CALIBRATION OF TURBINE GAS METER BY MATCHING REYNOLDS NUMBER AND DENSITY

PAUL W. TANG, *M.Sc.,P.Eng.*
TERASEN GAS
SURREY, BC, CANADA

Introduction

Accurate metering is essential to fair trading in the natural gas industry. The accuracy of a turbine meter starts with good calibration practices. The most common medium used for calibrating gas turbine meters is natural gas. Using natural gas as a calibration medium offers the closest physical properties match for turbine meters used in the natural gas industry. Unfortunately, it is often difficult and costly for natural gas based meter calibration facilities to operate over a wide pressure and temperature range due to the restrictions in their physical configurations.

The relationship between Reynolds number and the performance of a turbine meter is a well-established fact. A turbine meter is primarily a rotating machine that responds to the Reynolds number of the flow. The AGA No.7 Report [1] stipulates that the K-factor of a turbine meter determined by matching Reynolds number to the field operating conditions can be used directly for the measurement of natural gas regardless of the calibration gas medium used. In this paper, the author explores the effect of Reynolds number on the K-factors of turbine meters as demonstrated by current research data and introduces a unique turbine meter calibration technology based on Reynolds number matching using carbon dioxide gas as a test medium. This alternate fluid turbine meter calibration technology offers a very cost-effective solution for high precision gas metering.

Typical Performance of Turbine Meters

A turbine meter is essentially a machine that converts the kinetic energy in a flowing medium into rotational motion. The rotational speed of an ideal turbine meter should be exactly proportional to the volumetric flow rate of the flowing fluid.

In reality, the performance of a turbine meter is affected by additional factors that complicate the process. The rotational speed of the rotor in a non-ideal turbine meter is only roughly proportional to the volumetric flow rate of the flowing medium. A retarding torque causes a slippage of the rotational speed. The two components that constitute this retarding torque are:

a. Non-fluid forces (mechanical friction)
b. Fluid forces (fluid friction)

The friction of rotor bearings and the mechanical loading of the drive train in the flow indicating registers introduce the non-fluid retarding forces. The fluid retarding forces are made up of fluid drag; a function of Reynolds number of the flow, and turbulence; a function of the flow velocity. The individual and combined contribution of these factors to the overall performance of a turbine is shown in Figure 1.

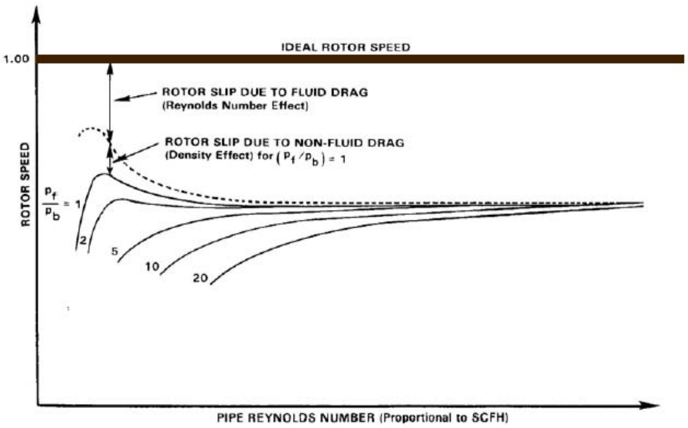

Figure 1: Effect of Fluid and Non-fluid Retarding Torques on Gas Turbine Meter Performance (Source: Sensus Metering Systems)

Reynolds Number

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

$$Re = \frac{\rho v D}{\mu} \qquad (1)$$

Reynolds number can be interpreted as a ratio of inertia force versus viscous force. A small Reynolds number ($Re < 2000$) indicates that viscous forces dominate and therefore the flow is laminar in nature. A large Reynolds number ($Re > 4000$) results in turbulent flow. The fluid flow is in a transition state when the Reynolds number is between 2000 and 4000.

Reynolds number is a very important parameter in the concept of dynamic similarity of fluid flow. Dynamic similarity makes it possible for engineers to test scaled models in a wind tunnel or flow channel to predict the corresponding behavior of a full size object. It also allows measurement engineers to characterize the performance of a turbine meter under different flow conditions. The AGA Report No. 7 [1] suggests "a meter calibration carried out in a test facility over a particular range of Reynolds numbers characterize the meter's performance when used to measure gas over the same range of Reynolds number when the meter is in service". It also further recommends "the expected operating Reynolds number range and/or density for a meter needs to be taken into account when designing a calibration program". Recently published research work by AGA and GRI [2, 3, and 4] cited large measurement discrepancies due to changes in line pressure and gas density, and confirmed the importance of matching the calibration Reynolds number and gas density to the field operating conditions.

Meter Calibration in Alternate Fluids

Calibrations of turbine meters intended for natural gas measurement are typically carried out in natural gas test facilities. However, calibrating natural gas turbine meters using a different fluid is also a common and long accepted practice. For example, atmospheric pressure calibration of turbine meters in air is recognized by most regulatory agencies in the world as a valid procedure. Alternate fluid calibration is often done in order to minimize calibration cost, or to achieve calibration conditions which are difficult to realize in a conventional natural gas test facility.

Since November 2002, Terasen Gas in British Columbia, Canada has engaged in research work in gas turbine meter proving technologies using alternate fluid. The objective of this work was to design and build an efficient turbine meter calibration facility for commercial meter testing purposes. The test media examined include natural gas, air, argon, carbon dioxide, and several other gases that have density substantially higher than that of natural gas. Carbon dioxide gas was chosen as the best test medium for the Terasen turbine meter proving facility.

Comparing Natural Gas, Air, and Carbon Dioxide

Since it has been established that Reynolds number and/or density matching to field operating conditions is a key consideration for obtaining optimal turbine meter calibration, we shall demonstrate the advantage of using a heavier gas, such as carbon dioxide, as a calibration medium in the following examples.

For natural gas flowing in a piece of pipe:

$$Re_{(ng)} = \frac{\rho_{(ng)}\ VD}{\mu_{(ng)}} \qquad (1)$$

where $R_{e(ng)}$ is the Reynolds number of the natural gas flow channel, $\rho_{(ng)}$ is the density of natural gas, V is the average velocity of the natural gas flow, and $\mu_{(ng)}$ is the dynamic viscosity of natural gas.

For air flowing in the same pipe at the same velocity under identical temperature and pressure:

$$Re_{(air)} = \frac{\rho_{(air)}\ VD}{\mu_{(air)}} \qquad (2)$$

where $R_{e(air)}$ is the Reynolds number of the air flow channel, $\rho_{(air)}$ is the density of air, and $\mu_{(air)}$ is the dynamic viscosity of air.

In this piece of pipe, assuming the gas composition to be that of the Gulf Coast natural gas as given in AGA Report No. 8, and the temperature and pressure to be 60ºF (15.5ºC) and 200 psia (14 bars) respectively. The density and dynamic viscosity of air and natural gas were calculated using the NIST Reference Fluid Thermodynamic and Transport Properties Database (REFPROP) [5]. Substituting these parameters in (2), the Reynolds number ratio of a flow of air compared to natural gas under the same condition can be expressed as:

$$\frac{R_{e(air)}}{R_{e(ng)}} = \frac{\rho_{(air)}\ \mu_{(ng)}}{\mu_{(air)}\ \rho_{(ng)}} = 1.024 \qquad (3)$$

Equation (3) implies that an air stream flowing at a certain velocity inside a piece of pipe can achieve 2.4% higher Reynolds number than a natural gas stream flowing at the same velocity. Applying the same analysis to a stream of carbon dioxide gas:

$$\frac{R_{e(CO2)}}{R_{e(ng)}} = \frac{\rho_{(CO2)}\ \mu_{(ng)}}{\mu_{(CO2)}\ \rho_{(ng)}} = 2.102 \qquad (4)$$

In this example, the Reynolds number ratio $Re_{(CO2)}\ /\ Re_{(ng)}$ is 2.102, indicating that carbon dioxide gas can more than double the Reynolds number of natural gas flow under the same operating conditions. The equivalent natural gas pressure which produces the same Reynolds number as the carbon dioxide stream in a prover meter run is known as the “effect test pressure”. Comparing equation (3) and (4), one can conclude that while air flow produces comparable Reynolds number as natural gas, it would be more advantageous to substitute the natural gas in a turbine meter test loop with carbon dioxide for a high Reynolds number prover.

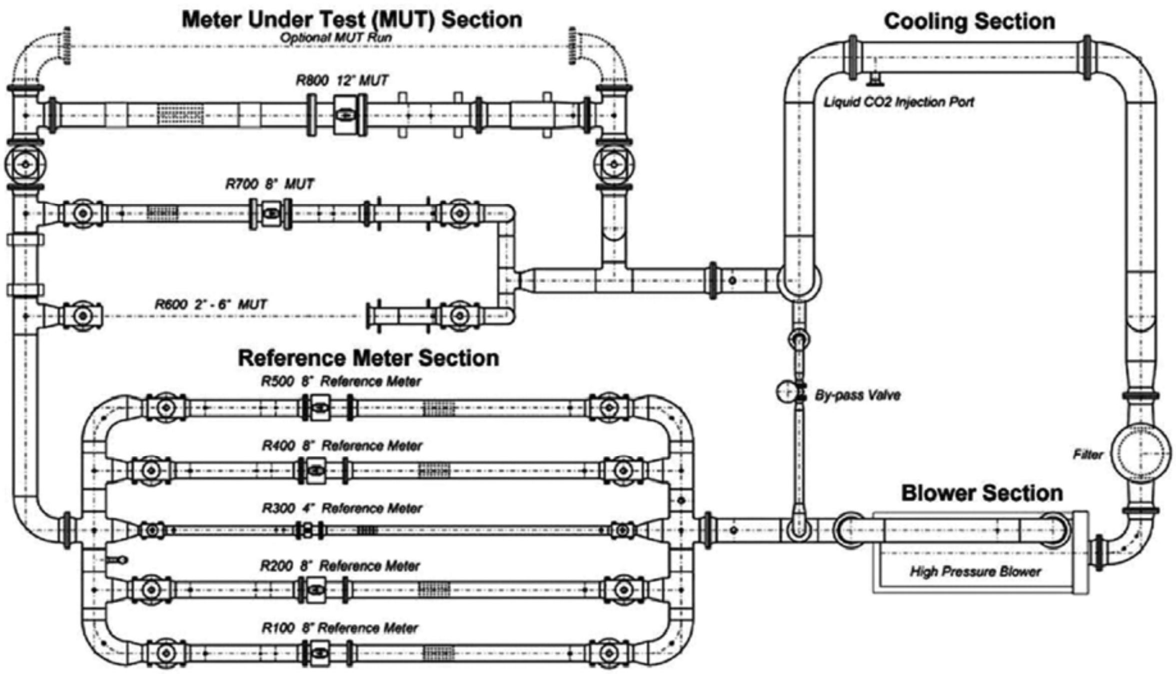

Figure 2: Triple Point Turbine Meter Testing Loop Schematic

Similar consideration can be given to the density ratios of the gases in the same example. Comparing air with natural gas under the same operating conditions, the density ratio is:

$$\frac{\rho_{(Air)}}{\rho_{(ng)}} = 1.67 \qquad (5)$$

The carbon dioxide to natural gas density ratio is:

$$\frac{\rho_{(CO2)}}{\rho_{(ng)}} = 2.75 \qquad (6)$$

One can also come to the same conclusion that carbon dioxide is a better substitute than air as a meter proving fluid when the density ratios of the gases are being considered.

Calibrating turbine meters in carbon dioxide gas presents several advantages: (1) carbon dioxide, being noncombustible, is safer to handle than natural gas; (2) comparing to both natural gas and air, the lower operating pressures needed to reach the target meter test Reynolds number require less compression; (3) the fact that the carbon dioxide meter proving loop can operate at a lower pressure means that time saving devices such as automated test meter clamps can be easily and inexpensively deployed; (4) because of the higher density of carbon dioxide, no density related correction would be necessary to improve the accuracy of calibration; (5) the triple point of carbon dioxide occurs much closer to ambient conditions than most gases, a property that allows the temperature of the flowing gas in the test loop to be controlled by direct injection of carbon dioxide in the liquid phase. Using this property of carbon dioxide and a temperature regulating process patented by Terasen, the temperature of the flowing gas in a meter test loop can be controlled to within ±1.8ºF (1ºC), between 40º to 104ºF (5º to 40ºC). This capability is unusual amongst large gas meter calibration facilities, few of which have variable operating temperature.

With these advantages in mind, Terasen Gas proceeded with a "proof-of-concept" test at Southwest Research Institute in fall of 2003 to validate the use of carbon dioxide gas as a calibration medium. The favorable results from this experiment led to the design and construction of the Triple Point Turbine Meter Testing Facility.

The Triple Point Facility

Terasen Gas, a subsidiary of Fortis Inc., supplies natural gas to more than 920,000 customers in the Province of British Columbia, Canada. Terasen Measurement tests, calibrates, repairs electricity and gas meters, and provides asset management services throughout North America. The Triple Point Facility is located at Terasen Measurement's headquarters in Penticton, British Columbia, Canada.

Facility Description

Triple Point is a closed loop facility designed specifically to calibrate turbine meters at their operating conditions. The test medium is carbon dioxide gas. The flow reference of the facility is provided by a bank of four 8-inch and one 4-inch Instromet X-Series turbine meters. The test meter section consists of three meter runs of nominal sizes twelve, eight, and four inches. Each of the test runs is equipped with a hydraulic clamp to facilitate the mounting of test meters. The reference and test runs are located in a building with environmental control, while the liquid carbon dioxide storage, temperature control arrangements, liquid carbon dioxide injection system, and high pressure blower are located outdoors. Figure 2 shows the physical layout of the facility's reference meter sections on the right and the meter-under-test sections on left.

Operating Capabilities

The recommendations found in the new AGA-7 are based on a comprehensive research program into the characteristics of modern commercial turbine gas meters [2, 3 and 4]. The research shows that these meters are quite sensitive to Reynolds number, particularly at lower flow rates and pressures. Based on this knowledge, Triple Point has been designed to operate over the range of measurement conditions in which turbine meters have been demonstrated to suffer from non-linearity.

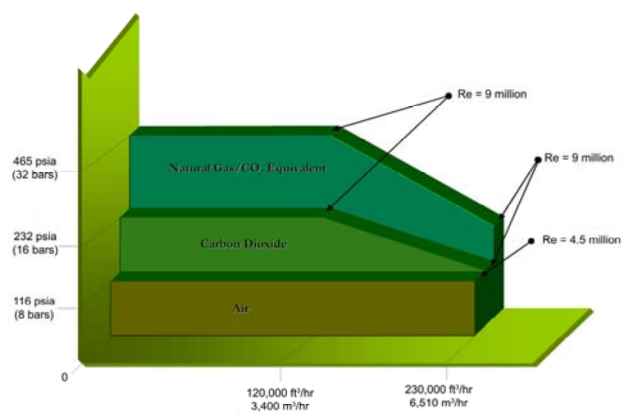

Figure 3: Triple Point's Calibration Capabilities

With a maximum flow rate of 230,000 ACFH (6,510 m^3/hr), Triple Point is capable of testing the full flow range of an extended-range 12 inch (300 mm) turbine meter. The test loop supports the maximum volumetric flow rate at an operating pressure of 116 psia (8 bars). With the test loop operating at the maximum design pressure of 232 psia (16 bars), the flow rates is reduced to approximately 120,000 ACFH (3,400 m^3/hr). The upper limit of the operating pressure and flow rate is defined by the mass flow capacity of the high pressure blower. The maximum Reynolds number generated by the test loop is well over 9 million. The facility's operating capabilities are shown in Figure 3.

A summary of Triple Point's operating specifications is shown below in Table 1.

Specifications

1.	**Type of Meter**	Gas Turbine Meter
2.	**Meter Size**	2" to 12"
3.	**Flange Rating**	ANSI 150, 300, 600
4.	**Test Medium**	Carbon Dioxide
5.	**Flow Range**	
	4",8", and 12" meter	2,700 to 230,000 ACFH
	2" and 3" meter	700 to 10,000 ACFH
6.	**Operating Pressure**	Atmospheric to 240 psig
7.	**Pressure Stability**	± 1.0 psig
8.	**Operating Temperature**	40 to 104ºF (±2ºF) ± .5°F stability during test
9.	**Reynolds Number**	100,000 to 9,000,000
10.	**Measurement Uncertainty**	±0.27 of deviation (GUM method) Confident level 95% (k = 2)
11.	**Traceability**	NMI (Netherlands)
12.	**Government Recognition**	Measurement Canada

Table 1: Triple Point Specifications

The facility was commissioned in the summer of 2005. After a year of vigorous evaluation and field testing, Triple Point was recognized by the Canadian government in August 2006 as an approved provider of high pressure test data for turbine gas meters under the provision of Measurement Canada Bulletin G-16 [6].

Traceability

The reference meters at Triple Point were calibrated at three facilities operated by the Nederlands Meetinstituut (NMi) in the Netherlands: Silvolde on atmospheric air, Utrecht on 7.6 bar (110 psia) natural gas, and Bergum on 18 bar (261 psia) natural gas. At these locations, data for the meters was taken in the range of Reynolds numbers over which they are being used at Triple Point. Thus, the reference meters are traceable to the European harmonized cubic metre.

Traceability of the pressure and temperature transmitters used at the facility is maintained by comparing them periodically to reference equipment that were calibrated and certified by Measurement Canada.

Measurement Uncertainty

The measurement uncertainty of the Triple Point Facility was developed using the ISO GUM (Guide to the Expression of Uncertainty in Measurement) 1995 model. Since the test loop operating principles used here were relatively new and test fluid unconventional, conservative values were used to develop the measurement uncertainty model. The expanded uncertainty of the calibration facility was determined to be ±0.27% with a confidence level of 95% (k =2). A detailed measurement uncertainty analysis is given in reference [7].

Inter-facility Comparisons

Since carbon dioxide is not a traditional calibration gas for metering devices, one of the concerns was to establish its suitability for use as a test fluid. Prior to the construction of Triple Point, a research program was conducted at the Meter Research Facility (MRF) at Southwest

Research Institute. Six turbine meters of 4-inch, 8-inch, and 12-inch (100, 200 and 300 mm) diameter from two different manufacturers were tested in both carbon dioxide and natural gas over the widest available range of matching Reynolds numbers. The result of this dual fluid work was published in reference [8]. The research data shows that the calibration for all six of the meters agreed within 0.15 %. A sample of the results is shown in Figure 4.

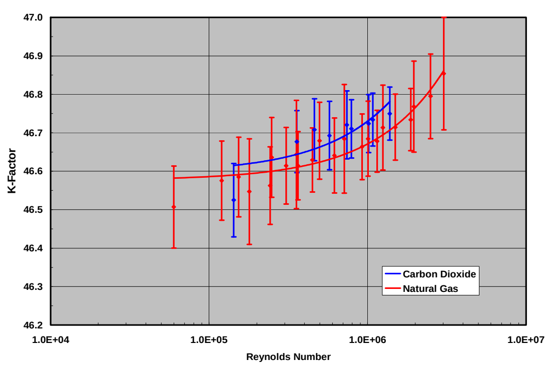

Figure 4: Dual Fluid Test Results

From the dual fluid test result, it can be seen that the corresponding K-factors with the two different gases was almost identical when plotted against Reynolds number. Both the natural gas and carbon dioxide K-factors tracked the meter's performance curve very well. From this evidence, it was concluded that carbon dioxide can reliably be used to calibrate natural gas meters. This conclusion was supported by subsequent round-robin tests comparing Triple Point's carbon dioxide test data against natural gas flow test results from other established flow test laboratories.

In order to further prove the validity of the test data from Triple Point, a series of inter-facility comparison were performed. Figure 5 shows the result of one of these comparisons performed at Triple Point with an 8-inch reference meter calibrated in natural gas at NMI. The error characteristic of the four master reference meters falls well within the stated measurement uncertainty of the facility.

Triple Point has participated in many inter-facility round-robin comparisons successfully in the past two years of operation and will continue to do so in the future. The design and construction of a dual turbine meter artifact was completed recently. Terasen Measurement, TransCanada Calibration, and the Southwest Research Institute currently are the contributors to this inter-facility quality assurance program. The first round-robin

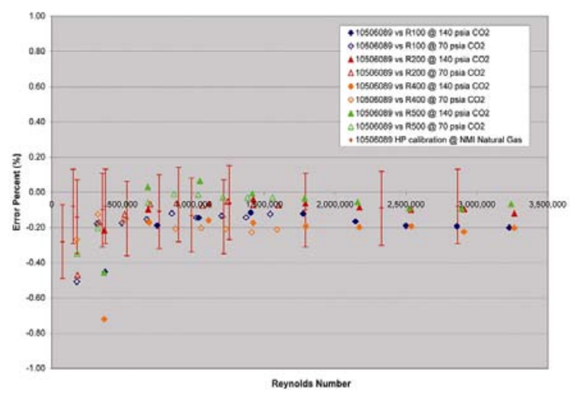

Figure 5 Inter-comparison of the four 8-inch master meters (R100, R200, R400, R500) at Triple Point with an 8-inch reference meter calibrated at NMi

comparison amongst the three test facilities is being conducted at present. This work is expected to be completed by the spring of 2009. Test results will be published shortly after the round robin test data is finalized.

Summary

Triple Point is a new calibration facility which has been designed specifically to address the calibration needs of industrial turbine gas meter users. Using a liquid and vapor phase carbon dioxide process, the facility is capable of calibrating turbine meters over a wide range of Reynolds numbers and operating temperatures. The Canadian government has recognized the facility as an approved high-pressure turbine meter calibration facility.

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