HIGH PRESSURE CALIBRATION OF GAS TURBINE METERS IN CARBON DIOXIDE

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Abstract: The pressure sensitivity of turbine meters is a well-observed phenomenon since the inception of these devices. Unfortunately, very little organized experimental data were available for study until recently. Due to the ever-rising energy costs, the natural gas industry is paying much more attention to improve the accuracy of natural gas flow measurement. The latest revision of the AGA No.7 report recommends that a turbine meter should be calibrated close to its intended operating conditions in order to minimize measurement error caused by pressure variation. This paper describes a novel approach in high-pressure turbine meter proving using carbon dioxide gas as a test medium. The concept of Reynolds number turbine meter proving is explained. Test data demonstrating the validity of the Reynolds number matching method are presented and the description of a high-pressure turbine meter calibration facility based on this new technology is given.

1. Introduction

Calibration of metering devices is essential to accurate measurement. The most common medium used for calibrating gas turbine meters is certainly natural gas. Using natural gas as a calibration medium offers the closest physical property match for meters used in the natural gas industry. However, it is often difficult and costly for natural gas based meter calibration facilities to operate over a wide pressure and temperature range. Nearly all natural gas facilities feeding meter prover stations are designed to optimize pipeline operations. Meter proving functions are considered to be of secondary importance and their inclusion are usually an afterthought. Consequently, a new type of high-pressure meter provers using alternate test fluids and Reynolds number/fluid density matching techniques was developed to address these difficulties.

Observation of the relationship between Reynolds number, fluid density, and the performance of turbine meters is a well-established phenomenon. A turbine meter is primarily a rotating machine, which responds to the Reynolds number of the flowing medium. This fact is recognized by many gas regulatory agencies as well as professional organizations around the world. Establishments such as the International Organization of Legal Metrology (OIML) [1], the European Committee for Standardization (CEN) [2], and the American Gas Association, etc. generally recommend turbine meters to be calibrated over a range of Reynolds numbers which characterizes these meters’ performance when they are operating in service. The current revision of the AGA No.7 Report [3] 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. Until recently, the effort to calibrate turbine meters at field conditions was hampered by the lack of high-pressure meter testing facilities both in North America and worldwide. 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 cost-effective solution for high pressure turbine meter testing.

2. Typical Performance of Turbine Meters

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

In reality, the performance of even a well-designed turbine meter would deviate from that of an ideal meter. The rotational speed of the rotor in a turbine meter is roughly proportional to the volumetric flow rate of the flowing medium. However, slippage of the theoretical rotational speed is always present. The slippage is caused by a retarding torque generally consisting of the following two components:

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

The non-fluid retarding forces are produced by the friction of rotor bearings and the mechanical loading of drive train in the flow indicating registers. The fluid retarding forces are made up of fluid drag, which is a function of Reynolds number of the flow, and turbulence, which is a function of the flow velocity. The degree of
influence of these retarding torque components depends very much on the design and construction of the turbine meter.

3. Comparing Natural Gas, Air, and Carbon Dioxide

Since it was understood 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:

\[ Re_{\text{ng}} = \frac{\rho_{\text{ng}} V D}{\mu_{\text{ng}}} \]  (1)

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

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

\[ Re_{\text{air}} = \frac{\rho_{\text{air}} V D}{\mu_{\text{air}}} \]  (2)

where \( Re_{\text{air}} \) is the Reynolds number of the airflow channel, \( \rho_{\text{air}} \) is the density of air, and \( \mu_{\text{air}} \) is the dynamic viscosity of air.

In this piece of pipe, assuming the gas is made up of the Gulf Coast natural gas composition, and the temperature and pressure to be 60°F (15.5°C) and 200 psia (14 bars) respectively, the Reynolds number ratio of air to natural gas can be calculated by substituting the relevant parameters:

\[ \frac{Re_{\text{air}}}{Re_{\text{ng}}} = \frac{\rho_{\text{air}}}{\rho_{\text{ng}}} \frac{\mu_{\text{ng}}}{\mu_{\text{air}}} = 1.024 \]  (3)

Equation (3) implies that the Reynolds number of an airflow stream flowing at a certain velocity inside a piece of pipe is very similar to that of a natural gas stream operating at the same pressure. The air stream has a Reynolds number only 2.4% higher than a natural gas stream flowing at the same velocity.

Air at atmospheric pressure is a common test fluid used for gas turbine meter calibration. Figure 1 shows a set of typical turbine meter performance curves obtained by atmospheric air as well as pressurized natural gas meter tests. The three vertical dotted lines on the chart represent the maximum Reynolds numbers attainable by the airflow at atmospheric pressure and the natural gas flow at 120 psig and 750 psig respectively. It can be seen on this chart that an atmospheric air calibration can only address a very narrow range of Reynolds numbers reached by a pressurized natural gas flow in a pipeline. A turbine meter calibration conducted in atmospheric air is hardly representative of the meter’s performance in a much wider Reynolds number range under the actual natural gas pipeline operating conditions.

Applying the same principle in equation (3) on a carbon dioxide gas stream in the pipe, it can be shown that:

\[ \frac{Re_{\text{CO2}}}{Re_{\text{ng}}} = \frac{\rho_{\text{CO2}}}{\rho_{\text{ng}}} \frac{\mu_{\text{ng}}}{\mu_{\text{CO2}}} = 2.102 \]  (4)

The Reynolds number ratio \( Re_{\text{CO2}} / Re_{\text{ng}} \) is 2.102, indicating that a carbon dioxide gas flow can achieve more than twice the Reynolds number of a 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 meter prover loop is known as the “effective test pressure.” Comparing equation (3) and (4), one can conclude that while airflow produces Reynolds number comparable to natural gas flow in a meter test loop, it would be more advantageous to use carbon dioxide gas in the test loop to generate flow with higher Reynolds number to simulate pipeline conditions.

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:

\[ \frac{\rho_{\text{air}}}{\rho_{\text{ng}}} = 1.67 \]  (5)

The carbon dioxide to natural gas density ratio is:
\[ \frac{\rho_{(CO2)}}{\rho_{(ng)}} = 2.75 \quad \text{(6)} \]

From (5) and (6), one may also come to a similar conclusion that carbon dioxide is a better substitute than air as a meter proving medium when the density ratios of the gases are being considered.

Calibrating turbine meters in carbon dioxide gas offers several advantages: (1) carbon dioxide is non-combustible, is therefore 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 implemented; (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 other common gases, a property that allows the temperature of the gas medium 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 ±1.8°F (1°C), between 40°F to 104°F (5°C to 40°C). This capability is unusual for large gas meter calibration facilities, few of which have variable operating temperature control.

With these considerations in mind, Terasen Gas conducted a series of “proof-of-concept” test at the Southwest Research Institute in the fall of 2003 to validate the use of carbon dioxide gas as a turbine meter calibration medium. The test results were published in reference [5]. The favorable results from this experiment led to the design and construction of the Triple Point Turbine Meter Test Facility in Penticton, BC, Canada. This facility has been fully operational since 2006. A similar facility is also being built in the Netherlands at this time.

3. Meter Prover Configurations

The most common type of conventional high-pressure turbine meter calibration station design is the transfer prover. This type of prover station relies on a meter under test (MUT) making direct comparison to a reference standard meter. The reference standards used at these facilities must meet a performance level acceptable to the appropriate governing regulatory agency. In Canada, the reference meters must either be calibrated by Measurement Canada, or by a facility approved by Measurement Canada under the Bulletin G-16, which defines the conditions for acceptance [6].

The two main high-pressure meter prover configurations are the open-loop prover and the closed-loop prover. An open-loop prover obtains its test flow by diverting natural gas from a high-pressure pipeline into a meter proving station. Test gas exiting from the outlet of the proving station is re-introduced into the high-pressure pipeline at a slightly reduced pressure (Figure 2). The operating pressure of the prover station is typically dictated by the operating pressure of the pipeline. At suitable pipeline locations, it is sometimes possible to discharge the test gas into a gas distribution system at a lower pressure. In this case, the prover facility would function as part of a gate station to produce the pressure drop required by the gas distribution system. The advantage of this configuration is that it would provide the prover station with a wider test pressure range. Unfortunately, it is rare to find pipeline locations with a favorable pressure and flow profile on a year round basis.

To overcome the dependency of the prover facility on a high-pressure pipeline, one of the solutions is to construct a meter test loop in a closed-loop configuration (Figure 3). In this case, a compressor would be required to drive the test flow. A cooling system is typically necessary to remove the compression heat from the loop in order to maintain a stable operating temperature throughout the duration of a meter test run.
4. Meter Calibration in Alternate Fluids

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

Terasen Gas has engaged in turbine meter proving research work using alternate test fluids since 2002. The objective of this research program was to design and build an efficient turbine meter calibration facility suitable for commercial meter calibration. The test media examined include natural gas, air, argon, carbon dioxide, and several other gases, which have density substantially higher than that of natural gas. Figure 4 shows the schematic layout of a carbon dioxide gas based meter test loop designed concept explored by Terasen Gas. In this configuration, carbon dioxide gas is circulated as a meter test medium, while liquid carbon dioxide is used as a cooling agent to remove compression heat. The result is a meter proving station of very compact dimensions.

5. The Triple Point Facility

Triple Point is a closed loop meter proving facility based on the alternate test fluid concept discussed in the previous sections. The facility was designed specifically to calibrate turbine meters close to 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 meter-under-test (MUT) section consists of three meter runs of nominal sizes 12-inch, 8-inch, and 4-inch in diameter. Each of the MUT runs is equipped with a hydraulic clamp to facilitate the mounting of test meters. These hydraulic meter clamps enable the test operator to mount a MUT in less than 15 minutes. Rapid engagement of MUTs is a key consideration for improving the productivity of a commercial meter test station.

The reference and MUT runs of the test loop are located in a building with environmental control, while the liquid carbon dioxide storage, temperature control equipment, liquid carbon dioxide injection system, and high-pressure blower are located outdoors. Programmable logic controllers (PLCs) and PCs are used to collect test data as well as to perform test loop control functions. Figure 5 shows the meter testing area of the Triple Point facility.

6. Operating Capabilities

The recommendations contained in the current revision of AGA-7 are based on a comprehensive research program in the characteristics of modern commercial gas turbine meters. The research work cited in references 7, 8, and 9 shows that turbine meters are generally sensitive to Reynolds number, particularly at lower flow rates and pressures. Based on this knowledge, the Triple Point facility was designed to operate over the range of measurement conditions in which turbine meters have been observed to suffer from non-linearity.

At a peak flow rate of 230,000 ACFH, Triple Point is capable of testing the full flow range of an extended-capacity 12-inch turbine meter. The test loop supports the maximum volumetric flow rate at 160 psia. With the test loop operating at the maximum design pressure of 240 psia (equivalent to a natural gas test loop operating at roughly 500 to 600 psia), the reduced peak flow rates is approximately 160,000 ACFH. The upper limit of the operating pressure and flow rate is dictated by the mass flow capacity of the high-pressure blower, which drives the test loop. The maximum Reynolds number generated by the test loop is well over 9 million. A summary of Triple Point’s operating characteristics is shown in Figure 6.
The Triple Point facility was commissioned in the summer of 2005. After a year of vigorous evaluation and tests, Triple Point was recognized by Measurement Canada as an approved high-pressure calibration facility for gas turbine meters in August of 2006.

7. Traceability

Since carbon dioxide is not a conventional calibration gas for metering devices, one of the immediate concerns regarding traceability was to establish its suitability for use as a test medium. Prior to construction of Triple Point, a research program was conducted at the Meter Research Facility (MRF) of the Southwest Research Institute. Six turbine meters of 4-inch, 8-inch, and 12-inch diameter from two different manufacturers were tested in both carbon dioxide and natural gas over the widest available range of matching Reynolds numbers. The results of this dual fluid work were published in reference [5]. This research work shows that the calibration results for all six of the meters operating at the same Reynolds number in different test fluids agreed within 0.15%. The K-factors with the different gases is almost identical when plotted against Reynolds number, both tracking non-linearity in the meter’s performance well. The experimental difference is well within the measurement uncertainty of the MRF. From this evidence, it was concluded that carbon dioxide could reliably be used to calibrate natural gas meters. This conclusion is further supported by subsequent observations of other meter test data obtained from Triple Point.

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 meter.

Traceability of other instruments utilized at the facility, such as pressure and temperature transmitters, is maintained by regularly comparing to reference standards, which have been calibrated and certified by Measurement Canada.

8. 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 document [10] as a guideline. The methodology and numerical results are discussed in separate paper entitled “Measurement Uncertainty Analysis of a Close Loop High Pressure Turbine Meter Calibration Facility” [11]. The expanded uncertainty of the calibration facility was determined to be ±0.27% with a confidence level of 95%, a coverage factor of $k = 2$.

9. Inter-facility Comparisons

It is necessary for a high-pressure gas meter calibration facility to compare its performance with those from other accepted test facilities in order to maintain a high level of quality control. Triple Point has participated in many inter-facility round-robin comparisons in the past and will continue to do so in the future. A special multi-facility sponsored artifact has been designed and fabricated for this purpose. This work is now complete and the initial test results will be published once they become available.

10. Conclusion

Pressure sensitivity is an important contributor of measurement errors in turbine meter. This type of error
can be accounted for and reduced by calibrating turbine meters at Reynolds numbers comparable to those anticipated at the pipelines in service. Carbon dioxide gas based prover is a cost effective alternative for testing turbine meters at high Reynolds number with considerably lower operating pressure than natural gas or air. The Terasen Triple Point turbine meter testing facility is a successful demonstration of the Reynolds number and fluid density matching meter calibration technology.

REFERENCES


