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Carbon Dioxide as a Test Fluid for Calibration of Turbine Meters

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Abstract

Terasen Gas Inc., a natural gas transmission and distribution utility in British Columbia, Canada, has proposed building a test facility for turbine gas meters using carbon dioxide as the test medium. This paper describes the advantages of using carbon dioxide as a test fluid for calibrating turbine meters. It also describes the design and results of a research program conducted at Southwest Research Institute in the fall of 2003. The program investigated the suitability of carbon dioxide for use in this application, through comparison of calibrations in carbon dioxide and natural gas.

Introduction

Transmission and distribution companies that use turbine meters for natural gas custody transfer rely on accurate meter calibrations to reduce measurement error and associated expenses related to 'unaccounted-for' gas volumes. The calibration factor of a turbine meter, whether mechanical revolutions per unit volume or electronic pulses per unit volume, is related to the line pressure, flow rate and composition of the gas stream. As stated in the current U.S. natural gas industry standard for turbine flow meter technology, American Gas Association Report No. 7, *Measurement of Gas by Turbine Meters* [1], "…the most accurate turbine meter performance is obtained when each meter is calibrated under density conditions approaching the meter's actual operating density." The upcoming revision to this document, scheduled for publication next year, will also recommend that turbine meters be calibrated under conditions that reflect the operating conditions where the meter will be used in the field.

Many turbine meter manufacturers calibrate their meters in air at atmospheric pressures and provide this data to meter users. However, for the meter to measure natural gas flows accurately at typical line pressures, they must be calibrated under similar conditions. Some manufacturers have facilities at which their meters can be calibrated in air at higher line pressures. These facilities can simulate high-pressure natural gas flows, but because of the wide operational range of turbine meters, they may not be able to match all the flow variables that a turbine meter will encounter in the field. This paper presents the results of a study, sponsored by Terasen Gas Inc., to determine the suitability of carbon dioxide gas as a test fluid for turbine meters used for natural gas custody transfer.

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The Use of Dynamic Similarity in Calibrating Natural Gas Turbine Meters

Although many turbine meter users apply a single constant calibration factor to compute flow rates, it is common practice to report calibration data as a function of flow rate and line pressure. It is generally known that natural gas turbine meter performance varies significantly with line pressure, particularly at lower pressures and flow rates. While these changes in performance are sometimes referred to as 'pressure effects' in the industry, they are actually related to changes in the density of the flowing gas with pressure, as expressed by the basic gas law:

$$P = \rho ZRT \,. \tag{1}$$

As the absolute line pressure, P, increases by a certain fraction, the density of the flowing gas, ρ, will increase by approximately the same fraction, influenced by the gas compressibility, Z. The rise in density will affect the drag on the turbine rotor, causing it to rotate at a different speed for a given volumetric flow rate.

As discussed in the current edition of AGA Report No. 7 [1], two types of drag can influence the behavior of a turbine rotor:

- Non-fluid drag in the rotor bearings and other meter mechanisms, which reflects the inertia and effective weight of the moving rotor. This type of drag varies with the density of the gas, and is most pronounced at low gas densities. Instead of the misnomer of 'pressure effect,' which is sometimes used to describe this type of drag, the term 'density-related effect' is used in this paper to emphasize the relationship between density and mechanical, non-fluid drag.

- Fluid drag on the rotor blades and hub, which is a function of Reynolds number.

The Reynolds number is a dimensionless number related to the gas flow rate, the meter tube diameter, and the properties of the gas. For a gas of density ρ and viscosity μ, flowing through a pipe of diameter D at velocity V, the Reynolds number is given by

$$\mathrm{Re} = \frac{\rho VD}{\mu} \,. \tag{2}$$

Figure 1 (on the next page) is a graph of calibration data from a typical natural gas turbine meter. The graph demonstrates how both types of drag can affect the rotor speed and calibration factor of a meter. In the figure, the calibration factor (or K factor) is plotted as a function of Reynolds number for different gas densities to show how the meter performance is best described by these quantities, rather than by line pressure and volumetric flow rate. This graph also demonstrates the need for calibrating meters at conditions that replicate field operating conditions. At low volumetric flow rates, the calibration factor for this meter varies by over 1% between natural gas line pressures of 30 psig (corresponding to a density of 0.14 lb_m/ft^3) and 700 psig (where the density is 2.30 lb_m/ft^3).

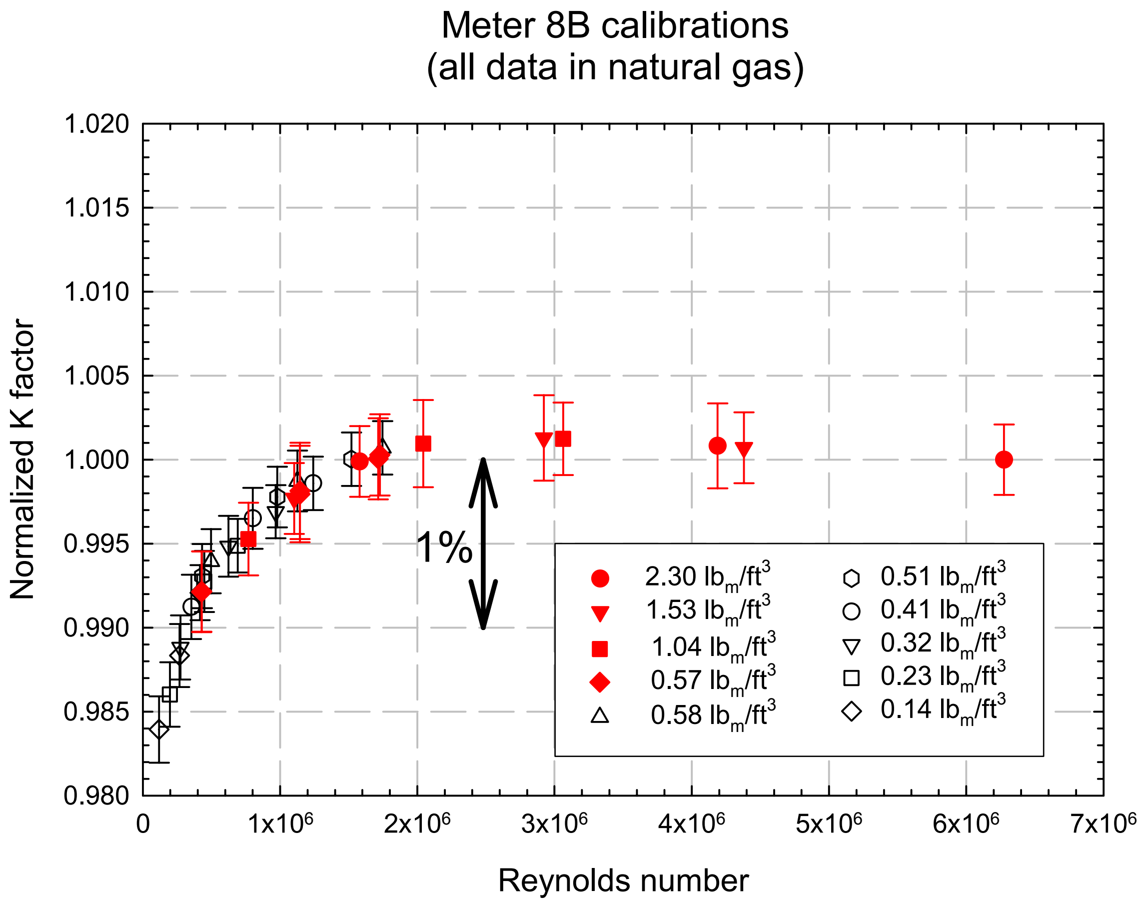

Figure 1. Example of the dependence of turbine meter performance on Reynolds number and gas density [2]. The data was collected from an 8-inch diameter turbine meter calibrated in natural gas at the Metering Research Facility (MRF) at SwRI. Closed red symbols denote data collected in the High Pressure Loop, while open symbols denote data collected in the Low Pressure Loop.

For best accuracy, a turbine meter calibration must be performed so that the forces and dynamic loads on the rotor are the same under test conditions as under field conditions where the meter will be used. Both the values of gas density and Reynolds number found in the field must be recreated in the calibration facility to exactly duplicate the meter's fluid and non-fluid drag response to a gas flow. This principle of matching forces on a test object to forces that the actual object will encounter when in use is known as 'dynamic similarity.' This principle allows a turbine meter to be accurately calibrated in fluids other than natural gas, just as it allows engineers to assess the performance of dams and airplanes using test data from scale models [3].

As an example, suppose a 4-inch-diameter, standard capacity turbine meter (maximum flow rate 18,000 actual cubic feet per hour) is to be installed in a natural gas distribution line at 150 psig that will carry gas at flow rates from 1,600 to 16,000 actual cubic feet per hour (acfh). However, it has been proposed to calibrate the meter at an air facility rather than a natural gas facility. By choosing matching test conditions – that is, by applying dynamic similarity – calibration conditions can be proposed for the air facility that can be used accurately in the field without correction. Table 1 shows the properties of natural gas and the range of gas velocities that would be encountered at the field site. The values of gas density and Reynolds number in natural gas will be used in applying similarity to the tests in air.

Table 1. Properties of a natural gas flow in a 4-inch pipeline at 150 psig and 60ºF.

Line pressure	150 psig
Gas density	0.5191 lb_m/ft^3
Gas viscosity	0.01086 cp
Range of flow rates	1,600 – 16,000 acfh
Range of gas velocities in 4-inch pipe	5.09 – 50.9 ft/s
Reynolds number range	120,700 – 1,207,000

To match the natural gas density (and non-fluid drag forces) during tests, the meter could be tested in air at 85 psig, which has the same density as natural gas at 150 psig. Next, flow rates in air would be chosen to match the Reynolds numbers (and drag forces) expected by the meter in natural gas service. Table 2 shows the properties of air at the planned test condition of 85.1 psig. Because of the difference in viscosity between natural gas and air, the range of flow rates in air during the tests would need to be approximately 2,610 to 26,100 acfh to achieve dynamic similarity.

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Table 2. Properties of an air flow dynamically similar to the natural gas flow in Table 1.

Air density (matched to natural gas)	0.5191 lb_m/ft^3
Reynolds number range (matched to natural gas)	120,700 – 1,207,000
Line pressure at 60ºF to obtain 0.5191 lb_m/ft^3 air density	85.1 psig
Air viscosity at 85.1 psig line pressure, 60ºF	0.01774 cp
Range of air velocities in 4-inch pipe (to match gas Reynolds numbers at given air density and viscosity)	8.32– 83.2 ft/s
Range of test flow rates in air	2,610 – 26,100 acfh

If the meter could be tested in 85-psig air between 2,610 and 26,100 acfh, the resulting calibration curve, plotted versus Reynolds number, could be used without correction in the 150-psig distribution line flowing natural gas between 1,600 and 16,000 acfh. The values of Reynolds number need only be converted to volume flow rates of 150-psig natural gas to apply the calibration in the field. One strong disadvantage of this planned approach, however, is that higher flow rates in air are required to match Reynolds numbers in natural gas. This could limit the range of attainable test conditions in air if the maximum test flow rate were to overspin the turbine rotor. In the case of the 4-inch standard capacity turbine meter, dynamically similar tests in air are only possible up to a Reynolds number of approximately 830,000, since the flow rates needed for similarity at higher Reynolds numbers are above the meter's maximum rating of 18,000 acfh. For many commercially available natural gas turbine meters, the calibration factor approaches a constant value at large Reynolds numbers. It is conceivable that data taken in air at low Reynolds numbers and densities could produce calibration factors useful at the conditions of interest in natural gas. However, the 'threshold' at which the meter performance becomes independent of Reynolds number and gas density would still have to be confirmed experimentally, using data over the full range of conditions for which the meter is rated.

The Use of Carbon Dioxide as a Calibration Gas

In 2003, personnel from Terasen Gas began plans to convert an existing metering facility to a calibration facility for turbine meters. Practical considerations at the site dictated that natural gas could not be used as the test medium, so other gases were investigated. One test gas considered for the site was carbon dioxide, which is readily available from industrial gas suppliers. To continue the example given earlier, Table 3 shows the properties of CO_2 at 49.4 psig, which also has the same density as natural gas at 150 psig and therefore matches the non-fluid drag forces to be experienced by the meter in the natural gas line. Carbon dioxide has a higher molecular weight than air, and can attain the desired density at line pressures even lower than air. This is an advantage both from a compression standpoint and in terms of the required pressure ratings of pipe and other equipment. To obtain the Reynolds numbers (and drag forces) expected during use of the meter in natural gas, flow rates in CO_2 during the tests would range from 2,130 to 21,300 acfh. Again, because of the higher viscosity of CO_2 relative to natural gas, the meter must be tested at higher volumetric flow rates to achieve the Reynolds numbers expected in the field. However, the increase in volume flow rates in carbon dioxide over natural gas is not as high as is required to achieve dynamic similarity with air, and the meter could be safely tested in carbon dioxide at Reynolds numbers up to 1,000,000 without exceeding the upper flow rate limit of the meter.

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Table 3. Properties of a carbon dioxide flow dynamically similar to the natural gas flow in Table 1.

CO_2 density (matched to natural gas)	0.5191 lb_m/ft^3
Reynolds number range (matched to natural gas)	120,700 – 1,207,000
Line pressure at 60ºF to obtain 0.5191 lb_m/ft^3 CO_2 density	49.4 psig
CO_2 viscosity at 49.4 psig line pressure, 60ºF	0.01447 cp
Range of CO_2 velocities in 4-inch pipe (to match gas Reynolds numbers at given CO_2 density and viscosity)	6.79 – 67.9 ft/s
Range of test flow rates in CO_2	2,130 – 21,300 acfh

Calibrating the meter in carbon dioxide in this way presents at least three practical advantages: (1) carbon dioxide, like air, is more easily handled than natural gas; (2) the lower pressures require less work to compress the test gas to the required density, compared to both natural gas and air; and (3) no density-related corrections would be needed to improve the accuracy of the calibration in the field. With these advantages in mind, Terasen Gas sponsored tests at Southwest Research Institute to validate the use of carbon dioxide as a calibration gas. The objective of the tests was to compare turbine flow meter performance in natural gas and carbon dioxide, over a large Reynolds number range, to determine if the effects of fluid density and Reynolds number on turbine meter performance were similar for the two gases. If the two gases produced similar calibrations at similar gas densities and Reynolds numbers, the results would support the use of carbon dioxide as a calibration fluid for turbine meters.

Dual-Fluid Tests at the MRF

A total of six turbine meters were tested for this project at the Metering Research Facility (MRF) at Southwest Research Institute in late 2003. Tests of the meters were conducted using different combinations of test fluid (natural gas and carbon dioxide) and line pressure. The natural gas was a typical distribution-quality blend available at the MRF, nominally 94% methane, 1% carbon dioxide and 1% nitrogen, with the remaining balance made up of typical hydrocarbons (ethane through nonane.) For the carbon dioxide testing, a local industrial gas distributor provided carbon dioxide of nominal 99.94% purity. The MRF utilized the Low Pressure Loop (LPL) for meter calibrations in both test gases over a pressure range of 45 to 190 psia (3 to 13 bar). The High Pressure Loop (HPL) was used to test the meters in natural gas only, over a pressure range of 230 to 465 psia (16 to 32 bar). At each line pressure, calibration factors were determined at five to seven flow rates. The test conditions were selected to determine the calibration factor over a range of Reynolds numbers, and at overlapping ranges of gas densities.

For both the LPL and HPL tests, the reference flow rate was provided by a bank of critical Venturi nozzles (sonic nozzles). The sonic nozzle bank in each loop is traceable through a primary weigh tank system to the U.S. National Institute of Standards and Technology (NIST). Sonic nozzle calibrations are checked regularly using the weigh tank system to verify the nozzle discharge coefficients for natural gas. The LPL nozzles were also calibrated separately using carbon dioxide before the meter tests in carbon dioxide were performed.

Test Meters

Terasen Gas provided six single-rotor turbine meters for testing at the MRF. As shown in Table 4, the six test meters consisted of two 4-inch diameter meters, two 8-inch diameter meters, and two 12-inch diameter meters. One meter of each line size was an Instromet X-Series turbine meter with ANSI 600 flanges, while the other was an Invensys Mark II meter with ANSI 300 flanges.

Table 4. Test meters provided by Terasen Gas for the dual-fluid test program at the MRF.

Line diameter	Manufacturer and model	Flow capacity	Maximum flow rate (scfh)
4-inch	Instromet X-Series	Standard	18,000
	Invensys Mark-II T-18	Standard	18,000
8-inch	Instromet X-Series	Standard	60,000
	Invensys Mark-II T-60	Standard	60,000
12-inch	Instromet X-Series	Standard	150,000
	Invensys Mark-II T-230	Extended	230,000

Installation Configurations and Instrumentation

Both meters of the same line size were tested in series, in order to reduce test time. Installation effects on the meters were minimized by using Canada Pipeline Accessories Company Ltd. (CPA) 50E Type A flow conditioners upstream of the meters, and by placing a sufficient length of straight pipe between the meters. The nominal installations consisted of a minimum of 5 nominal pipe diameters of straight pipe upstream of the flow conditioner, followed by a minimum of 8 pipe diameters of straight pipe between the flow conditioner and the test meter. The nominal installations also included a minimum of 5 pipe diameters of straight pipe downstream of the meter. These configurations were chosen to conform to requirements of AGA Report No. 7 [1] and the flow conditioner manufacturer's recommendations.

The actual installation configurations used in the tests are shown in Figures 2 through 4. The piping and adapter spool pieces were taken from MRF pipe stock, and had walls of commercial-grade roughness. In the 4-inch and 8-inch-diameter meter runs, the five-diameter length of pipe downstream of the first meter was followed by another length of pipe, approximately 5 diameters long, immediately upstream of the second CPA flow conditioner. In the 12-inch-diameter run, to conserve space in the HPL, the second CPA plate was placed immediately after the five-diameter length downstream of the first test meter.

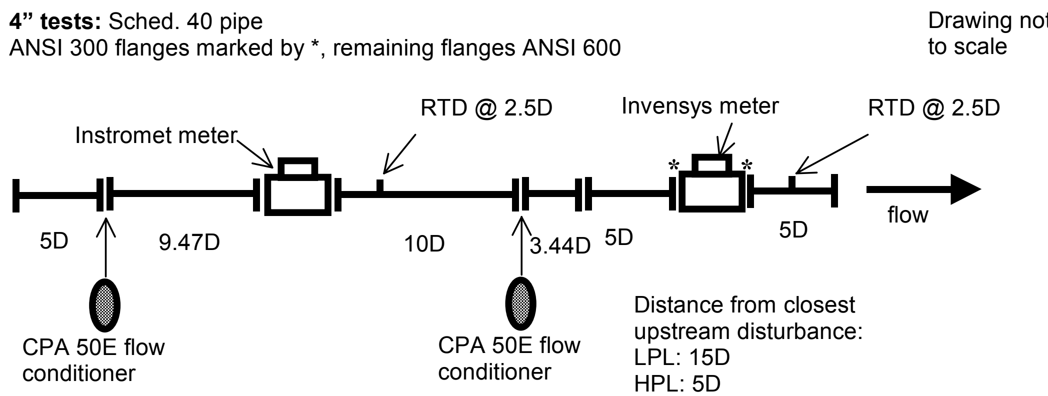

Figure 2. Installation configuration of 4-inch diameter test meters.

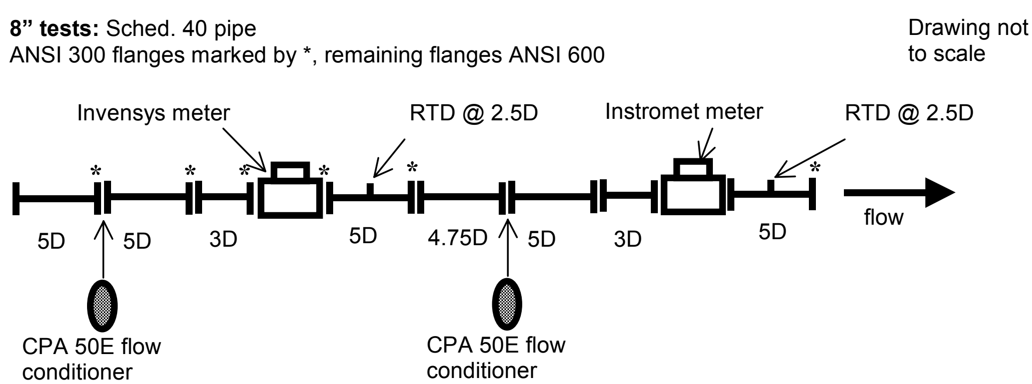

Figure 3. Installation configuration of 8-inch diameter test meters.

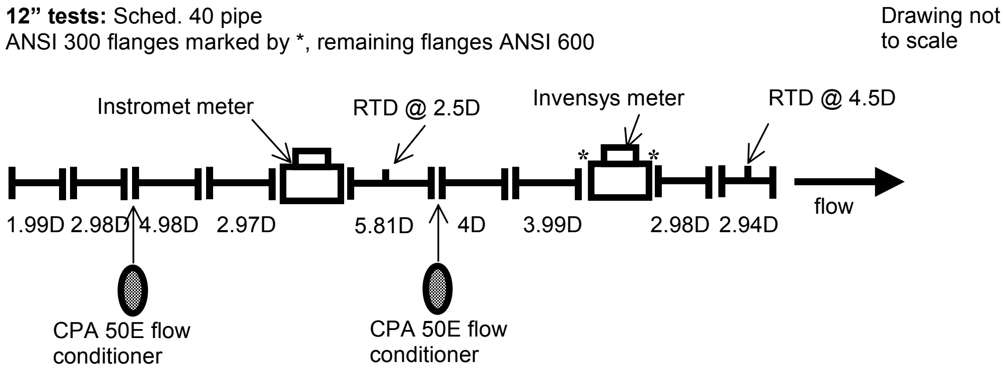

Figure 4. Installation configuration of 12-inch diameter test meters.

The static pressure was measured at each meter using an industrial-grade Rosemount smart pressure transmitter. Temperatures were measured downstream of each meter with a direct insert resistance temperature device (RTD), without a thermowell, and an industrial-grade Rosemount smart temperature transmitter. Each RTD was nominally located 2.5 pipe diameters downstream of each meter, except in the case of the Invensys 12-inch turbine meter, where the RTD was placed at 4.5 pipe diameters downstream due to limitations of the available pipe. The gas composition during each run was analyzed by a Daniel 2350 dual-column gas chromatograph, capable of identifying hydrocarbons through C_9.

Each test meter was equipped with high-frequency pulse outputs to indicate the rotor speed. The MRF reference sonic nozzles in each loop provided the flow rate at each test condition. The high-frequency pulse output from each meter was used with the reference flow rate to determine the calibration factor for the meter at each flow condition. At each flow condition, repeat meter data was collected from six 90-second test runs. The results shown later in this paper present the average calibration factors from the six repeat runs.

Test Procedure

The test meters were installed first in the Low Pressure Loop (LPL) at the Metering Research Facility. The 4-inch, 8-inch and 12-inch meters were tested, in turn, in natural gas. The 4-inch and 8-inch diameter meters were tested at 190, 115 and 45 psia; due to limitations on the flow rate of the LPL, the 12-inch diameter meters were tested only at 115 and 45 psia. The average gas composition over all natural gas tests in the LPL, as determined by the MRF GC, is shown in Table 5 to be close to the nominal composition of 94% methane, 1% nitrogen and 1% CO_2 with the balance composed of a hydrocarbon blend of ethane through nonane. The meters were calibrated against the LPL sonic nozzles, using the natural gas discharge coefficients for the nozzles.

The meter runs were then broken apart into as few segments as practical, removed from the LPL, and installed in the HPL in the same configurations. The meters were again tested in natural gas, and calibrated against the HPL sonic nozzles using their natural gas discharge coefficients. The average analytical composition of the natural gas during the HPL tests is given in Table 5. The composition was slightly richer in ethane and leaner in methane and nitrogen than during the LPL tests, but by calibrating the meters as a function of gas density and Reynolds number, useful comparisons can still be made between the LPL and HPL datasets. The 4-inch diameter meters were tested at 465, 345 and 230 psia, while the 12-inch and 8-inch diameter meters were tested at a single pressure of 230 psia.

Table 5. Average compositions of test gases used in the dual-fluid test program at the MRF.

Component	Low Pressure Loop, natural gas tests	High Pressure Loop, natural gas tests	Low Pressure Loop, carbon dioxide tests
Methane	93.613	93.292	0.005
Ethane	3.719	4.445	0.000
CO_2	1.014	1.018	99.906
Nitrogen	0.909	0.674	0.089
Propane	0.507	0.440	0.000
Isobutane	0.059	0.032	0.000
n-Butane	0.091	0.049	0.000
Isopentane	0.025	0.013	0.000
n-Pentane	0.025	0.013	0.000
n-Hexane	0.021	0.011	0.000
n-Heptane	0.017	0.009	0.000
n-Octane	0.009	0.005	0.000
n-Nonane	0.000	0.000	0.000

Following the tests in the HPL, the LPL compressor was modified for operation in carbon dioxide gas. The loop was purged with nitrogen and charged with carbon dioxide, and the sonic nozzles were calibrated using CO_2 over the range of planned test pressures using the LPL weigh tank system. The discharge coefficients for the nozzles in CO_2 compared well with the coefficients for the same nozzles in natural gas, and also with universal correlations for nozzle coefficients recently published by Arnberg and Ishibashi [4] and Ishibashi and Takamoto [5]. With the new nozzle coefficients confirmed, the meter runs were again broken into as few segments as practical, and the runs were reassembled in the Low Pressure Loop for tests in carbon dioxide gas. The average analytical composition of the carbon dioxide test gas is shown in Table 5. The only significant impurities in the test gas were nitrogen and methane. The methane and part of the nitrogen may have been left over from the purging process. Some of the nitrogen may have been an impurity in the CO_2 delivered to the test facility. The 4-inch diameter meters were tested at 125 and 90 psia in CO_2, the 8-inch diameter meters were tested at 115 and 90 psia, and the 12-inch diameter meters were tested at 115 and 45 psia. These carbon dioxide line pressures were chosen to provide reasonable overlap in Reynolds number between natural gas and CO_2 calibration conditions. In some cases, the densities were matched between the two gases to allow direct comparison of the results.

Results and Discussion

To assess the usefulness of carbon dioxide as a test medium, calibration factors from each meter in natural gas and in carbon dioxide were compared on a single graph. The calibration data was graphed as a function of Reynolds number and density, rather than of flow rate and line pressure, to assess the magnitude of density-related effects and Reynolds number effects on meter performance. This approach to data presentation also allowed any differences between calibrations in the two gases (i.e. lack of dynamic similarity) to be easily identified.

Average calibration factors from the six repeat runs at each test condition were plotted, along with 95% confidence intervals on the average values. Differences in average calibration factors are considered statistically significant if the confidence intervals of the factors being compared do not overlap. The 95% confidence intervals on the average values are computed from precision uncertainties and average bias uncertainties in the average values. Average bias uncertainties during these tests were ±0.18% in the LPL and ±0.24% in the HPL.

The results for the six test meters are presented on the following pages in Figures 5 through 10. The range on the vertical axis for each graph is approximately ±1% about the central K factor, except for Figure 10, where the vertical span is ±2% about the central value. In general, turbine meter calibration factors at low Reynolds numbers tend to increase with increasing gas density. For all six test meters, this trend is evident, and the trend is uniform among the data from both test gases. This indicates that Reynolds number and density-related effects are consistent between natural gas and carbon dioxide, and supports the use of CO_2 to calibrate turbine meters for natural gas service.

For the 4-inch and 8-inch diameter meters, a direct comparison can be made between CO_2 data at 75 psig (6 bar) and natural gas data at 210 psig (15 bar), which have approximately the same density. For each meter, calibration data from these two flow conditions, and at similar Reynolds numbers, agree to within the confidence intervals of the data, indicating statistical agreement. Except for the data from the 8-inch Invensys meter at a Reynolds number of about 160,000, the agreement between data at these two conditions is better than 0.15% for each meter. The calibration factors in CO_2 are slightly higher, but this may be due to the slightly higher density of the carbon dioxide in the 75-psig tests, when compared to the natural gas density in the 210-psig tests. For the 4-inch meters, data in CO_2 at 110 psig (8 bar) and natural gas data at 325 psig (23 bar) can also be compared directly. Data from each meter at these two conditions also agree to within the confidence intervals of the data. In most cases, the agreement is better than 0.15%. Exceptions are the 4-inch Instromet meter data at Reynolds numbers between 400,000 and 600,000, and the 4-inch Invensys meter data at Re > 1,600,000, though the 95% confidence intervals on these data still overlap.

Finally, for the 12-inch diameter meters, the calibration factors for CO_2 at 30 psig and natural gas at 100 psig (conditions with similar gas densities) also have overlapping confidence intervals. For the Instromet meter, data from the different test gases at similar Reynolds numbers, except for a single data point in CO_2 near Re = 300,000, agree to within better than 0.15%. The 12-inch diameter Invensys meter exhibits more scatter in individual calibration factors at low Reynolds numbers, due to the fact that these flows are at the extreme low end of the meter's range. This results in larger 95% confidence intervals on the average calibration factors in this region. However, above a Reynolds number of 250,000, the calibration factors in the two gases are again in good agreement, to within 0.15% or better.

In summary, the calibrations of all six turbine meters in carbon dioxide were consistent with calibrations of the same meters in natural gas. Where a meter was tested in both gases at similar Reynolds numbers and gas densities, the calibration factors agreed to within their uncertainties; in most cases, agreement was to within 0.15%, better than the 95% confidence intervals on data from both the MRF LPL and HPL. It can be concluded that turbine meter calibrations in carbon dioxide can be used in natural gas service by applying the principle of dynamic similarity.

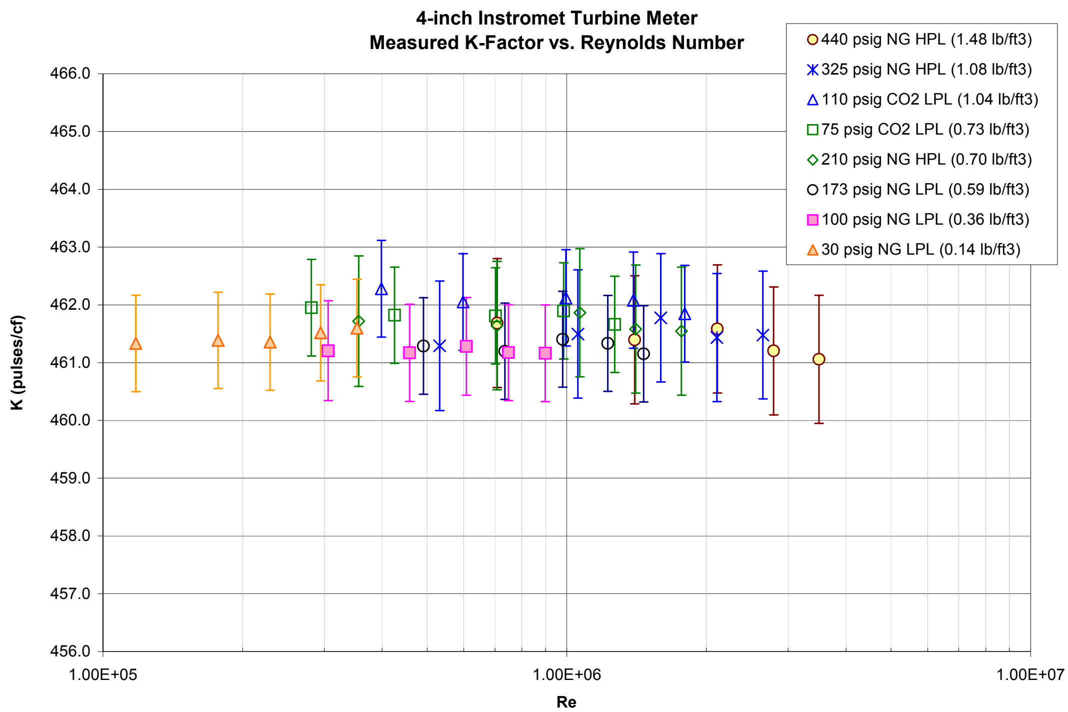

Figure 5. Calibration data from the 4-inch-diameter Instromet meter in natural gas and CO_2.

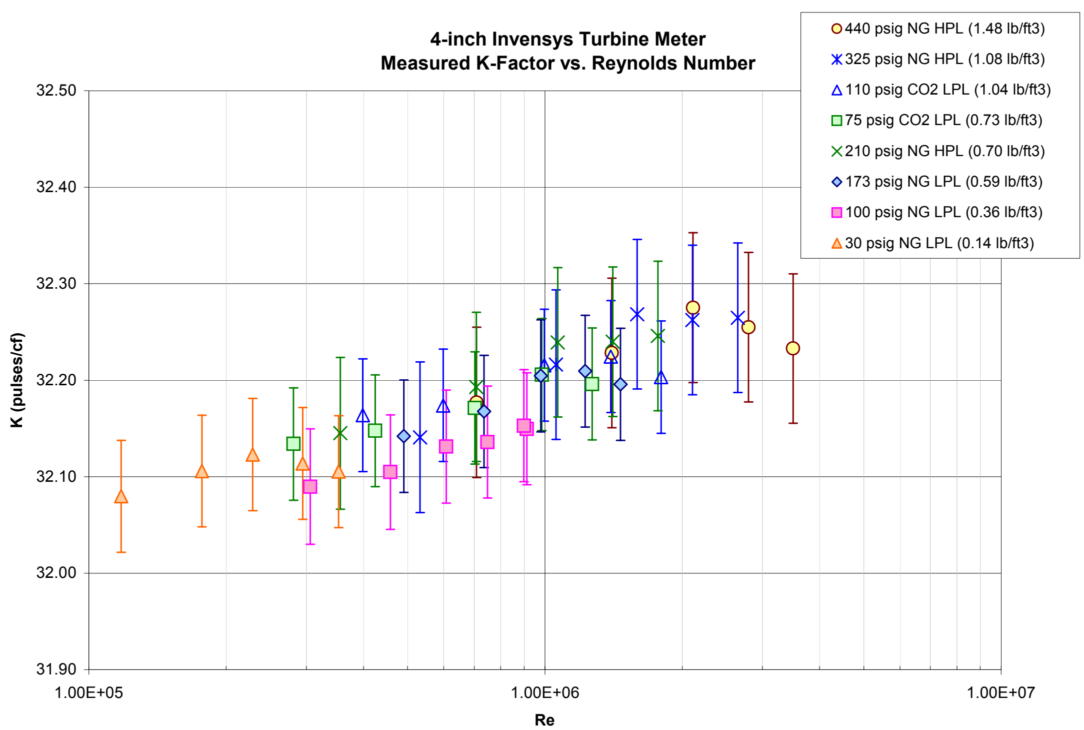

Figure 6. Calibration data from the 4-inch-diameter Invensys meter in natural gas and CO_2.

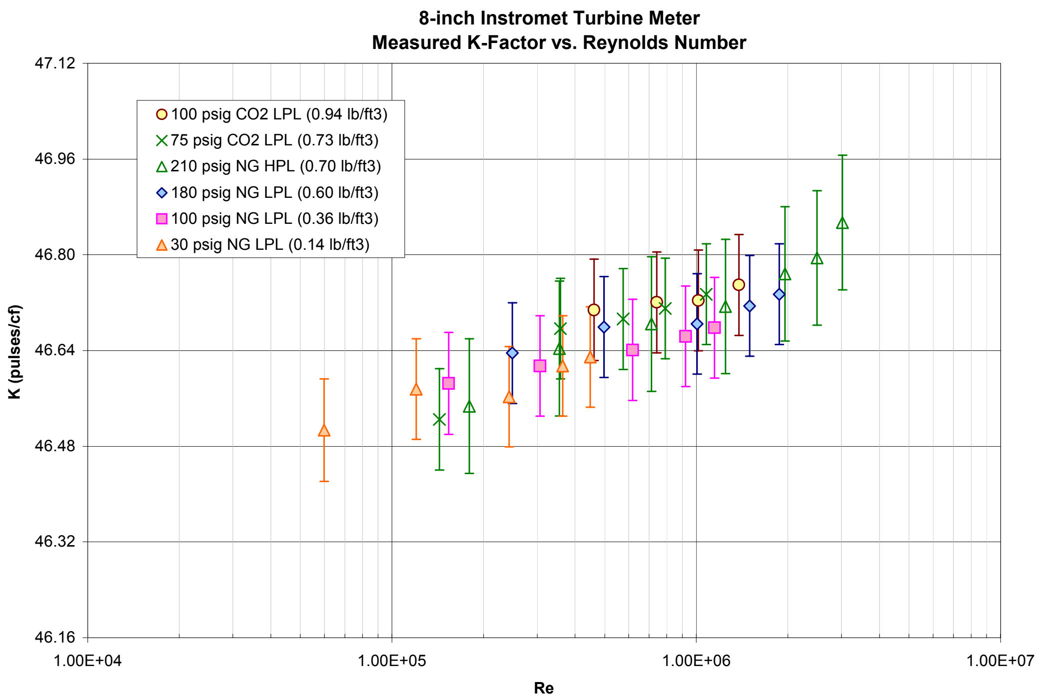

Figure 7. Calibration data from the 8-inch-diameter Instromet meter in natural gas and CO_2.

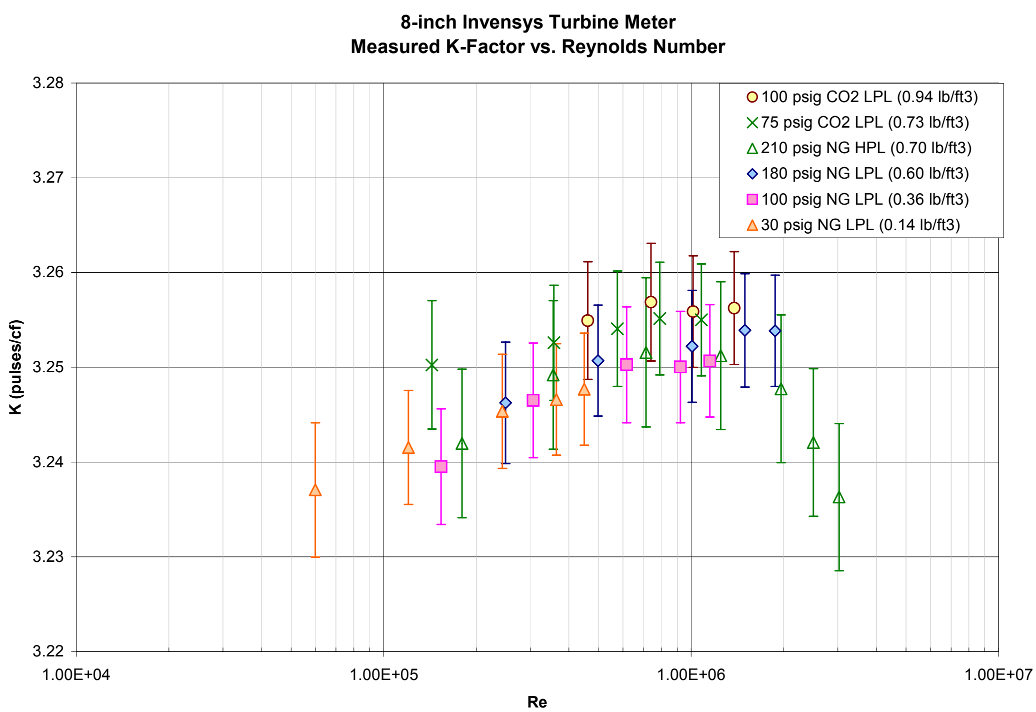

Figure 8. Calibration data from the 8-inch-diameter Invensys meter in natural gas and CO_2.

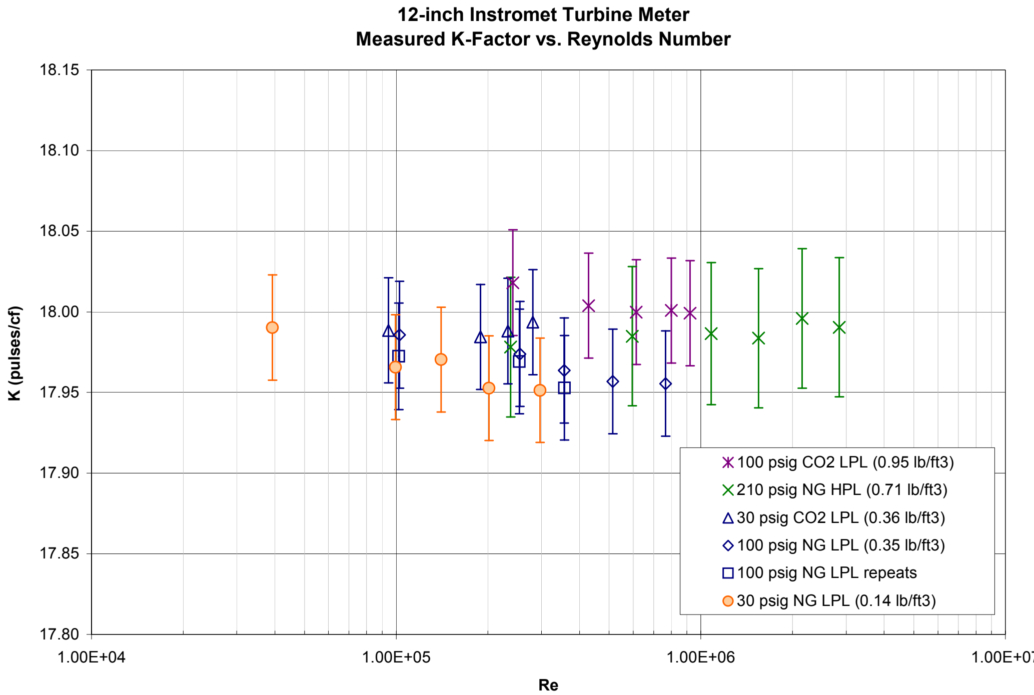

Figure 9. Calibration data from the 12-inch-diameter Instromet meter in natural gas and CO_2.

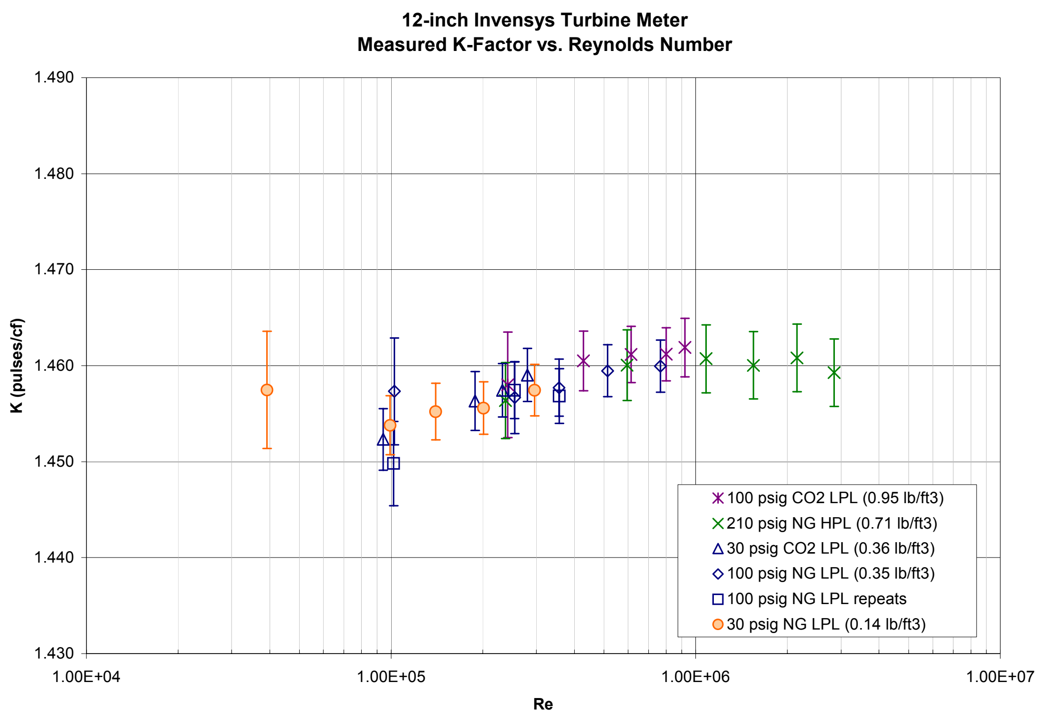

Figure 10. Calibration data from the 12-inch-diameter Invensys meter in natural gas and CO_2.

Conclusions

A total of six turbine meters for natural gas custody transfer have been calibrated at the SwRI Metering Research Facility in both natural gas and carbon dioxide. Calibration factors in the two different gases, obtained at the same densities and Reynolds numbers, agreed in nearly all cases to within 0.15%. Measurement errors of this magnitude would be well within the maximum uncertainty allowed by American Gas Association Report No. 7, *Measurement of Natural Gas by Turbine Meters*. The consistent performance of all the meters between carbon dioxide and natural gas indicates that dynamic effects related to Reynolds number and gas density are similar in the two gases, and that matching these two quantities is sufficient to predict meter behavior for the flow conditions of interest.

Where calibration of turbine meters in natural gas is not practical, another flowing medium such as air is often used. These experiments have shown that carbon dioxide can also be used successfully to obtain turbine calibration data. To apply the results in the field most effectively, the CO_2 data should be obtained at the flowing gas densities and Reynolds numbers that are expected in the natural gas installation where the meter will be used. Density values would be converted to line pressures in natural gas, and Reynolds numbers would be converted to actual or standard volumetric flow rates in natural gas, to apply the data directly in the field. The line pressures and flow rates needed for dynamic similarity in CO_2 are not as high as in air, which provides advantages in safety and efficiency that can be applied in the construction of a CO_2 test facility.

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References

1. *Measurement of Gas by Turbine Meters*, American Gas Association Transmission Measurement Committee Report No. 7, AGA, Arlington, Virginia, USA, 1996.

2. George, D. L., "Metering Research Facility Program: Effects of Line Pressure and Gas Density on Turbine Meter Measurement Accuracy Between 30 and 700 psig in Natural Gas," GRI Topical Report GRI-03/0050, Gas Research Institute, Des Plaines, Illinois, USA, July 2003.

3. Fox, R. W., and McDonald, A. T., *Introduction to Fluid Mechanics*, Fourth Edition, John Wiley and Sons, New York, New York, USA, 1992, pp. 294-308.

4. Arnberg, B. T., and Ishibashi, M., "Discharge Coefficient Equations for Critical-Flow Toroidal-Throat Venturi Nozzles," in *Proceedings of the ASME Fluids Engineering Division Summer Meeting*¸ American Society of Mechanical Engineers, New Orleans, Louisiana, May 29 – June 1, 2001, paper FEDSM2001-18030.

5. Ishibashi, M., and Takamoto, M., "Discharge Coefficient of Super-Accurate Critical Nozzles Accompanied with the Boundary Layer Transition Measured by Reference Super-Accurate Critical Nozzles Connected in Series," in *Proceedings of the ASME Fluids Engineering Division Summer Meeting*¸ American Society of Mechanical Engineers, New Orleans, Louisiana, May 29 – June 1, 2001, paper FEDSM2001-18036.