c\frac{(P_1 - P_2)}{\rho}}$$

The net differential pressure produced can be rewritten as:

Equation 4-3

$$\Delta h = \frac{P_1 - P_2}{\rho}$$

Substituting Equation 4-3 into Equation 4-2 yields:

Equation 4-4

$$V_2 = \sqrt{2g_c\Delta h}$$

Like the orifice plate and venturi meter, the general equation describing the actual flow in a pipe for the Rosemount 485 is:

Equation 4-5

$$Q_a = K_A A V$$

In Equation 4-4, V_2 is the average velocity of the fluid traveling past the sensor on the downstream side; whereas, in Equation 4-5, V is the average velocity in the pipe. Differences between these two velocities (V_2 and V) are absorbed in the flow coefficient (K_A).

Combining Equation 4-4 and Equation 4-5 yields:

Equation 4-6

$$Q_a = K_A A_1 \sqrt{2g_c\Delta h}$$

Equation 4-6 is the flow equation used to relate differential pressure induced across the primary element to flow rate for the Rosemount 485 Annubar.

BLOCKAGE EQUATION DERIVATION

Because the flow coefficient compensates for the difference between V_2 and V, it must be recognized that (K_A) will be a function of the amount of obstructed area the sensor itself causes in the pipe. More specifically, (K_A) is a function of the sensor's blockage in the pipe.

Equation 4-7
$$K_A = f(B)$$

This is analogous to the velocity-of-approach factor for an orifice plate or a venturi meter. The following derivation uniquely determines *f*(B) in Equation 4-7. Discussion is limited to fluid flows in the turbulent regime for which Rosemount 485 Annubar flow measurement is intended. Development of the equations applies to primary flow elements that are geometrically similar.

Beginning with Equation 4-6, the differential pressure produced by a primary flow element can be dissected into two parts:

- Differential pressure due to the primary flow element's blockage (Δh_B)
- Differential pressure due to the shape of the primary flow element (Δh_S)

Focusing on the differential pressure contribution due to the primary flow element's blockage (Δh_B), Equation 4-1 can be rearranged:

Equation 4-8
$$\Delta h_B = \frac{(P_1 - P_2)}{\rho} = \frac{1}{2g_c}[V_2^2 - V_1^2]$$

In the derivation of the blockage equation V_1 is defined as the average fluid velocity in the pipe prior to encountering the primary flow element, V_2 equals the accelerated velocity past the primary flow element.

Using the conservation of mass:

Equation 4-9
$$A_1 V_1 \rho_1 = A_2 V_2 \rho_2$$

For incompressible fluids, $\rho_1 = \rho_2$, Equation 4-9 can be simplified:

Equation 4-10
$$V_2 = \frac{A_1}{A_2} V_1$$

Where:
A_1 = Cross-sectional area of the pipe
A_2 = Cross-sectional area of the pipe less the amount blocked by the sensor

A_2 can be rewritten in terms of A and the flow element's blockage:

Equation 4-11
$$A_2 = (1 - B)A_1$$

Substituting into Equation 4-10 yields:

Equation 4-12
$$V_2 = \left(\frac{1}{1 - B}\right) V_1$$

Substituting Equation 4-12 into Equation 4-8:

Equation 4-13 $$\Delta h_B = \frac{V_1^2}{2g_c}\left[\left(\frac{1}{(1-B)^2}\right) - 1\right]$$

Recall the general equation relating the actual flow in a pipe to the Rosemount 485 Annubar signal (Equation 4-6): $Q_a = K_A \cdot A_1 \cdot \sqrt{2g_c\Delta h}$

Where:
Δh = The total differential pressure produced by the flow element
$\Delta h = \Delta h_B + \Delta h_S$

Substituting into Equation 4-6 and rearranging yields:

Equation 4-14 $$K_A = \frac{Q}{A_1\sqrt{2g_c}\sqrt{\Delta h_B + \Delta h_S}}$$

Differentiate Equation 4-14 with respect to the differential pressure contribution due to the primary flow element's blockage (Δh_B), assuming h_S remains constant.

Equation 4-15 $$\frac{\partial K_A}{\partial h_B} = -\frac{1}{2}\frac{Q_a}{A_1\sqrt{2g_c}}(\Delta h_B + \Delta h_S)^{-\frac{3}{2}}$$

Differentiate Equation 4-13 with respect to the primary flow element's blockage (B).

Equation 4-16 $$\frac{\partial h_B}{\partial B} = \frac{V_1^2}{g_c}(1-B)^{-3}$$

Combine $\frac{\partial K_A}{\partial h_B} = \frac{\partial K_A}{\partial \Delta h_B} \cdot \frac{\partial \Delta h_B}{\partial B}$ with Equation 4-15 and Equation 4-16.

Equation 4-17 $$\frac{\partial K_A}{\partial B} = \left[\left(-\frac{1}{2}\right)\frac{Q_A}{A_1\sqrt{2g_c}}(\Delta h_B + \Delta h_S)^{-\frac{3}{2}}\right] \cdot \left[\frac{V_1^2}{g_c}(1-B)^{-3}\right]$$

Substitute $V_1 = \frac{Q}{A_1}$ and $\Delta h = \Delta h_B + \Delta h_A$ and simplify:

Equation 4-18 $$\frac{\partial K_A}{\partial B} = -\left(\frac{Q_a}{A_1\sqrt{2g_c\Delta h}}\right)^3 \cdot (1-B)^{-3}$$

Substitute $K_A = \frac{Q_a}{A_1\sqrt{2g_c\Delta h}}$ and simplify:

Equation 4-19 $$\frac{\partial K_A}{\partial B} = K_A^3(1-B)^{-3}$$

Rearrange and integrate: $\int -\left(\frac{dK_A}{K_A^3}\right) = \int (1-B)^{-3}dB$

Equation 4-20 $$\frac{1}{2}K_A^{-2} + C_1 = \frac{1}{2}(1-B)^{-2}$$

Where C_1 = constant of integration, solve for K_A, redefining the integration constant C_1 as $2C_1$.

Equation 4-21

$$K_A = \frac{(1-B)}{\sqrt{1-C_1(1-B)^2}}$$

(B) represents the actual blockage in the pipe caused by the Rosemount 485 Annubar. Because downstream pressure is sensed past the flow element's widest cross-section, the effective blockage of the sensor will be a fraction of the actual blockage. Therefore, define an effective blockage as C_2B where C_2 represents a fraction of the actual blockage. Equation 4-21 can be rewritten:

Equation 4-22

$$K_A = \frac{(1-C_2B)}{\sqrt{1-C_1(1-C_2B)^2}}$$

Equation 4-22 shows that there is a direct relationship between a primary flow element flow coefficient K_A and its blockage. As blockage approaches zero, Equation 4-22 becomes:

Equation 4-23

$$\underset{B \to 0}{K_A} = \frac{1}{\sqrt{1-C_1}}$$

Thus, as blockage approaches zero, the primary flow element flow coefficient approaches a constant value $\frac{1}{\sqrt{1-C_1}}$, the stream-flow coefficient.

This constant value is the primary flow element flow coefficient due only to the primary flow element's shape (Δh_S), and is analogous to placing the primary flow element in an infinitely large pipe with no confining walls.

The constants C_1 and C_2 in Equation 4-22 are determined experimentally. Once determined, Equation 4-22 becomes the theoretical link between the flow coefficient and the flow element blockage.

CONCLUSION

While empirical testing of a flowmeter is the most accurate means of determining the meter's flow coefficient, many flowmeters use untested predicted flow coefficient.

- Untested flow coefficients are based on a representative sample of empirically determined flow coefficients and on theories that link the flow coefficient to physical parameters in the pipe.
- Like an orifice plate or a venturi meter, an averaging pitot tube has a theoretical relationship between its flow coefficient and parameters in the pipe.
- An averaging pitot tube's flow coefficient is related to its blockage in the pipe. This blockage dependency is necessary because the sensor itself reduces the effective pipe flow area.
- For an orifice plate and a venturi meter, the velocity-of-approach factor is the theoretical link between the meter's flow coefficient and it's beta ratio. For a Rosemount 485 Annubar, Equation 4-22 describes the theoretical relationship between the sensor's flow coefficient and its blockage in the pipe.
- Using a theoretical basis, in addition to empirical testing, for the prediction of untested flow coefficients provides a much higher degree of confidence in these untested values.

Section 5 Test Facilities and Procedures

OVERVIEW

The following descriptions of tests and testing methods are abbreviated versions. For detailed descriptions of the individual laboratories contact the facility in question.

TESTING LABORATORIES

Rosemount Boulder, Colorado Flow Laboratory

The Rosemount 485 Annubar is tested and calibrated in water at Rosemount Inc. Line sizes available for testing range from 0.50 in. to 12 in. A secondary set of reference meters, routinely calibrated against a gravimetric primary standard, provide an uncertainty of 0.25 percent. Calibrations that use the primary-measurement device, gravimetric method, can be calibrated with an uncertainty of 0.1 percent.

Alden Research Laboratories (ARL)

Flowmeters are calibrated at ARL using the gravimetric method. This method has been found to produce a consistent accuracy of ±0.25% over extended periods.

SwRI Gas Research Institute (GRI), Meter Research Facility (MRF)

Flowmeters are tested and calibrated on a recirculating natural gas loop. A sonic nozzle bank provides secondary flow calibration. This permits high repeatability and excellent test accuracies via calibration against the gravimetric primary standards. The sonic nozzle banks produce an accuracy on flow rate of 0.25% of reading.

GRAVIMETRIC PROCEDURE

Piping is selected to match the inside diameter of the flowmeter under test. Carbon steel piping is normally used for these tests. Gaskets between pipe flanges are carefully installed and checked to ensure that they not interfere with the flow. Proper alignment of the flowmeter with the piping is maintained.

After all piping is secured with bolts, couplings, or clamps. Water is gradually introduced into the line. Flows are set to purge air from the system and to bring the flowmeter to steady-state temperature. After operating the system for a period of time, the control valve (at the downstream end of the test line) is closed. Air is then purged from all instrumentation lines, instruments, and the flowmeter.

After air purging, and with the control valve in the closed position, all instrumentation is checked for zero-flow indication. Calibration test runs are not started until all instrumentation reads zero at the no flow condition.

The flow rate is set by adjusting the control valve at the end of the test line to a desired flow. This flow is allowed to stabilize and reach steady-state condition. This condition is achieved when the average flow-meter readout is constant with time. At this point, the calibration run begins.

A calibration run consists of simultaneously recording the flowmeter output while the weighing tank is filled and the filling process is timed. Electronic timers are activated and deactivated by electric eyes on the switch way. Outputs are recorded at 1–15 Hz during this time. The duration of the run is typically between 50 and 100 seconds. For higher flow rates, the limiting factor is the capacity of the weighing tank.

In addition to recording weight and time, the water temperature, air temperature weigh tank, and air temperature adjacent to the readout are recorded. Barometric pressure is also recorded at the start and at the end of the test.

After a run is completed, the control valve is reset to another flow rate and the process is repeated. Runs are normally conducted at 12 different flow rates, approximately equally spaced from the maximum to the minimum flow rates. In some cases, the maximum flow obtainable by the test facility determines the upper flow limit of the test.

The followings tests are provided on the following pages

Sensor Size 1:

Sensor Size 2:

Sensor Size 3

SENSOR SIZE 1

Test Laboratory: Rosemount Boulder, Colorado Flow Lab

Sensor Size: 1	Test Date: May 15, 2000
Fluid: Water	Pipe I.D.: 3.097-in (78.66 mm)
Sensor Serial Number: FI-210	Blockage: 24.26%
Nominal Pipe Size: 3-in. Schedule 40	K_{pub}: 0.5099

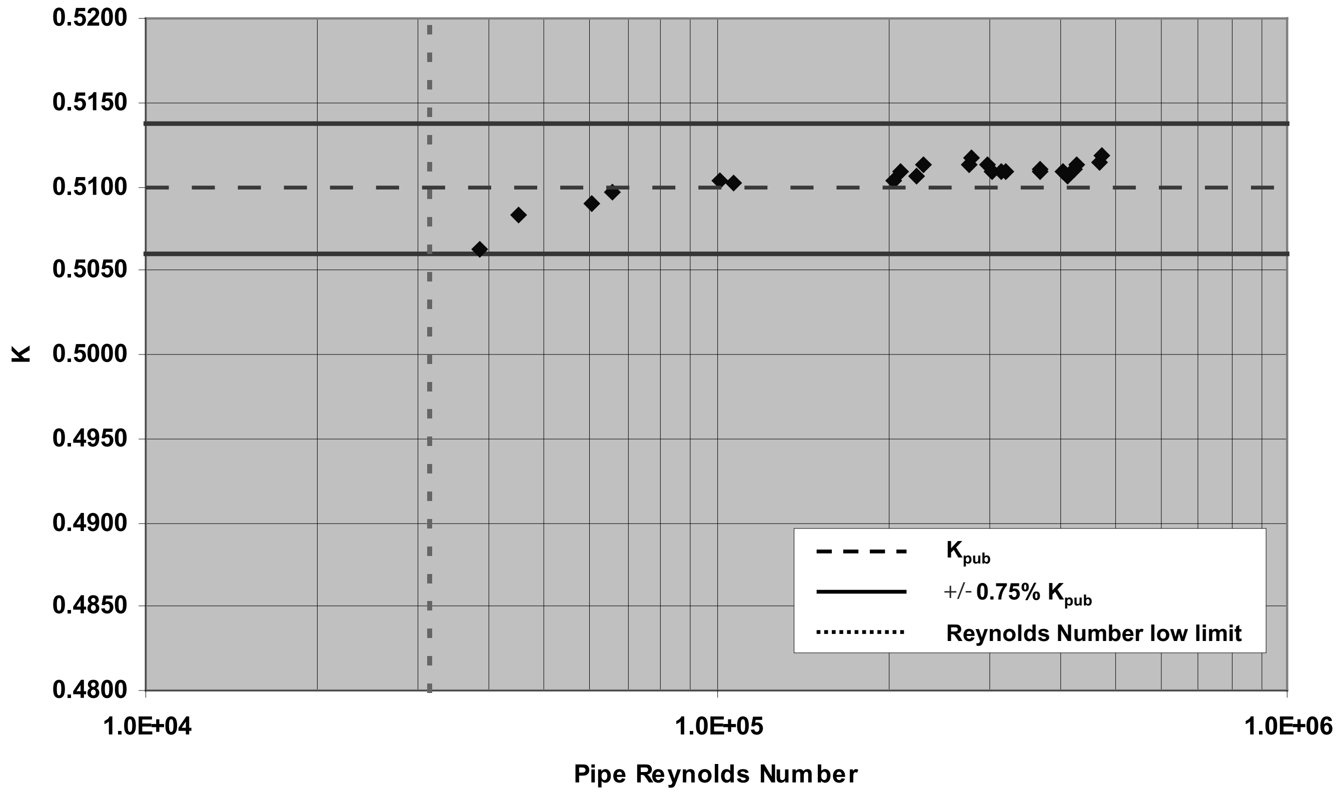


Table 5-1. Rosemount Boulder, Colorado Flow Lab, Water.

Data Point Number	Pipe Reynolds Number	Velocity	Differential Pressure	Temperature		Pressure		Viscosity	Density	Flow Rate	K
		ft/sec.	*in Water*	*°F*	*°C*	*psig*	*bar*	*cP*	*lb/ft^3*	*GPM*	
1	4.70E + 05	20.00	285.186	66.7	19.3	38.7	2.67	1.020	62.32	469.63	0.5115
2	4.75E + 05	20.25	291.907	66.7	19.3	38.7	2.67	1.020	62.32	475.45	0.5118
3	4.25E + 05	18.09	233.873	66.7	19.3	39.1	2.70	1.019	62.32	424.91	0.5110
4	4.29E + 05	18.22	237.029	66.9	19.4	39.1	2.70	1.017	62.31	427.95	0.5113
5	4.05E + 05	17.17	210.633	67.0	19.4	39.3	2.71	1.016	62.31	403.09	0.5108
6	4.14E + 05	17.49	218.940	67.3	19.6	39.2	2.70	1.012	62.31	410.78	0.5106
7	3.70E + 05	15.66	175.154	67.2	19.6	39.6	2.73	1.013	62.31	367.64	0.5109
8	3.68E + 05	15.58	173.340	67.2	19.6	39.6	2.73	1.012	62.31	365.77	0.5110
9	3.16E + 05	13.39	128.240	67.0	19.4	36.5	2.52	1.015	62.31	314.53	0.5108
10	3.20E + 05	13.59	132.030	67.0	19.4	36.5	2.52	1.015	62.31	319.18	0.5109
11	2.99E + 05	12.70	115.145	67.0	19.4	36.9	2.54	1.015	62.31	298.33	0.5113
12	3.04E + 05	12.89	118.684	67.0	19.4	36.9	2.54	1.015	62.31	302.63	0.5109
13	2.76E + 05	11.71	97.853	67.0	19.4	37.2	2.56	1.015	62.31	274.96	0.5112
14	2.80E + 05	11.89	100.734	67.0	19.4	37.2	2.58	1.015	62.31	279.21	0.5117
15	2.24E + 05	9.51	64.686	67.0	19.4	37.5	2.59	1.015	62.31	223.30	0.5107
16	2.30E + 05	9.75	67.826	67.0	19.4	37.4	2.58	1.015	62.31	228.95	0.5113
17	2.04E + 05	8.67	53.779	67.0	19.4	37.5	2.59	1.015	62.31	203.49	0.5103
18	2.09E + 05	8.88	56.323	67.0	19.4	37.5	2.59	1.016	62.31	208.48	0.5109
19	1.02E + 05	4.32	13.357	66.9	19.4	35.2	2.43	1.017	62.31	101.40	0.5103
20	1.07E + 05	4.54	14.751	66.9	19.4	35.2	2.43	1.017	62.32	106.53	0.5102
21	6.06E + 04	2.58	4.795	66.8	19.3	35.9	2.48	1.019	62.32	60.60	0.5090
22	6.56E + 04	2.79	5.610	66.7	19.3	35.9	2.148	1.020	62.32	65.62	0.5096
23	3.86E + 04	1.65	1.973	66.5	19.2	25.4	1.75	1.022	62.32	38.66	0.5062
24	4.49E + 04	1.92	2.658	66.5	19.2	25.4	1.75	1.023	62.32	45.06	0.5083

Reynolds Number Low Limit: 31495

Test Laboratory: SwRI Flow Lab	
Sensor Size: 1	Test Date: August 22, 2002
Fluid: Natural gas (185 psi)	Pipe I.D.: 3.068-in (77.9 mm)
Sensor Serial Number: FI-260	Blockage: 24.49%
Nominal Pipe Size: 3-in. Schedule 40	K_{pub}: 0.5084

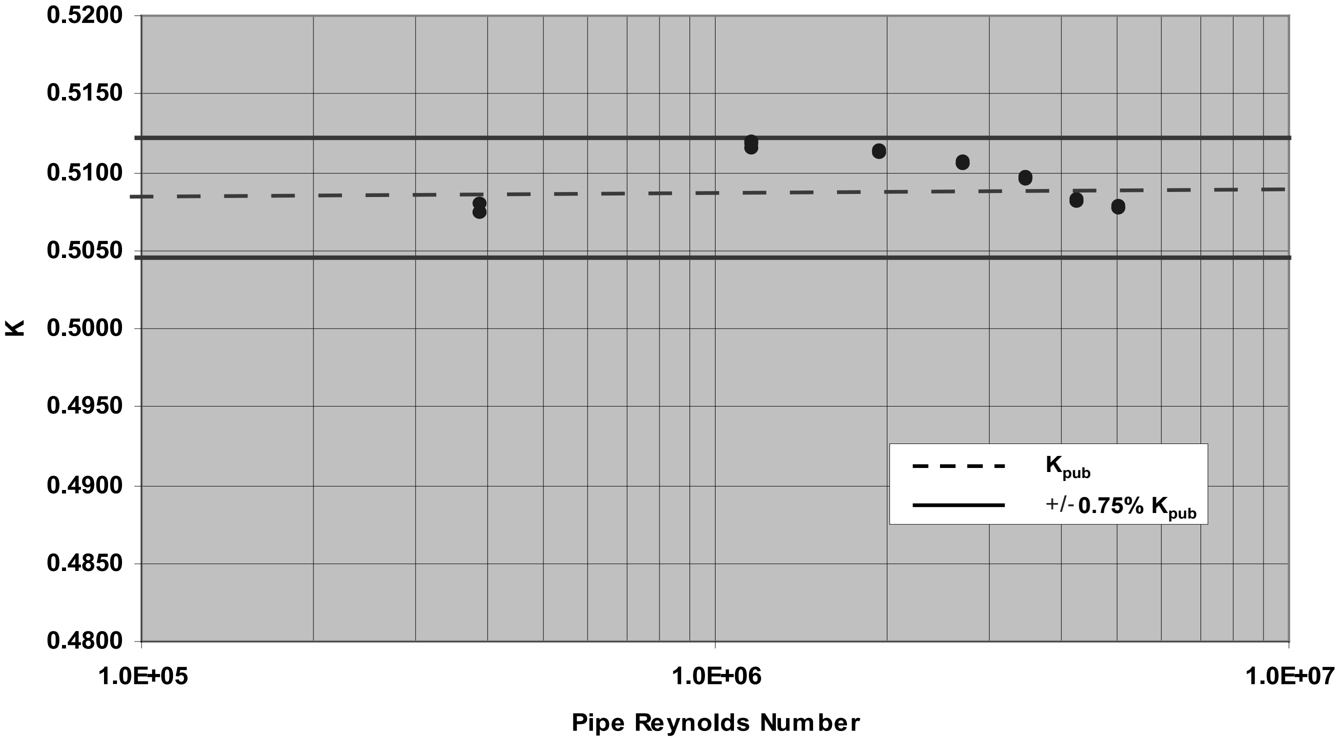


Table 5-2. SwRI Flow Labs, Natural Gas (185 psi)

File	Pressure	Temperature	Density	DP	Re D	K	Gas Exp. Factor	Probe Width	Mass Flow
	psia	*°F*	*lb/ft³*	*in H_2O*				in.	lb/s
000	202.5993	69.18282	0.625256	425.7187	5170457	0.51071	0.99523	0.59	7.782182
001	202.6013	69.18553	0.625259	425.7972	5170316	0.51066	0.99523	0.59	7.782003
002	202.5994	69.15164	0.625297	425.7294	5170481	0.51067	0.99523	0.59	7.781837
003	201.5583	69.43139	0.621619	306.1838	4374677	0.51048	0.99655	0.59	6.586276
004	201.5599	69.40691	0.621656	306.2264	4374799	0.51042	0.99655	0.59	6.586208
005	201.5369	69.3722	0.621652	306.1974	4374683	0.5104	0.99655	0.59	6.585636
006	200.8503	69.7511	0.619006	204.6737	3578087	0.51138	0.99768	0.59	5.389227
007	200.8377	69.7335	0.618989	204.7528	3577890	0.51125	0.99768	0.59	5.388787
008	200.7973	69.67277	0.618939	204.592	3577455	0.51135	0.99769	0.59	5.387597
009	200.1507	69.95492	0.616529	123.6027	2778837	0.51174	0.9986	0.59	4.186452
010	200.1393	69.91759	0.616541	123.5444	2778784	0.51182	0.9986	0.59	4.186121
011	200.1204	69.91065	0.616489	123.5626	2778465	0.51174	0.9986	0.59	4.18559
012	199.8453	70.4162	0.614976	63.06322	1983918	0.51214	0.99928	0.59	2.990931
013	199.8302	70.45454	0.614873	63.04856	1983498	0.51216	0.99928	0.59	2.990477
014	199.8061	70.47626	0.61477	63.05495	1983119	0.5121	0.99928	0.59	2.989999
015	199.3174	71.82439	0.611521	22.80306	1191144	0.51365	0.99974	0.59	1.79961
016	199.2619	71.86183	0.611299	22.77319	1190568	0.51386	0.99974	0.59	1.798835
017	199.2151	71.81538	0.61121	22.79317	1190234	0.51349	0.99974	0.59	1.798191
018	199.5703	72.70587	0.611203	2.65138	401055	0.50791	0.99997	0.59	0.606773
019	199.5145	73.05611	0.610585	2.64952	400679	0.50814	0.99997	0.59	0.606531
020	199.4588	73.31953	0.610078	2.64417	400334	0.50863	0.99997	0.59	0.606254

Test Laboratory: SwRI Flow Lab	
Sensor Size: 1	Test Date: August 22, 2002
Fluid: Natural gas (185 psi)	Pipe I.D.: 3.068-in (77.9 mm)
Sensor Serial Number: FI-261	Blockage: 24.49%
Nominal Pipe Size: 3-in. Schedule 40	K_{pub}: 0.5084

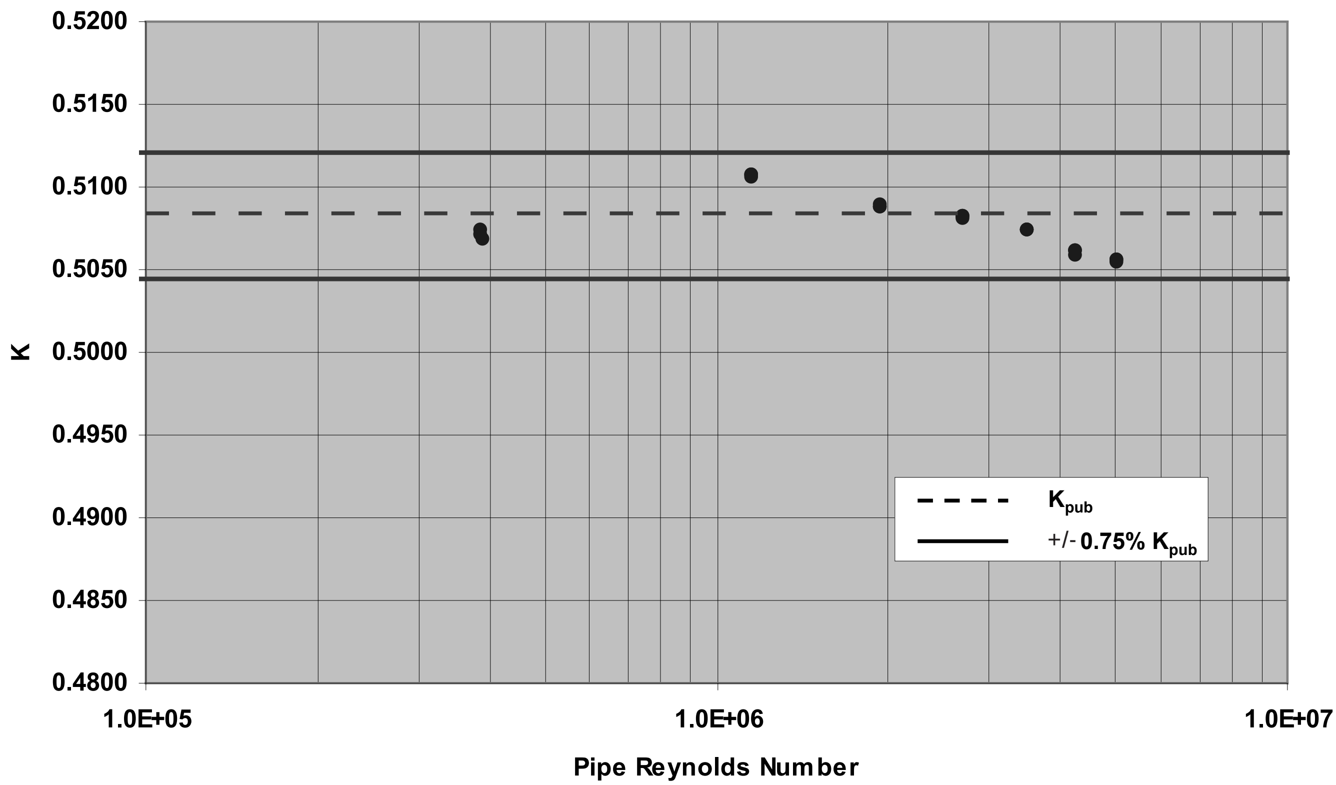


Table 5-3. SwRI Flow Labs, Natural Gas (185 psi)

File	Pressure	Temperature	Density	DP	Re D	K	Gas Exp. Factor	Probe Width	Mass Flow
	psia	*°F*	*lb/ft^3*	*in H_2O*				in.	lb/s
022	202.8247	69.03876	0.626134	429.9236	5170632	0.50779	0.99519	0.59	7.780826
023	202.8007	69.03179	0.626067	429.6451	5169961	0.50791	0.99519	0.59	7.779712
024	202.7756	68.96634	0.626073	429.6553	5169905	0.50784	0.99519	0.59	7.778808
025	201.6693	69.20293	0.622241	308.8323	4373337	0.50771	0.99652	0.59	6.581931
026	201.6491	69.24744	0.622096	309.0335	4372184	0.50751	0.99652	0.59	6.580654
027	201.6101	69.23643	0.621986	308.6848	4371092	0.5077	0.99652	0.59	6.578869
028	201.1633	69.68273	0.619948	206.8046	3578432	0.50837	0.99766	0.59	5.389369
029	201.1247	69.68246	0.619826	206.7449	3577270	0.50833	0.99766	0.59	5.387594
030	201.0782	69.66862	0.619697	206.6449	3576206	0.50834	0.99767	0.59	5.385848
031	200.505	69.53053	0.618117	124.5604	2778664	0.50877	0.99859	0.59	4.183545
032	200.4762	69.37682	0.618224	124.5957	2778848	0.50856	0.99859	0.59	4.182799
033	200.447	69.30812	0.61822	124.5066	2778721	0.50867	0.99859	0.59	4.182145
034	200.0181	69.9976	0.615975	63.51227	1981658	0.509	0.99928	0.59	2.985605
035	199.9286	70.08919	0.615575	63.49648	1980105	0.5089	0.99928	0.59	2.983665
036	199.8472	70.19513	0.615182	63.44048	1978503	0.50896	0.99928	0.59	2.98172
037	199.1532	71.49677	0.611342	22.84423	1186026	0.51079	0.99974	0.59	1.790918
038	199.0394	71.29086	0.611244	22.84238	1185647	0.51052	0.99974	0.59	1.789749
039	198.9264	71.09116	0.611141	22.79827	1185285	0.51073	0.99974	0.59	1.788623
040	199.3829	74.01337	0.608892	2.64419	398073	0.50679	0.99997	0.59	0.603472
041	199.241	74.74033	0.607537	2.6376	397198	0.50743	0.99997	0.59	0.602815
042	199.1592	75.24209	0.606655	2.64077	396584	0.5071	0.99997	0.59	0.602347

SENSOR SIZE 2

Test Laboratory: SwRI Flow Lab and Rosemount Boulder, Colorado Flow Lab

Sensor Size: 2	Test Date: February 13, 2001 (SwRI), December 18, 2000 (DSI)
Fluid: Natural gas (350 psi) and Water	Pipe I.D.: 7.634-in (193.9 mm)
Sensor Serial Number: FI-156	Blockage: 17.38%
Nominal Pipe Size: 8-in. Schedule 80	K_{pub}: 0.5544

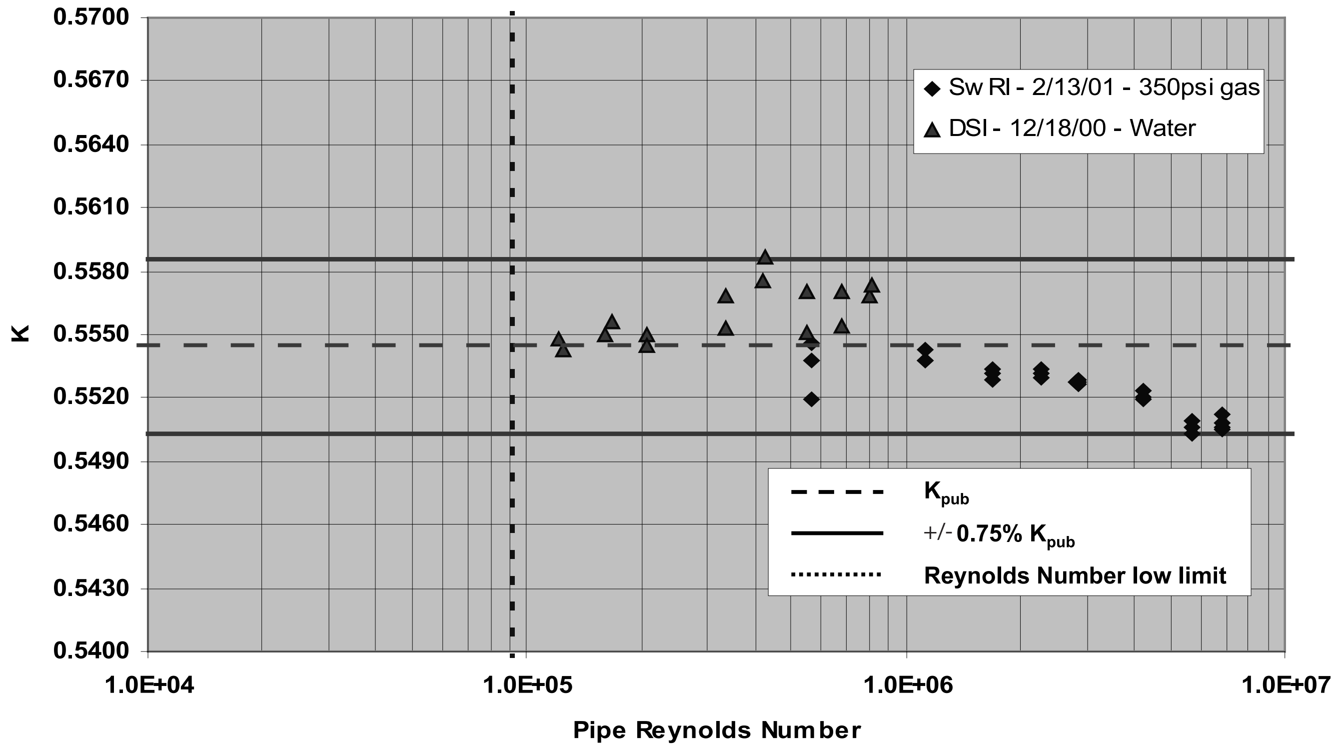


Table 5-4. SwRI Flow Labs, Natural Gas (350 psi)

File	Pressure	Temperature	Density	DP	Re D	K	Gas Exp. Factor	Probe Width	Mass Flow
	psia	*°F*	*lb/ft³*	*in H_2O*				in.	lb/s
000	351.05	70.420	1.16231	57.073	6860864	0.5529	0.9995	1.042	26.083
001	350.97	70.117	1.16415	57.074	6866857	0.5525	0.9995	1.042	26.086
002	350.94	70.140	1.16398	57.146	6866155	0.5522	0.9995	1.042	26.084
003	350.91	70.133	1.16390	57.110	6865564	0.5523	0.9995	1.042	26.082
004	350.53	70.182	1.16242	39.673	5718707	0.5522	0.9996	1.042	21.725
005	350.49	70.187	1.16237	39.633	5718194	0.5525	0.9996	1.042	21.723
006	350.50	70.172	1.16242	39.706	5718456	0.5519	0.9996	1.042	21.724
007	350.10	70.182	1.16096	22.302	4294705	0.5534	0.9998	1.042	16.314
008	350.07	70.175	1.16091	22.288	4294396	0.5535	0.9998	1.042	16.313
009	350.07	70.201	1.16083	22.272	4294104	0.5537	0.9998	1.042	16.313
010	349.91	70.141	1.16043	9.887	2863651	0.5542	0.9999	1.042	10.877
011	349.88	70.136	1.16033	9.890	2863475	0.5541	0.9999	1.042	10.877
012	349.82	70.139	1.16011	9.886	2863079	0.5542	0.9999	1.042	10.875
019	349.19	70.415	1.15714	0.399	572224	0.5525	1.0000	1.042	2.174
022	349.32	70.746	1.15670	0.395	571852	0.5547	1.0000	1.042	2.174
023	349.38	70.618	1.15724	0.395	572081	0.5553	1.0000	1.042	2.174
026	348.77	70.058	1.15662	9.844	2853932	0.5543	0.9999	1.042	10.837
027	349.61	70.138	1.15934	6.308	2288047	0.5546	0.9999	1.042	8.691
028	349.57	70.130	1.15924	6.301	2287657	0.5548	0.9999	1.042	8.689
029	349.54	70.099	1.15920	6.307	2287696	0.5545	0.9999	1.042	8.689
030	349.50	70.131	1.15902	3.541	1713710	0.5544	1.0000	1.042	6.509
031	349.46	70.159	1.15882	3.538	1713422	0.5547	1.0000	1.042	6.508
032	349.44	70.157	1.15880	3.536	1713262	0.5548	1.0000	1.042	6.507
033	349.58	70.125	1.15935	1.563	1141348	0.5557	1.0000	1.042	4.335
034	349.53	70.091	1.15928	1.565	1141235	0.5552	1.0000	1.042	4.334
035	349.51	70.057	1.15929	1.565	1141168	0.5551	1.0000	1.042	4.334
				Forced Zero DP Run					
025	349.38	70.618	1.15724	R2 –0.014 R1 0.001	572081	0.5553	1	1.042	2.174

Table 5-5. Rosemount Boulder, Colorado Flow Lab, Water

Data Point Number	Pipe Reynolds Number	Velocity	Differential Pressure	Temperature		Pressure		Viscosity	Density	Flow Rate	K
		ft/sec.	*in Water*	*°F*	*°C*	*psig*	*bar*	*cP*	*lb/ft³*	*GPM*	
1	8.03E + 05	14.02	118.295	66.0	18.89	22.8	1.57	1.030	62.32	2642.15	0.5568
2	8.09E + 05	14.13	119.941	66.0	18.89	22.8	1.57	1.030	62.32	2643.91	0.5573
3	6.73E + 05	11.75	83.542	66.0	18.89	24.5	1.69	1.030	62.32	2404.31	0.5554
4	6.77E + 05	11.82	83.958	66.0	18.89	24.4	1.68	1.030	62.32	2425.52	0.5571
5	5.46E + 05	9.54	54.750	66.0	18.89	27.3	2.02	1.030	62.32	1995.94	0.5571
6	5.46E + 05	9.54	55.095	66.0	18.89	27.1	1.87	1.030	62.32	2011.41	0.5551
7	4.23E + 05	7.38	32.526	66.0	18.89	29.0	2.00	1.029	62.32	1673.09	0.5587
8	4.21E + 05	7.35	32.407	66.0	18.89	29.0	2.00	1.030	62.32	1682.18	0.5575
9	3.35E + 05	5.84	20.657	66.0	18.89	31.5	2.17	1.029	62.32	1358.43	0.5553
10	3.33E + 05	5.81	20.330	66.0	18.89	31.5	2.17	1.029	62.32	1357.83	0.5568
11	2.07E + 05	3.62	7.917	66.1	18.94	33.9	2.34	1.029	62.32	1050.11	0.5550
12	2.07E + 05	3.61	7.902	66.1	18.94	33.9	2.34	1.029	62.32	1045.96	0.5545
13	1.61E + 05	2.80	4.755	66.1	18.94	35.7	2.46	1.028	62.32	831.75	0.5550
14	1.67E + 05	2.90	5.083	66.1	18.94	35.8	2.47	1.028	62.32	827.42	0.5556
15	1.21E + 05	2.10	2.685	66.2	19.00	37.6	2.59	1.027	62.32	514.62	0.5548
16	1.25E + 05	2.18	2.881	66.2	19.00	37.7	2.60	1.027	62.32	513.65	0.5543

Reynolds Number Low Limit: 91471

Test Laboratory: Rosemount Boulder, Colorado Flow Lab	
Sensor Size: 2	Test Date: December 19, 2000
Fluid: Water	Pipe I.D.: 8.006-in (203.4 mm)
Sensor Serial Number: FI-162	Blockage: 16.60%
Nominal Pipe Size: 3-in. Schedule 40	K_{pub}: 0.5588

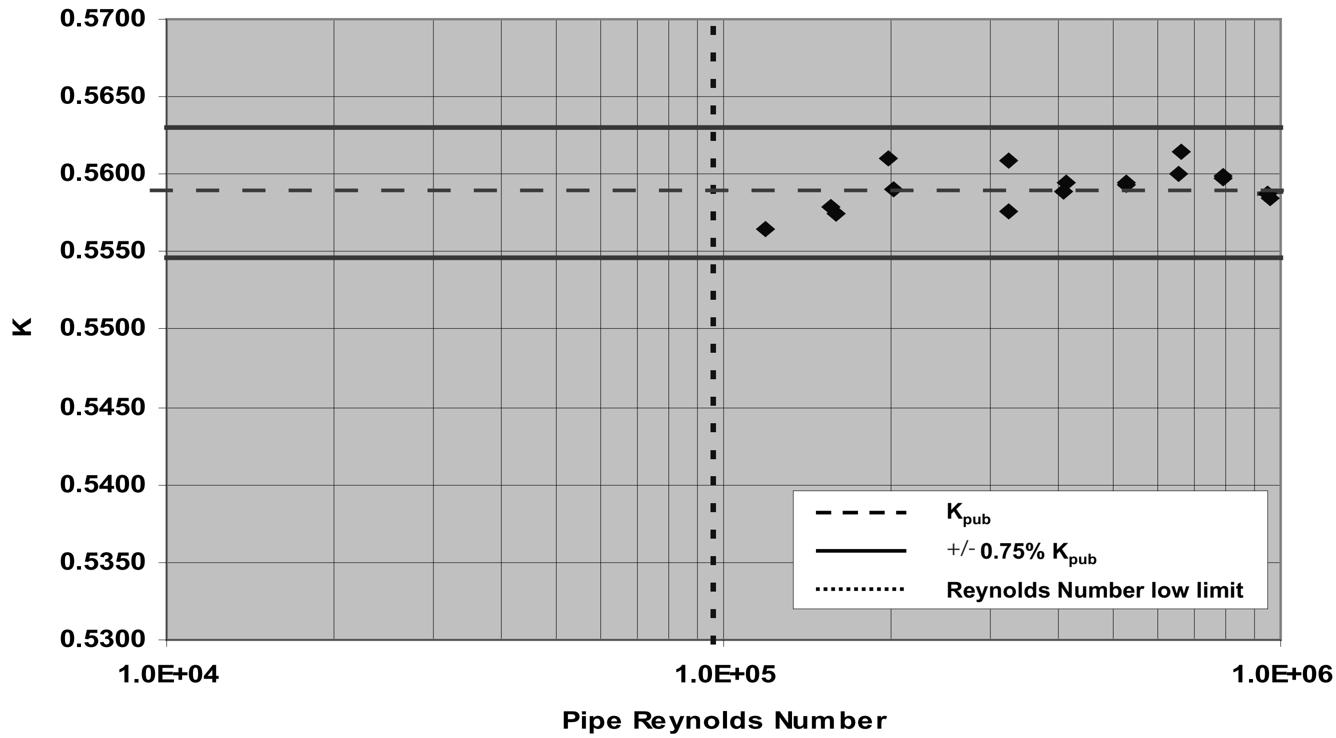


Table 5-6. Rosemount Boulder, Colorado Flow Lab, Water.

Data Point Number	Pipe Reynolds Number	Velocity	Differential Pressure	Temperature		Pressure		Viscosity	Density	Flow Rate	K
		ft/sec.	*in Water*	*°F*	*°C*	*psig*	*bar*	*cP*	*lb/ft³*	*GPM*	
1	1.05E + 06	17.16	176.063	67.5	19.7	23.2	1.60	1.009	62.31	2692.78	0.5586
2	1.04E + 06	16.91	170.395	67.6	19.8	23.5	1.62	1.008	62.31	2653.94	0.5596
3	9.52E + 05	15.51	143.617	67.6	19.8	25.0	1.72	1.008	62.31	2432.93	0.5588
4	9.56E + 05	15.57	144.939	67.6	19.8	24.9	1.72	1.008	62.31	2442.91	0.5585
5	7.86E + 05	12.81	97.625	67.5	19.7	27.8	1.92	1.008	62.31	2009.60	0.5598
6	7.90E + 05	12.87	98.542	67.5	19.7	27.7	1.91	1.008	62.31	2018.65	0.5597
7	6.57E + 05	10.70	68.137	67.5	19.7	29.6	2.04	1.008	62.31	1679.69	0.5601
8	6.61E + 05	10.77	68.602	67.5	19.7	29.6	2.04	1.008	62.31	1689.70	0.5615
9	5.29E + 05	8.63	44.337	67.5	19.7	32.1	2.21	1.008	62.31	1353.36	0.5594
10	5.29E + 05	8.62	44.258	67.5	19.7	32.1	2.21	1.009	62.31	1352.01	0.5594
11	4.10E + 05	6.68	26.607	67.5	19.7	34.5	2.38	1.008	62.31	1048.52	0.5595
12	4.09E + 05	6.67	26.595	67.5	19.7	34.5	2.38	1.009	62.31	1047.05	0.5588
13	3.24E + 05	5.27	16.488	67.5	19.7	36.4	2.51	1.008	62.31	827.35	0.5608
14	3.24E + 05	5.29	16.780	67.5	19.7	36.4	2.51	1.008	62.31	829.84	0.5576
15	2.01E + 05	3.27	6.402	67.6	19.8	38.3	2.64	1.007	62.31	513.85	0.5590
16	1.99E + 05	3.23	6.194	67.6	19.8	38.3	2.64	1.007	62.31	507.30	0.5610
17	1.56E + 05	2.54	3.866	67.7	19.8	39.1	2.70	1.007	62.31	398.49	0.5578
18	1.59E + 05	2.59	4.033	67.6	19.8	39.1	2.70	1.007	62.31	406.78	0.5575
19	1.19E + 05	1.94	2.274	67.4	19.7	36.9	2.54	1.010	62.31	304.88	0.5565
20	1.21E + 05	1.97	2.365	67.4	19.7	36.9	2.54	1.010	62.31	309.76	0.5544

Reynolds Number Low Limit: 95851

Test Laboratory: Rosemount Boulder, Colorado Flow Lab

Sensor Size: 2
Fluid: Water
Sensor Serial Number: FI-163
Nominal Pipe Size: 3-in. Schedule 40

Test Date: December 19, 2000
Pipe I.D.: 8.006-in (203.4 mm)
Blockage: 16.57%
K_{pub}: 0.5589

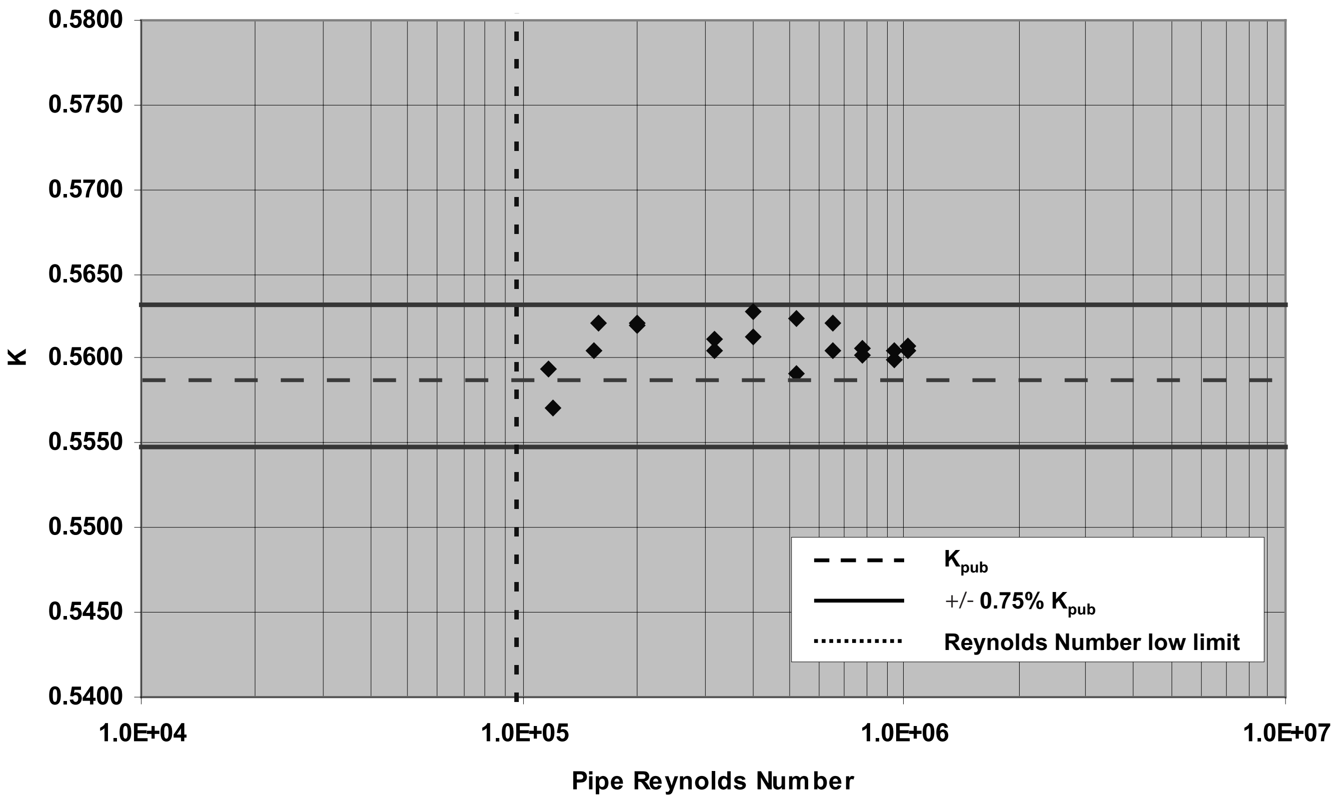


Table 5-7. Rosemount Boulder, Colorado Flow Lab, Water.

Data Point Number	Pipe Reynolds Number	Velocity	Differential Pressure	Temperature		Pressure		Viscosity	Density	Flow Rate	K
		ft/sec.	*in Water*	*°F*	*°C*	*psig*	*bar*	*cP*	*lb/ft^3*	*GPM*	
1	1.02E + 06	16.86	168.772	66.4	19.11	23.4	1.61	1.024	62.32	2645.00	0.5605
2	1.02E + 06	16.88	169.030	66.4	19.11	23.4	1.61	1.024	62.32	2648.52	0.5608
3	9.37E + 05	15.50	142.682	66.4	19.11	24.9	1.72	1.024	62.32	2431.94	0.5604
4	9.40E + 05	15.56	144.054	66.4	19.11	24.9	1.72	1.024	62.32	2441.24	0.5599
5	7.74E + 05	12.81	97.615	66.4	19.11	27.7	1.91	1.024	62.32	2010.45	0.5601
6	7.76E + 05	12.85	98.035	66.4	19.11	27.6	1.90	1.024	62.32	2016.53	0.5606
7	6.46E + 05	10.69	67.498	66.4	19.11	29.6	2.04	1.024	62.32	1677.80	0.5622
8	6.50E + 05	10.76	68.786	66.4	19.11	29.5	2.03	1.024	62.32	1688.54	0.5604
9	5.20E + 05	8.61	44.210	66.4	19.11	32.1	2.21	1.024	62.32	1350.52	0.5591
10	5.22E + 05	8.65	44.141	66.4	19.11	32.0	2.21	1.025	62.32	1357.34	0.5624
11	4.02E + 05	6.65	26.214	66.4	19.11	34.5	2.38	1.024	62.32	1043.95	0.5613
12	4.03E + 05	6.67	26.242	66.4	19.11	34.4	2.37	1.024	62.32	1047.24	0.5627
13	3.19E + 05	5.27	16.480	66.4	19.11	36.3	2.50	1.024	62.32	827.58	0.5612
14	3.20E + 05	5.29	16.649	66.4	19.11	36.3	2.50	1.024	62.32	830.79	0.5605
15	1.98E + 05	3.28	6.340	66.5	19.12	38.2	2.63	1.022	62.32	514.15	0.5621
16	1.98E + 05	3.28	6.348	66.5	19.12	38.2	2.63	1.023	62.32	514.42	0.5620
17	1.53E + 05	2.53	3.806	66.6	19.22	39.1	2.70	1.022	62.32	397.26	0.5605
18	1.59E + 05	2.62	4.047	66.5	19.12	39.0	2.69	1.022	62.32	410.80	0.5621
19	1.17E + 05	1.94	2.242	66.4	19.11	37.7	2.60	1.024	62.32	304.33	0.5594
20	1.19E + 05	1.98	2.345	66.4	19.11	37.6	2.60	1.024	62.32	309.91	0.5571
21	8.40E + 04	1.39	1.178	66.5	19.12	38.8	2.68	1.023	62.32	217.69	0.5522
22	8.51E + 04	1.41	1.214	66.5	19.12	38.9	2.68	1.023	62.32	220.67	0.5513

Reynolds Number Low Limit: 96035

Test Laboratory: Rosemount Boulder, Colorado Flow Lab

Sensor Size: 2	Test Date: December 14, 2000
Fluid: Water	Pipe I.D.: 10.020-in (254.5 mm)
Sensor Serial Number: FI-169	Blockage: 13.24%
Nominal Pipe Size: 10-in. Schedule 40	K_{pub}: 0.5766

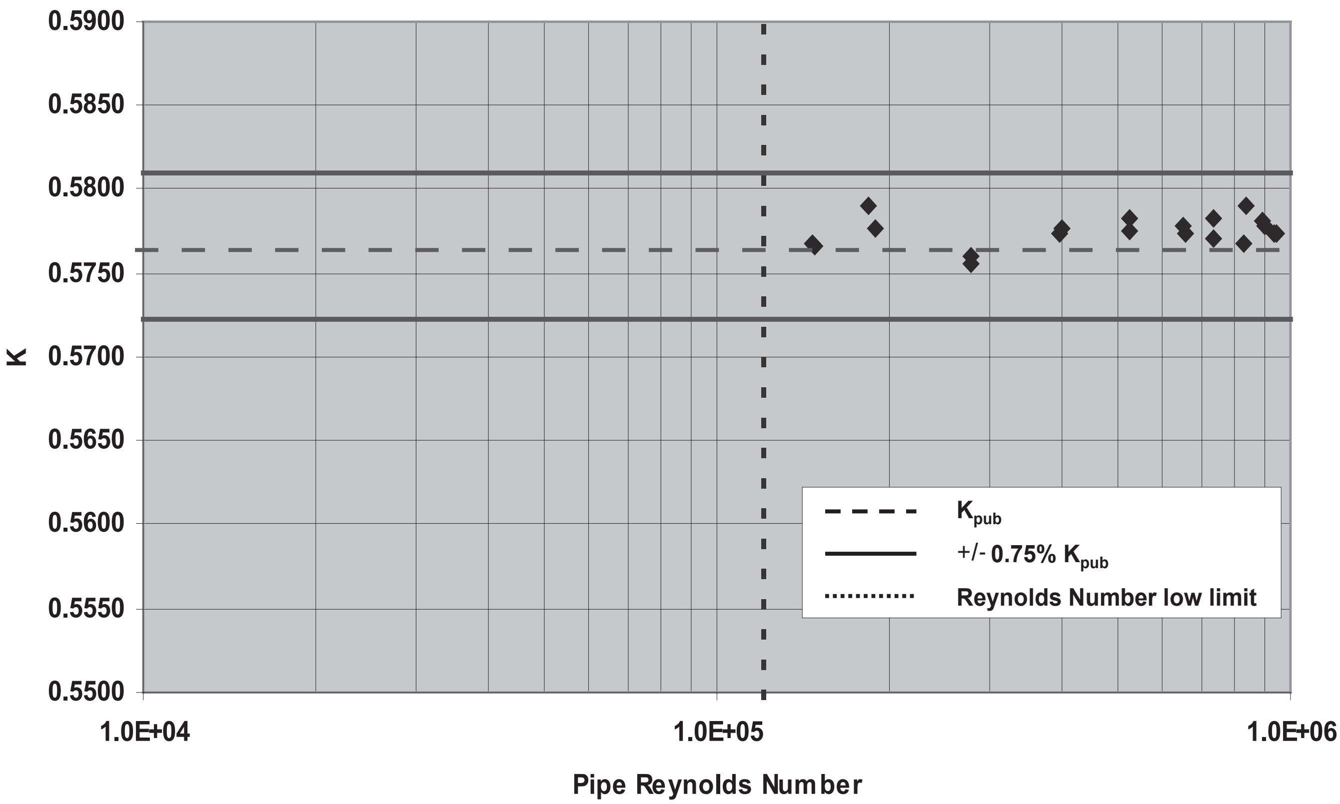


Table 5-8. Rosemount Boulder, Colorado Flow Lab, Water.

Data Point Number	Pipe Reynolds Number	Velocity	Differential Pressure	Temperature		Pressure		Viscosity	Density	Flow Rate	K
		ft/sec.	*in Water*	*°F*	*°C*	*psig*	*bar*	*cP*	*lb/ft^3*	*GPM*	
1	9.40E + 05	12.42	86.257	66.5	19.17	19.7	1.36	1.023	62.32	3053.31	0.5777
2	9.44E + 05	12.47	86.908	66.5	19.17	19.6	1.35	1.023	62.32	3065.38	0.5778
3	8.92E + 05	11.78	77.591	66.5	19.17	21.1	1.45	1.023	62.32	2895.02	0.5775
4	9.00E + 05	11.88	79.133	66.5	19.17	20.9	1.44	1.023	62.32	2920.24	0.5768
5	8.31E + 05	10.97	67.272	66.5	19.17	22.7	1.57	1.023	62.32	2697.62	0.5779
6	8.36E + 05	11.04	67.803	66.5	19.17	22.6	1.56	1.023	62.32	2714.69	0.5793
7	7.36E + 05	9.72	52.897	66.5	19.17	25.0	1.72	1.023	62.32	2389.81	0.5774
8	7.35E + 05	9.71	52.731	66.5	19.17	25.1	1.73	1.023	62.32	2386.74	0.5775
9	6.52E + 05	8.61	41.499	66.5	19.17	26.8	1.85	1.023	62.32	2115.39	0.5770
10	6.55E + 05	8.64	41.433	66.5	19.17	26.8	1.85	1.023	62.32	2124.83	0.5800
11	5.23E + 05	6.90	26.152	66.5	19.17	29.4	2.03	1.023	62.32	1696.60	0.5829
12	5.23E + 05	6.90	26.481	66.5	19.17	29.4	2.03	1.023	62.32	1696.31	0.5792
13	3.99E + 05	5.26	15.470	66.5	19.17	32.4	2.23	1.022	62.32	1293.20	0.5777
14	3.98E + 05	5.25	15.417	66.5	19.17	32.4	2.23	1.023	62.32	1290.32	0.5774
15	2.76E + 05	3.65	7.493	66.6	19.22	35.8	2.47	1.022	62.32	896.62	0.5756
16	2.77E + 05	3.66	7.518	66.6	19.22	35.8	2.47	1.022	62.32	898.83	0.5760
17	1.83E + 05	2.41	3.242	66.6	19.22	37.7	2.60	1.021	62.32	593.42	0.5791
18	1.89E + 05	2.49	3.453	66.6	19.22	37.6	2.59	1.021	62.32	610.98	0.5777
19	1.49E + 05	1.96	2.153	66.7	19.28	38.4	2.65	1.020	62.32	481.46	0.5766
20	1.47E + 05	1.93	2.090	66.7	19.28	38.4	2.65	1.020	62.32	474.56	0.5767

Reynolds Number Low Limit: 120202

Test Laboratory: SwRI Flow Lab and Rosemount Boulder, Colorado Flow Lab

Sensor Size: 2
Fluid: Natural gas (400 psi) and Water
Sensor Serial Number: FI-178
Nominal Pipe Size: 8-in. Schedule 80

Test Date: August 20, 2002 (SwRI), August 12, 2002 (DSI)
Pipe I.D.: 7.591-in (192.8 mm)
Blockage: 17.70%
K_{pub}: 0.5527

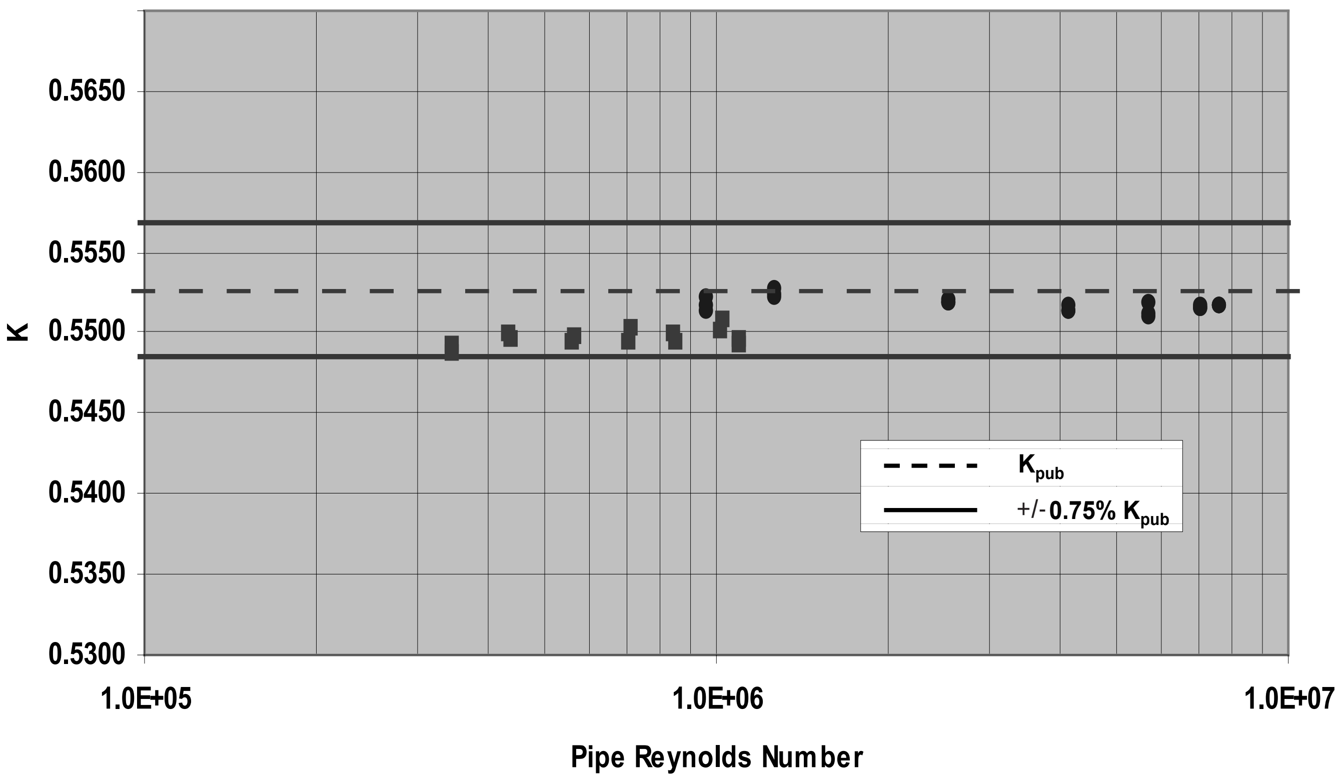


Table 5-9. SwRI Flow Labs, Natural Gas (400 psi)

File	Pressure	Temperature	Density	DP	Re D	K	Gas Exp. Factor	Probe Width	Mass Flow
	psia	*°F*	*lb/ft³*	*in H_2O*				in.	lb/s
000	399.2381	70.36406	1.264664	66.712	7612648	0.55186	0.99949	1.062	29.10727
001	399.2067	70.32793	1.264664	66.68185	7612393	0.55194	0.99949	1.062	29.10464
002	399.1785	70.35466	1.264492	66.67262	7611555	0.55197	0.99949	1.062	29.10245
003	401.0847	70.26102	1.271108	56.3852	7013626	0.55166	0.99957	1.062	26.81987
004	401.0365	70.26235	1.270862	56.38691	7012511	0.55161	0.99957	1.062	26.81553
005	401.0253	70.27148	1.270798	56.31914	7012143	0.55193	0.99957	1.062	26.81443
006	399.3239	70.3362	1.264849	37.65638	5720938	0.55183	0.99971	1.062	21.8737
007	399.3395	70.2757	1.265077	37.74814	5721538	0.55112	0.99971	1.062	21.87411
008	399.3772	70.27707	1.265199	37.72615	5722033	0.55131	0.99971	1.062	21.87617
009	398.9396	70.29922	1.263531	19.68531	4132344	0.55145	0.99985	1.062	15.79815
010	398.9114	70.32668	1.263357	19.68902	4131817	0.55138	0.99985	1.062	15.7967
011	398.8833	70.27533	1.263412	19.6594	4131944	0.55176	0.99985	1.062	15.79594
012	399.3192	70.55387	1.263538	7.45387	2544265	0.55195	0.99994	1.062	9.731082
013	399.2472	70.64496	1.263034	7.45405	2542988	0.55184	0.99994	1.062	9.727386
014	399.1706	70.67073	1.262704	7.45083	2542013	0.55184	0.99994	1.062	9.723914
015	399.5884	70.81895	1.263728	1.05499	958885	0.55309	0.99999	1.062	3.669006
016	399.414	70.77697	1.263284	1.05756	958396	0.55219	0.99999	1.062	3.666819
017	399.2506	70.66026	1.263075	1.05486	958057	0.55264	0.99999	1.062	3.664815
018	398.4257	69.58176	1.263432	1.82996	1265740	0.55333	0.99999	1.062	4.833638
019	398.424	69.60608	1.263355	1.8346	1265675	0.55264	0.99999	1.062	4.833563
020	398.4658	69.5973	1.263521	1.83347	1265838	0.55284	0.99999	1.062	4.83415

Table 5-10. Rosemount Boulder, Colorado Flow Lab, Water.

Data Point Number	Pipe Reynolds Number	Velocity	Differential Pressure	Temperature		Pressure		Viscosity	Density	Flow Rate	K
		ft/sec.	*in Water*	*°F*	*°C*	*psig*	*bar*	*cP*	*lb/ft³*	*GPM*	
1	1.10E + 06	18.798	218.205	67.9	19.9	23.4	1.61	1.003	62.31	2652.10	0.5496
2	1.10E + 06	18.766	217.799	68.2	20.1	23.4	1.61	0.999	62.31	2647.54	0.5492
3	1.03E + 06	17.563	189.676	68.3	20.2	24.7	1.70	0.998	62.30	2477.85	0.5507
4	1.02E + 06	17.356	185.657	68.4	20.2	24.8	1.71	0.997	62.30	2448.66	0.5501
5	8.46E + 05	14.359	127.131	68.5	20.3	27.6	1.90	0.995	62.30	2025.88	05500
6	8.50E + 05	14.399	128.115	68.6	20.3	27.6	1.90	0.994	62.30	2031.52	0.5494
7	7.05E + 05	11.946	88.169	68.6	20.3	29.7	2.05	0.994	62.30	1685.45	0.5494
8	7.08E + 05	11.987	88.495	68.6	20.3	29.7	2.05	0.994	62.30	1691.21	0.5503
9	5.63E + 05	9.534	56.159	68.6	20.3	32.1	2.21	0.993	62.30	1345.12	0.5494
10	5.67E + 05	9.608	56.961	68.6	20.3	32.0	2.21	0.993	62.30	1355.48	0.5498
11	4.35E + 05	7.364	33.437	68.7	20.4	34.4	2.37	0.993	62.30	1038.89	0.5499
12	4.40E + 05	7.442	34.197	68.7	20.4	34.3	2.36	0.993	62.30	1049.99	0.5496
13	3.44E + 05	5.827	20.989	68.7	20.4	36.2	2.50	0.992	62.30	822.03	0.5492
14	3.47E + 05	5.873	21.365	68.7	20.4	36.2	2.50	0.992	62.30	828.55	0.5487

Test Laboratory: SwRI Flow Labs and Rosemount Boulder, Colorado Flow Lab

Sensor Size: 2
Fluid: Natural gas (400 psi) and Water
Sensor Serial Number: FI-179
Nominal Pipe Size: 8-in. Schedule 80

Test Date: August 20, 2002 (SwRI), August 12, 2002 (DSI)
Pipe I.D.: 7.591-in (192.8 mm)
Blockage: 17.70%
K_{pub}: 0.5527

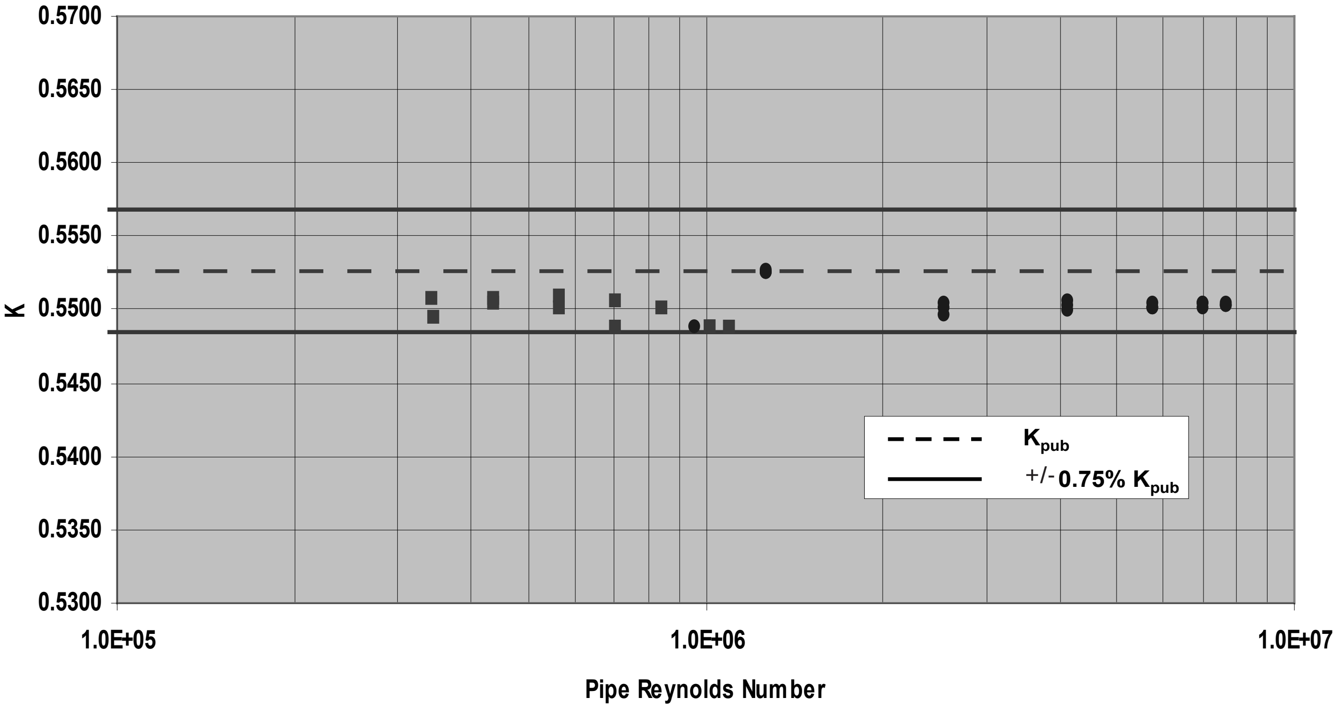


Table 5-11. SwRI Flow Labs, Natural Gas (400 psi)

File	Pressure	Temperature	Density	DP	Re D	K	Gas Exp. Factor	Probe Width	Mass Flow
	psia	*°F*	*lb/ft^3*	*in H_2O*				in.	lb/s
022	400.5934	70.09192	1.26894	67.19104	7636204	0.55056	0.99949	1.062	29.19194
023	400.5734	70.11051	1.268819	67.15411	7634966	0.55067	0.99949	1.062	29.18791
024	400.5566	70.02399	1.269014	67.15976	7635645	0.55058	0.99949	1.062	29.18677
025	400.1057	70.14067	1.267159	56.44205	6991771	0.55035	0.99957	1.062	26.72838
026	400.0123	70.13284	1.266849	56.37616	6989717	0.55057	0.99957	1.062	26.71984
027	400.0015	70.0372	1.267091	56.36834	6990797	0.55056	0.99957	1.062	26.72022
028	400.3373	70.21033	1.267706	37.88483	5730654	0.55046	0.99971	1.062	21.91022
029	400.269	70.10329	1.267769	37.9004	5730493	0.55023	0.99971	1.062	21.90594
030	400.1888	69.96667	1.267898	37.90305	5731232	0.55014	0.99971	1.062	21.90417
031	399.6013	69.87253	1.266207	19.74952	4137256	0.55034	0.99985	1.062	15.80868
032	399.5592	69.84549	1.266144	19.76687	4137037	0.55006	0.99985	1.062	15.80713
033	399.5333	69.77977	1.266249	19.73404	4137651	0.55052	0.99985	1.062	15.80791
034	399.5284	70.37971	1.26449	7.5027	2542949	0.54953	0.99994	1.062	9.723809
035	399.3698	70.32362	1.264122	7.48151	2541621	0.55004	0.99994	1.062	9.717724
036	399.2254	70.17006	1.264083	7.46435	2540924	0.5504	0.99994	1.062	9.712693
037	398.3805	69.89757	1.262096	1.83461	1263339	0.55212	0.99999	1.062	4.826624
038	398.196	69.68668	1.262089	1.83028	1263176	0.55252	0.99999	1.062	4.824399
039	398.0698	69.56982	1.262005	1.8311	1262935	0.5522	0.99999	1.062	4.822573
040	399.5883	69.26618	1.267972	1.06446	958785	0.54841	0.99999	1.062	3.660332
041	399.4414	69.1862	1.267713	1.06426	958549	0.54831	0.99999	1.062	3.658928
042	399.3669	69.1327	1.267599	1.06372	958345	0.54831	0.99999	1.062	3.657825

Table 5-12. Rosemount Boulder, Colorado Flow Lab, Water.

Data Point Number	Pipe Reynolds Number	Velocity	Differential Pressure	Temperature		Pressure		Viscosity	Density	Flow Rate	K
		ft/sec.	*in Water*	*°F*	*°C*	*psig*	*bar*	*cP*	*lb/ft^3*	*GPM*	
1	1.09E + 06	18.731	217.392	67.5	19.7	23.4	1.61	1.008	62.31	2642.59	0.5487
2	1.10E + 06	18.783	218.619	67.8	19.9	23.3	1.61	1.005	62.31	2649.95	0.5486
3	1.01E + 06	17.333	186.289	67.9	19.9	24.8	1.71	1.004	62.31	2445.36	0.5485
4	1.02E + 06	17.353	186.452	68.0	20.0	24.7	1.70	1.002	62.31	2448.23	0.5489
5	8.41E + 05	14.353	126.967	68.1	20.1	27.5	1.90	1.001	62.31	2025.02	0.5501
6	8.43E + 05	14.362	128.085	68.2	20.1	27.5	1.90	0.999	62.31	2026.28	0.5481
7	7.02E + 05	11.936	88.252	68.3	20.2	29.6	2.04	0.998	62.30	1683.93	0.5487
8	7.05E + 05	11.983	88.378	68.4	20.2	29.6	2.04	0.997	62.30	1690.66	0.5505
9	5.64E + 05	9.567	56.423	68.5	20.3	32.0	2.21	0.995	62.30	1349.74	0.5500
10	5.65E + 05	9.576	56.368	68.6	20.3	32.0	2.21	0.994	62.30	1351.00	0.5508
11	4.36E + 05	7.383	33.529	68.6	20.3	34.4	2.37	0.993	62.30	1041.66	0.5507
12	4.37E + 05	7.410	33.805	68.6	2.3	34.3	2.36	0.994	62.30	1045.43	0.5504
13	3.44E + 05	5.826	20.874	68.7	20.4	36.2	2.50	0.993	62.30	821.93	0.5507
14	3.46E + 05	5.853	21.162	68.6	20.3	36.1	2.49	0.993	62.30	825.71	0.5494
15	2.17E + 05	3.662	8.351	68.7	20.4	37.8	2.61	0.992	62.30	516.64	0.5472
16	2.18E + 05	3.691	8.474	68.7	2.4	37.8	2.61	0.992	62.30	520.75	0.5476

Test Laboratory: SwRI Flow Labs

Sensor Size: 2	Test Date: August 20, 2002
Fluid: Natural gas (400 psi)	Pipe I.D.: 6.059-in (153.9 mm)
Sensor Serial Number: FI-180	Blockage: 22.17%
Nominal Pipe Size: 6-in. Schedule 40	K_{pub}: 0.5257

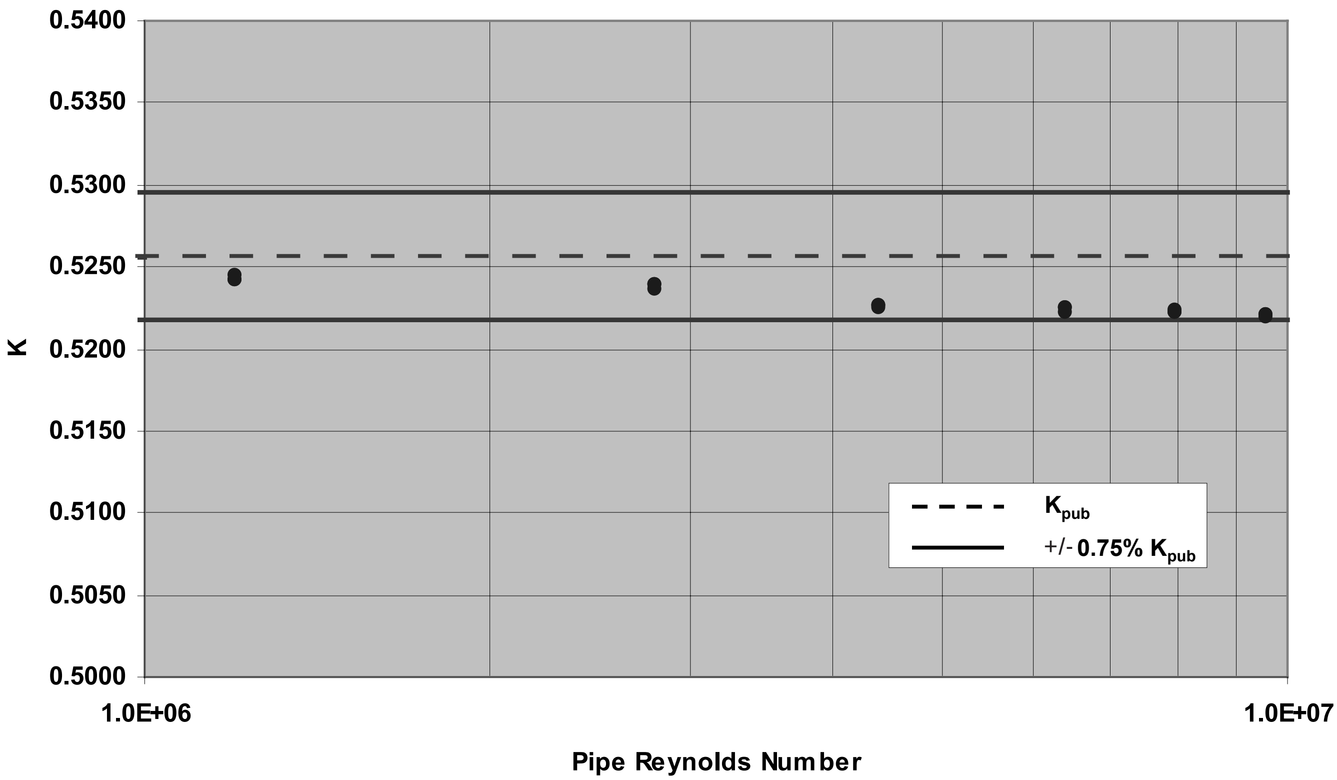


Table 5-13. SwRI Flow Labs, Natural Gas (400 psi)

File	Pressure	Temperature	Density	DP	Re D	K	Gas Exp. Factor	Probe Width	Mass Flow
	psia	*°F*	*lb/ft³*	*in H_2O*				in.	lb/s
044	402.2264	69.78825	1.275065	183.1904	9572419	0.52261	0.99888	1.062	29.20216
045	402.2249	69.78545	1.275068	183.1652	9571925	0.52262	0.99888	1.062	29.20053
046	402.2003	69.78291	1.274993	183.2267	9571523	0.52252	0.99888	1.062	29.19909
047	401.3388	69.80605	1.272042	127.3168	7973641	0.52258	0.99922	1.062	24.3224
048	401.324	69.81554	1.271968	127.2576	7973870	0.52273	0.99922	1.062	24.32337
049	401.2841	69.82552	1.271805	127.3385	7973102	0.52255	0.99922	1.062	24.32124
050	400.6831	69.95078	1.269517	81.63868	6380432	0.52263	0.9995	1.062	19.46474
051	400.6703	69.78475	1.269958	81.62017	6382775	0.52267	0.9995	1.062	19.46715
052	400.6707	69.83695	1.26979	81.6921	6382281	0.52247	0.9995	1.062	19.46712
053	399.7075	69.59795	1.267281	38.66373	4391472	0.52268	0.99976	1.062	13.38829
054	399.6934	69.57008	1.267315	38.6696	4391638	0.52263	0.99976	1.062	13.38823
055	399.7024	69.64079	1.26714	38.67824	4391271	0.52262	0.99976	1.062	13.3885
056	398.9556	69.13239	1.266025	15.53221	2790645	0.52382	0.9999	1.062	8.501159
057	398.9794	69.18728	1.265945	15.53455	2790692	0.52385	0.9999	1.062	8.50201
058	398.9846	69.26121	1.265675	15.55648	2790406	0.52354	0.9999	1.062	8.502069
059	399.77	70.43433	1.264888	2.89146	1202055	0.52419	0.99998	1.062	3.669187
060	399.5529	70.87255	1.262895	2.8918	1200207	0.52408	0.99998	1.062	3.665766
061	399.2911	71.17313	1.261155	2.89022	1198483	0.52404	0.99998	1.062	3.66196

Test Laboratory: SwRI Flow Labs

Sensor Size: 2
Fluid: Natural gas (400 psi)
Sensor Serial Number: FI-181
Nominal Pipe Size: 6-in. Schedule 40

Test Date: August 21, 2002
Pipe I.D.: 6.059-in (153.9 mm)
Blockage: 22.17%
K_{pub}: 0.5257

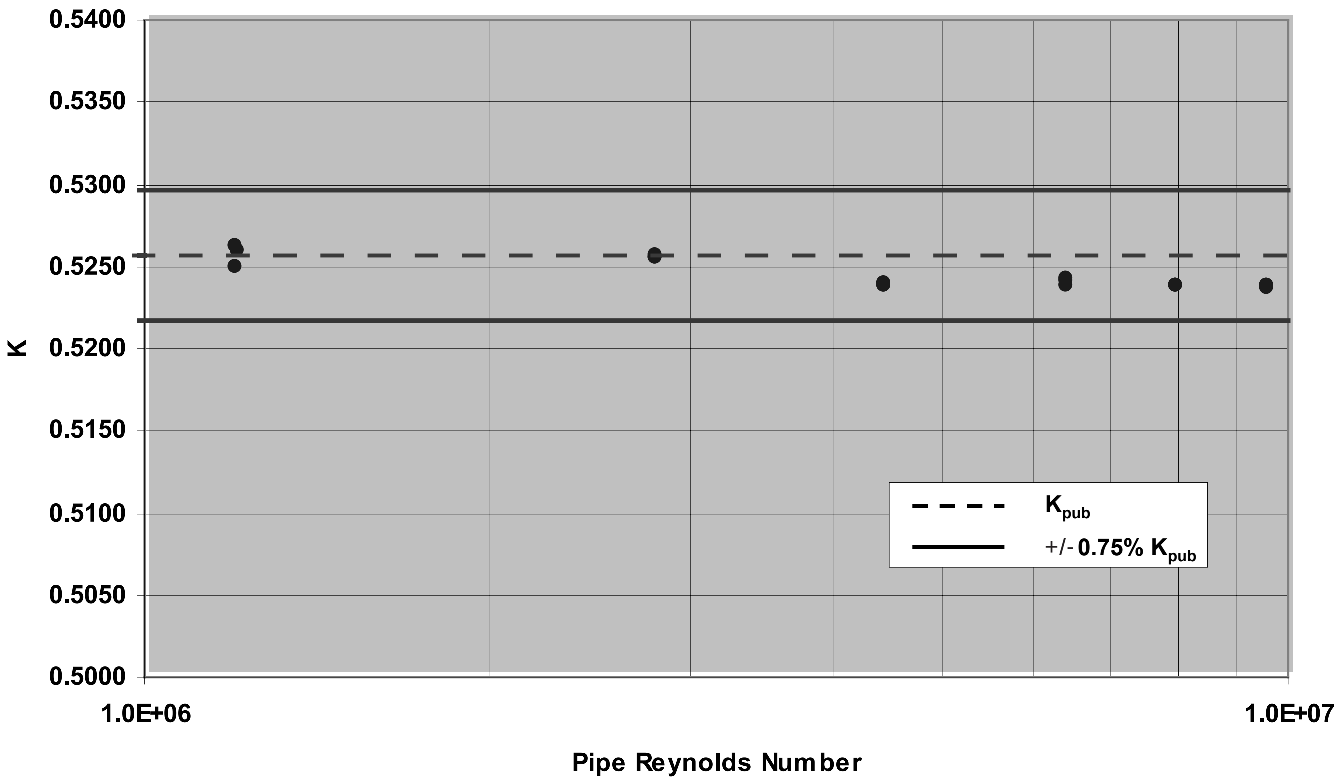


Table 5-14. SwRI Flow Labs, Natural Gas (400 psi)

File	Pressure	Temperature	Density	DP	Re D	K	Gas Exp. Factor	Probe Width	Mass Flow
	psia	*°F*	*lb/ft^3*	*in H_2O*				in.	lb/s
000	402.1318	70.22332	1.273031	182.2164	9567169	0.52445	0.99888	1.062	29.20375
001	402.1396	70.23601	1.27302	182.2515	9565927	0.52435	0.99888	1.062	29.20053
002	402.1459	70.20831	1.273122	182.2548	9566150	0.52431	0.99888	1.062	29.20007
003	401.4724	70.12239	1.271117	126.7637	7974761	0.52422	0.99922	1.062	24.33706
004	401.4468	70.15948	1.270924	126.7554	7973279	0.5242	0.99922	1.062	24.33376
005	401.4389	70.22195	1.270708	126.6872	7971112	0.52429	0.99922	1.062	24.32932
006	400.8714	70.22616	1.268799	81.33865	6382353	0.52412	0.9995	1.062	19.47868
007	400.8555	70.18685	1.26886	81.21389	6382646	0.5245	0.9995	1.062	19.47842
008	400.7853	70.12505	1.268806	81.24182	6382324	0.52434	0.9995	1.062	19.4755
009	403.3504	69.91417	1.278022	38.91319	4431173	0.524	0.99976	1.062	13.52238
010	403.3576	69.91348	1.278048	38.9336	4431585	0.52391	0.99976	1.062	13.52364
011	403.3601	69.92616	1.278038	38.91548	4431612	0.52405	0.99976	1.062	13.52397
012	399.7687	70.02187	1.266071	15.51266	2794122	0.52552	0.9999	1.062	8.523624
013	399.7375	69.97731	1.266096	15.51172	2794003	0.52547	0.9999	1.062	8.522671
014	399.6968	69.91672	1.266136	15.49649	2793974	0.52567	0.9999	1.062	8.521782
015	399.6242	70.38922	1.264523	2.87541	1202830	0.52601	0.99998	1.062	3.671184
016	399.5218	70.62444	1.2635	2.87366	1201883	0.52614	0.99998	1.062	3.669494
017	399.4349	70.80791	1.26268	2.88596	1201079	0.52497	0.99998	1.062	3.66797

SENSOR SIZE 3

Test Laboratory: Alden Research Labs	
Sensor Size: 3	Test Date: July 25, 2001
Fluid: Water	Pipe I.D.: 23.340-in (592.8 mm)
Sensor Serial Number: FI-307	Blockage: 10.47%
Nominal Pipe Size: 24-in. Schedule Standard	K_{pub}: 0.5845

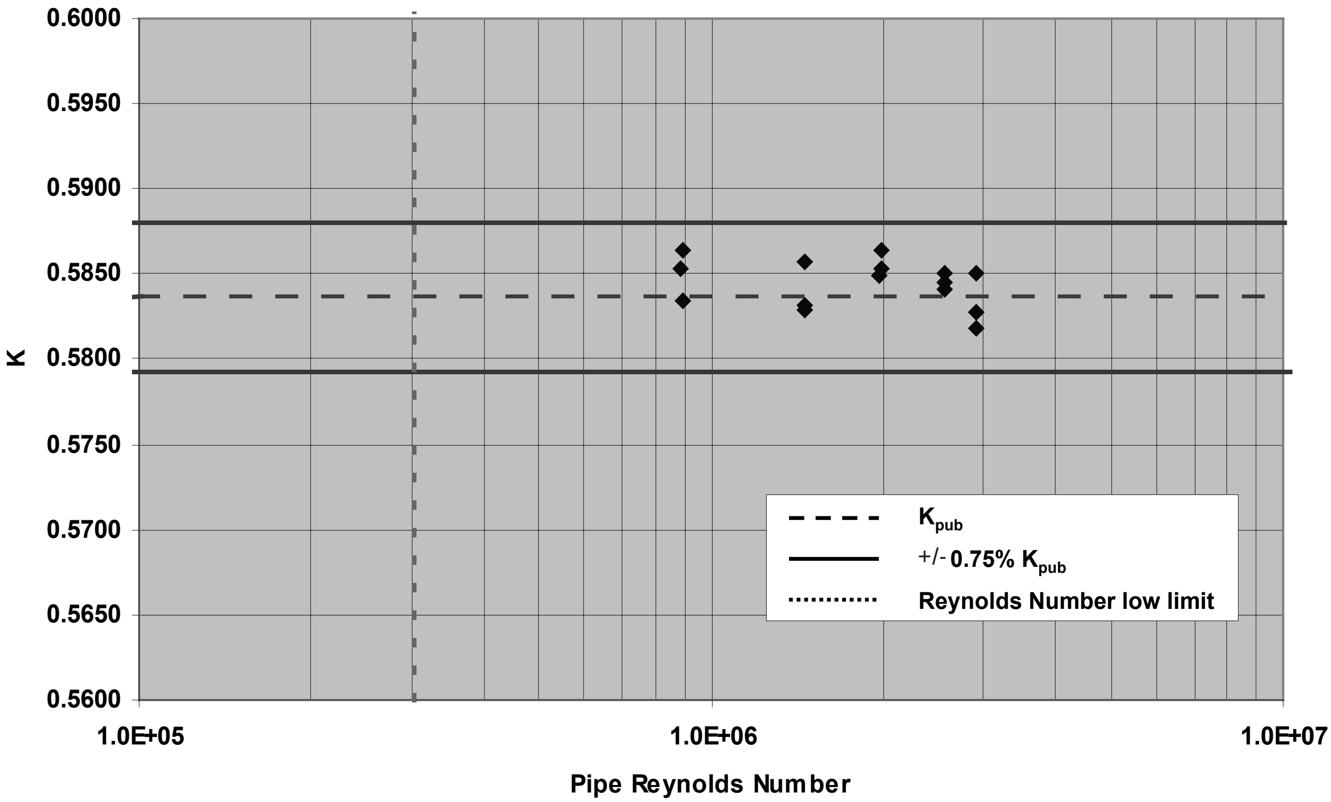


Table 5-15. Alden Research Labs, Water.

Run Number	Line Temp		Air Temp		Net Weight		Run Duration	mA Square Root Output	Flow	Differential Head	Pipe Reynold Number	K
	°F	*°C*	*°F*	*°C*	*lb*	*kg*	*seconds*		*GPM*	*Inch W/C*	*x 10^6*	
1	107	41.5	95	35	97008	44002	40.024	16.7074	17592	94.790	3.6997	0.5829
2	107	41.5	95	35	96976	43987	40.017	16.7274	17590	95.088	3.7028	0.5820
3	107	41.5	95	35	97022	44008	40.093	16.6368	17565	93.741	3.6976	0.5853
4	107	41.5	95	35	96403	43727	44.924	15.2151	15576	73.852	3.2855	0.5848
5	107	41.5	95	35	96375	43715	44.969	15.2099	15557	73.784	3.2813	0.5844
6	107	41.5	95	35	96306	43684	44.876	15.2076	15578	73.754	3.2890	0.5852
7	107	41.5	95	35	95867	43485	57.724	12.6661	12056	44.124	2.5479	0.5855
8	107	41.5	95	35	96041	43564	57.810	12.6539	12060	44.000	2.5513	0.5867
9	107	41.5	95	35	95863	43483	57.746	12.6681	12051	44.144	2.5521	0.5852
10	107	41.5	95	35	95307	43231	77.732	19.7422	8901	24.253	1.8868	0.5832
11	108	42.2	95	35	95388	43267	77.879	19.6499	8892	23.970	1.8868	0.5859
12	108	42.2	95	35	95370	43259	77.865	19.7187	8892	24.180	1.8887	0.5834
13	108	42.2	95	35	94838	43017	126.452	13.5666	5445	8.969	1.1577	0.5867
14	108	42.2	95	35	94929	43059	126.555	13.6116	5446	9.053	1.1579	0.5837
15	108	42.2	95	35	94885	43039	126.432	13.5905	5449	9.014	1.1596	0.5855
Reynolds Number Low Limit: 303906												

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Index

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