Pressure, Temperature, and Other Effects on Turbine Meter Gas Flow Measurement

Paul W. Tang, *M.Sc.,P.Eng.*
FortisBC Energy
16705 Fraser Highway
Surrey, B.C. V4N0E8
Canada

Abstract

This paper explains the general working principle of gas turbine meters and the common causes for turbine metering errors. Field observations and laboratory test examples are presented in this paper. The author also suggests methods to optimize the measurement performance of turbine meter installations.

Introduction

Natural gas billing is typically calculated based on the energy content of the gas consumed. The energy content of the natural gas consumed can be determined accurately by the volume of gas delivered under standard conditions when the gas composition is known. Most gas meters measure flow volume under actual flow conditions. It is therefore necessary to convert the actual flow volume to a base volume under standard conditions for billing purposes. A clear understand of the relationship between the flow volume, temperature, pressure, and other factors affecting gas measurement is crucial to the accurate accounting of gas flow.

The Gas Laws

The general behavior of gases is defined by a set of equations known as the Gas Law equations. The Ideal Gas Law equation describes the relationship between the volume, temperature, pressure, and the quantity of gas molecules under a set of given conditions. The Ideal Gas Law is valid only for a relatively narrow range of pressures and temperatures. A factor known as compressibility is used to account for the difference between a real gas and an ideal gas under a wider range of operating conditions. The "Real" (or Non-Ideal) Gas Law equation is written as follow:

$$PV = ZnRT \qquad (1)$$

In Equation (1), P is the pressure of the gas, V is the volume, T is the absolute temperature, n is the number of moles, R is the universal gas constant, and Z is the compressibility factor of the gas. The compressibility factor Z is characterized by the composition of the gas and is also a function of the temperature and pressure. The temperature, pressure, and the quantity of the gas can be measured. The compressibility of the gas can be modelled and calculated by one of the many Equations of State (EoS). There are many computer software applications available for determining the compressibility of a gas.

Equation (1) may be used to calculate the corresponding volume of a gas under base conditions when a set of temperature and pressure is known. It should be noted that base conditions are legal definitions and may vary under different legal jurisdictions. In the USA, base conditions are defined as 14.696 psia at 60ºF, while in Canada, the base conditions are defined as 101.325 kPa absolute at 15ºC. It is also common for trading parties in the natural gas industry to establish their own contractual base conditions where government regulations are not required. Care must be taken to make sure that the appropriate base conditions are chosen for the base volume calculation.

Temperature and Pressure Measurement

From Equation (1), one can interpret that the precise measurement of temperature and pressure is essential for the accurate determination of standard gas volume. The guidelines for the measurement of temperature and pressure associated with a turbine meter installation is well documented by government agencies and industrial organizations such as the American Gas Association (AGA), Measurement Canada (MC), the European Committee for Standardization (CEN), International Organization of Legal Metrology (OIML)…etc.. Recommendations offered by these organizations should be carefully observed to avoid or minimize measurement error.

The placement of thermowell and pressure tap in a turbine meter run is very important for the proper sensing of the flow temperature and pressure. Modern temperature and pressure sensors are extremely accurate and reliable. The common errors in temperature and pressure measurement are usually caused by the improper installation of the sensors and rarely due to the inaccuracy of the sensing instruments. For a meter installation operating close to an ambient temperature of 60ºF, a rule of thumb estimate is for every 1ºF error in temperature measurement, the corresponding base volume calculation error would be approximately 0.2%. The base volume error due to pressure measurement is proportional to the percentage error of the pressure measurement.

While the Gas Law consideration in a flow channel is significant, the internal temperature and pressure effect of a turbine meter should not be overlooked. Temperature and pressure affect turbine meters of different designs in different ways. Extreme temperature and pressure can bring about dimensional changes in a meter body. In some cases, even small changes in the flow temperature or pressure can shift the calibration of a flow meter. Meter manufacturers should be consulted if a flow meter is to be operated under extreme conditions.

Temperature and pressure also affect a turbine meter beyond dimensional changes. Figure 1 shows the typical error performance curve of a turbine meter. It is possible to express the error performance of an ideal turbine meter by a straight line with a fixed amount of measurement error throughout the entire capacity range. However, other conditions must be considered for a more realistic representation of the

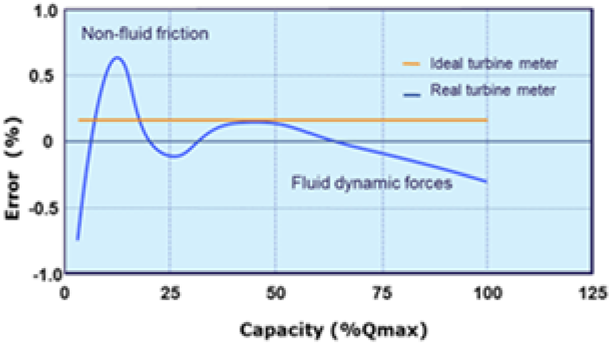
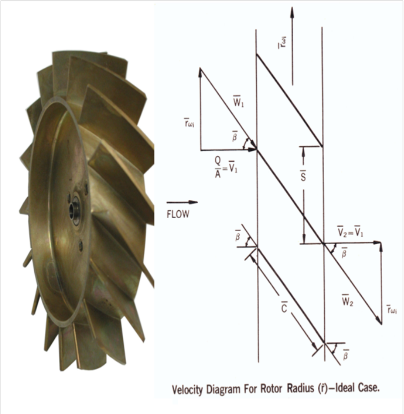


Figure 1 Effect of fluid and non-fluid retarding torques on gas turbine meter performance

behavior of a turbine meter. At high flow rates, the meter responds to the pipe Reynolds number of the flow. Further explanation about Reynolds number will be given later in this paper. Under low flow conditions, bearing friction plays a dominant role in the error characteristic of a turbine meter. The pressure exerted by the gas flow on the bearings together with the viscosity of lubricant acting on the bearings overshadow the fluid dynamics force on the rotor. This force is known as the non-fluid friction. The calibration shift of a turbine meter due to this retardation force can be accurately predicted by mathematical models. Users of turbine meter should be aware of this effect and make suitable adjustments in their measurement.

How Turbine Meters Work

Turbine gas meters are inferential meters. A gas turbine meter is basically an instrument that converts a portion of the kinetic energy of a moving gas stream into the movement of a rotor. It measures gas volume by counting the number of revolutions accumulated by the rotor. At a given flow rate Q, the rotor of the turbine meter spins at an angular velocity ω_i as shown in Figure 2. For an ideal turbine meter, the rotational speed of the rotor should be directly proportional to the volumetric flow rate of the flowing gas. The relationship between the flow rate Q and the angular velocity ω_i can be expressed as follow:



$\bar{r}$	is the average of the rotor radius
Q	is the volume flow rate
A	is the annular flow area
$\bar{\beta}$	is the blade angle
V_1, V_2	are the gas velocities at point (1) and (2)
W_1, W_2	is the fluid velocity relative to the rotor blades
ω_i	is the ideal angular velocity

$$\frac{\omega_i}{Q} = \frac{\tan\bar{\beta}}{\bar{r}A} \qquad (1)$$

$$Q = \frac{\bar{r}A\omega_i}{\tan\bar{\beta}} \qquad (2)$$

The angular velocity of the rotor is proportional to the volume flow rate

Figure 2 Angular velocity of a turbine meter rotor

$$Q = \frac{\bar{r}\ A\ \omega i}{\tan\bar{\beta}} \qquad (1)$$

From equation (1), one can assume that the volumetric flow rate of the gas is proportional to the angular velocity of the rotor:

$$Q \propto \omega\imath \qquad (2)$$

However, the performance of a real turbine gas meter is far from ideal. It is affected by many more additional factors. In fact, the angular velocity of the rotor in the turbine meter is only roughly proportional to the volumetric flow rate of the flowing gas. Slippage occurs due to the retarding torque at the rotor. This retarding torque is composed of the following two components:

a. Non-fluid forces - dominated by mechanical friction;
b. Fluid dynamic forces - caused mainly by fluid drag and turbulence.

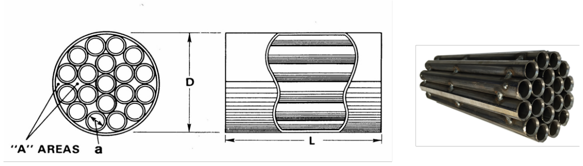
The non-fluid retarding forces are caused by the friction of the rotor bearings and the mechanical loading of the drive train in the flow indicating registers as explained in the previous section. The fluid dynamic retarding forces are made up of the fluid drag which is a function of the Reynolds number of the flow, and the flow turbulence which is a function of the flow velocity. The contribution of these factors to the overall performance of a turbine meter was illustrated in Figure 1.

Performance of Turbine Metering System

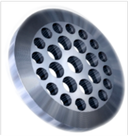
Turbine meters measure flow velocity. They can only make accurate flow measurement in a pipe conduit with a properly formed flow profile. Careful consideration therefore must be given to the design of the piping immediately upstream and downstream of a turbine meter to facilitate the forming of a proper flow profile. An effective way of dealing with flow profile distortion is to provide sufficient length of straight pipe upstream and downstream of a turbine meter. A long piece of straight upstream piping allows all of the energy of the flow disturbance to dissipate in the pipe before it reaches the turbine meter. A great deal of research work has been done in the past by the gas industry to define the minimum piping configuration for turbine metering stations. In North America, the AGA Report No. 7 [1] is often used to provide guidance for the design of metering stations for various types of turbine meters under different field conditions. A typical installation requires ten pipe diameters of straight pipe upstream and five pipe diameters of straight pipes downstream of a turbine meter as shown in Figure 3. In Canada, Measurement Canada requires turbine meters to be type approved and metering stations to follow piping configurations recommended by the meter manufacturers. Following these guidelines greatly reduces the risk of flow measurement errors caused by flow profile related problems [2].

The most common types of flow profile distortion are caused the swirling and the jetting of gas flow brought on by placing a turbine meter too close to a control valve or reducer fittings. An upstream elbow in proximity to a turbine meter is problematic. Providing sufficient length of pipe upstream and downstream of a turbine meter will help to smooth out most of these types of disturbances. The flow profile will eventually settle back into a uniform pattern in a long straight pipe. Unfortunately, most metering stations do not have the luxury of space for long meter runs. Many metering stations were designed only to meet the minimum pipe length requirements. It is therefore very important to pay attention to the auxiliary equipment used to mitigate the flow profile distortion. A conventional flow profile correcting device is the 19-tube bundle straightening vanes. A flow conditioning plates may alternately be used to serve the same purpose. Examples of these flow profile correcting devices are shown in Figure 4. Tube bundles are effective in removing swirl conditions [3]. However, they have a

Figure 3 AGA 7 recommended meter run configuration tendency to freeze the velocity profile of the flow. Experimental results show that tube bundles are not particularly effective in removing jetting flow problems. Flow conditioning plates are better suited for this task. Conditioning plates are plates perforated with special patterns designed to isolate the flow in order to produce an optimal profile for the turbine meter.



19-tube bundle straightening vanes



Flow conditioning plate

Figure 4 Tube bundle and flow conditioning plate

Conditioning plates are very effective in eliminating swirling and jetting problems. However, they may introduce higher pressure loss than tube bundles. Some turbine meter manufacturers have incorporated the design of a flow conditioner inside the flow channel of their meters. These products can be used in "close-coupled" installations where space is at a premium.

While swirling and jetting problems are typically generated in the vicinity of a turbine meter, measurement errors caused by pulsating flow may originate a long distance away from a metering station. Pulsating flow is a series of longitudinal waves generated by unsteady flow conditions. This can be caused by the presence of a reciprocating compressor, or an unstable pressure regulator upstream or downstream along the pipeline. A well-built turbine gas meter has good bearings to minimize mechanical

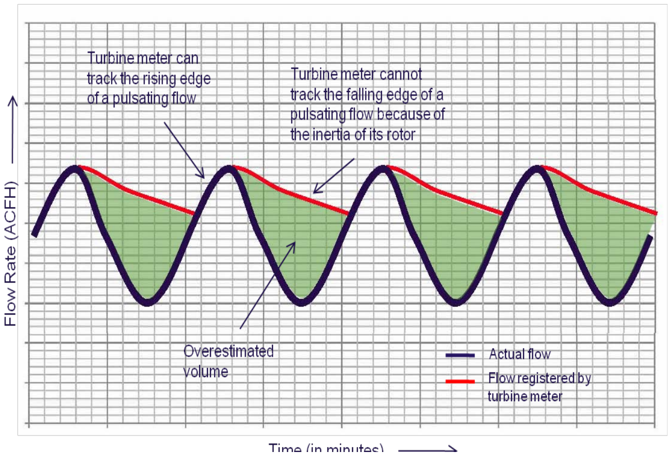


Figure 5 Typical turbine meter response to a pulsating gas flow

friction. It also has rugged and heavy rotor body built to withstand the stress exerted by the gas flow. A good turbine meter typically has a very long spin time. Unfortunately, the same physical attributes that make a good turbine meter also cause it to display an asymmetrical transient response to gas flow. A turbine meter can typically respond quickly and track an accelerating flow well, but unable to slow down as fast when the flow is quickly reduced or interrupted. Figure 5 shows a turbine meter's response when it was subjected to a pulsating flow. The meter correctly captured the flow measurement on the rising portion of a sinusoidal flow curve. It failed to track the flow on the trailing portion when the flow was slowing down. This resulted in the overestimation of the total flow volume. The asymmetrical transient response characteristic of a turbine gas meters varies depending on their sizes. The time scale shown in Figure 5, in minutes, is typical for a turbine meter of 8-inch diameter or less. Larger turbine meters have longer time constants. Flow pulsation can be reduced to certain extent by incorporating surge filtering devices at a metering station. However, such filtering devices are expensive and their presence adds unnecessary complexity to a metering station. It is far more desirable to identify any potential pulsating flow problems in advance and to avoid the placement of a turbine metering station at such locations.

Many other internal factors affect the accuracy of a turbine meter. A well-built and well calibrated turbine meter is capable of measuring flow volume with error that is less than ±0.25% error. However, maintaining such level of performance requires due care. A common field problem experienced by turbine meters is the result of excessive mechanical friction caused by dried out or damaged bearings. The bearings in a turbine meter must be oiled regularly according the manufacturer's recommendation. Excessive mechanical drag due to dirt or the lack of maintenance can cause a turbine meter to slow down substantially, and eventually damage the bearings as shown in Figure 6.

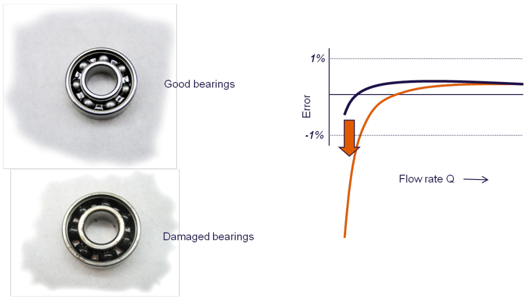

Dirt accumulated in bearings slows down a turbine meter, therefore results in underestimated flow volume.

Figure 6 Typical error caused by bearings damage

Spin test is a very effective way of determining the health status of a turbine meter. A well-built turbine meter has a consistent spin time that is repeatable within a few seconds out of several hundreds. Comparing the field spin time with the factory published figures provides a good estimate about the condition of a turbine meter. A shorter than expected spin time for a turbine meter module is typically a warning sign for potential bearing damage. It usually results in a reduction of the meter's rangeability. Failed spin time tests may also be a symptom of mechanical problem within the drive train mechanism of the top plate. A spin time test can be performed either on the bench or in situ. The detailed procedure for performing a spin test can be found in most turbine meter manufacturers' maintenance manuals.

One of the often-overlooked source of turbine meter measurement errors is the flow path within the meter. Operating with a mismatched meter body or a damaged flow conditioning element will alter the fluid dynamic characteristic of the meter. Even minute damage or deformation on the nose cone flow straightening element can produce an unacceptably large measurement error. Figure 7 shows the nose cone of a turbine meter with an almost unnoticeable corner of one of the straightening fins being broken. Laboratory test result shown that this meter had shifted in excess of 2% from its original calibration. This example demonstrates the importance of keeping the flow channel of a turbine meter clean and free of debris or damage.

A conventional turbine meter has a single rotor. The dual rotor turbine meter was developed much later by meter manufacturers to address several turbine meter error problems discussed earlier. The secondary rotor is typically used for checking the measurement integrity of the primary rotor. In some advanced products of this category, the output of the secondary rotor is used to make automatic adjustment to the output of the primary rotor to nullify or reduce the effect of some of the error contributing factors discussed earlier [4]. This type of turbine meters is very effective in preserving measurement accuracy under hostile operating conditions. To demonstrate this fact, the damaged nose cone shown in Figure 7 was installed in a dual rotor turbine meter body in our laboratory and tested again under the same flow conditions. The adjusted flow measurement error shift was observed to be less than 0.5%. This magnitude of measurement improvement seemed to substantiate the manufacturer's claim about the product's immunity to certain types of mechanical damage and aerodynamic disturbances.

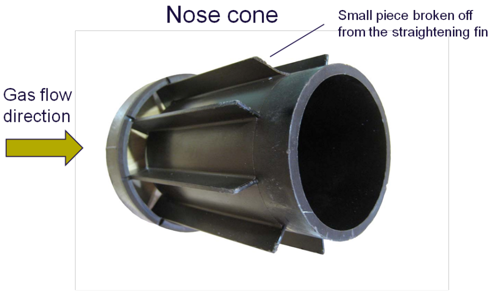


Figure 7 Laboratory tests showed that small damage on the nose cone resulted in a measurement error of nearly 2%

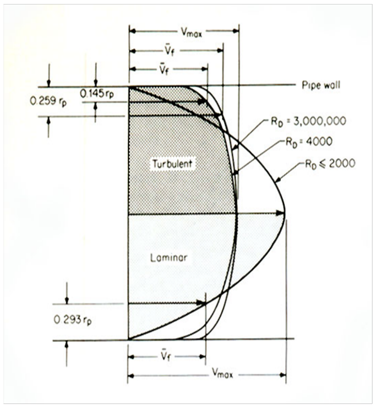
Reynolds Number

The pipe Reynolds number is a dimensionless number. It is calculated by using the gas flow velocity, the meter run diameter, and the physical properties of the gas flowing in the pipe. For a gas with density ρ, dynamic viscosity μ, flowing through a meter run of diameter D, and at a velocity ν, the Reynolds number is :

$$Re = \frac{\rho v D}{\mu} \qquad (3)$$

Reynolds number can be interpreted as a ratio of inertia force versus viscous force in a pipe flow. A relatively low Reynolds number ($Re < 2000$) indicates that viscous forces dominate and the flow is laminar in nature. The velocity of a laminar flow exhibits a parabolic cone shaped profile across the pipe diameter as shown in Figure 8. A high Reynolds number ($Re > 4000$) indicates a turbulent flow. The flow is in a transitional state when the Reynolds number is roughly between 2000 and 4000. The profile of a transitional fluid flow is typically complex and unstable.

Reynolds number is a very important parameter in explaining the concept of dynamic similarity of fluid flow. The principle of dynamic similarity stipulates that an object will behave the same way when it is exposed to a fluid flow with the same Reynolds number. For example, the rotor of a turbine meter will rotate at the same angular velocity when it is subjected to a flow of fluid with the same Reynolds number regardless of the composition, pressure, or temperature of the fluid. The dynamic similarity principle makes it possible for engineers to test scaled model of an object in a wind tunnel or flow channel in order to predict the corresponding behavior of the full-size item. It also allows measurement engineers to characterize the performance of a turbine meter operating in a different fluid or under a different set of flow conditions.



Laminar if Re < 2000

Transient if 2000 < Re < 4000

Turbulent if Re > 4000

Reynolds Number examples:

12” Standard Capacity Meter at 350 psia

at 10% of capacity Re = 700,000

at 95% of capacity Re = 6,800,000

Velocity Profiles in Laminar and Turbulent Pipe Flow

Flow Measurement Engineering Handbook – R.W. Miller, McGraw-Hill

Figure 8 Flow profiles at various Reynolds numbers

Pressure Effect on Turbine Meters

The pressure dependency of a turbine meter is a well-known phenomenon. Figure 9 shows a series of turbine meter error versus Reynolds number curves plotted at three different operating pressures. Both atmospheric air and pressurized natural gas were used in this example in order to cover a wider Reynolds number range. This example shows that the flow rate and operating pressure has significant effects on the

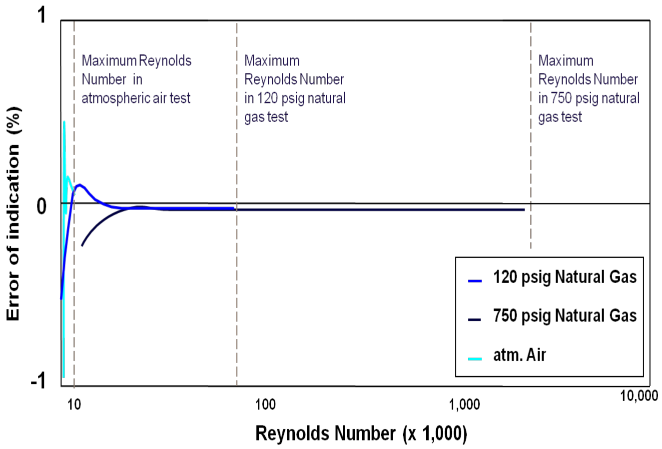


Figure 9 Turbine meter error vs Reynolds number

accuracy of a turbine meter. At low flow rates and low operating pressures, i.e. low Reynolds number, the non-fluid force has a dominant influence on the error performance of the meter. At high flow rates and high pressures, i.e. high Reynolds number, the non-fluid drag component of the retarding torque diminishes, and the meter responds strictly to the Reynolds number of the flow. Hence the error curve of the meter becomes much more linear and predictable.

A turbine meter's performance curve is typically expressed in terms of its flow measurement errors versus the corresponding volumetric flow rates. A family of curves is necessary to characterize the error performance of a turbine meter at different pressures or in a different fluid. An example of this is given in Figure 10. In this example, an 8-inch turbine meter was first calibrated in air at atmospheric pressure in our laboratory. The meter was then calibrated again in carbon dioxide gas at both 40 psia and 134 psia respectively. A set of three error curves was produced to demonstrate the meter's error performance operating in the two test fluids at different pressures and densities. Each one of these three curves was distinctly different from the other two. It was not possible to visualize their physical relationship by observing the curves in this form. Furthermore, it is quite evident from Figure 10 that any one of these three performance curves did not represent the behavior of the meter operating at the same flow rate under different conditions. In this example, most of the error differences did not exceed 1% when the operating conditions were changed. However, research work published by the AGA and also by the Gas Research Institute [6, 7, and 8] reported that metering errors of this magnitude or higher are not uncommon. It was suggested that accurate turbine meter calibrations can only be obtained when a calibration program is tailored to a set of specific flow conditions under which the meter is expected to be used in the field. The latest revision of the AGA No. 7 Report [1] suggested that "*a meter calibration carried out in a test facility over a particular range of Reynolds numbers characterizes the meter's performance when used to measure gas over the same range of Reynolds numbers when the meter is in service*". It further recommended that "*the expected operating Reynolds number range and/or density for a meter needs to be taken into account when designing a calibration program*".

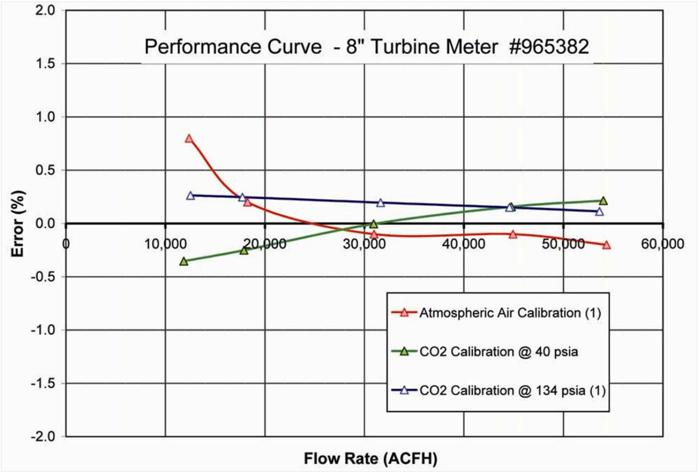


Figure 10 Line pressure effect on turbine meter flow measurement error

To understand the turbine meter test result from a different perspective, the data points in Figure 10 were consolidated and the error curves redrawn and plotted against Reynolds numbers in one single line. The resulting Reynolds numbers account for the differences in flow velocity and densities of the two different test fluids. The performance curve thus obtained showed a new level of simplicity. The shape of the new curve shown in Figure 11 bore much resemblance to the theoretic curve expressed in Figure 9. It is also apparent that the data points with similar Reynolds numbers exhibited the same error characteristics, thus confirming the validity of the AGA 7 recommendations [1].

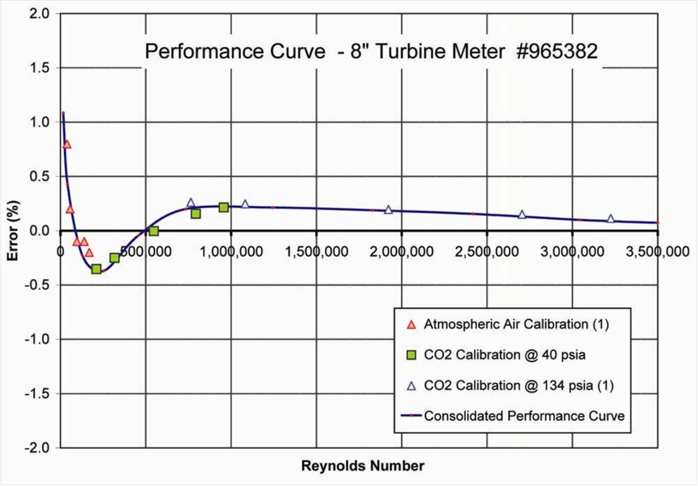


Figure 11 Error performance of the same turbine meter vs Reynolds Number

Calibration of Turbine Meters

Proper calibration is the key for ensuring good measurement accuracy for a turbine meter. Calibration is a process of comparing an instrument under test to a reference standard of known accuracy. This process either validates or provides correction for the instrument under test based on the comparative result with the reference standard.

Calibrations of turbine meters intended for natural gas applications are typically carried out in test facilities using natural gas test medium. Natural gas based meter calibration facilities capable of working over a wide range of pressures and temperatures are difficult and costly to build and operate. Calibrating natural gas turbine meters with a different gas is an alternative solution. For example, calibration of turbine meters in atmospheric pressure air is recognized by most regulatory agencies in the world as a valid procedure. Most turbine meter manufacturers provide an atmospheric air calibration certificate when a meter is shipped. An atmospheric air calibration is easy and inexpensive to performance, but the data is only applicable for a flow range with very low Reynolds numbers. Using atmospheric air calibration factors for high pressure natural gas applications can result in excessive measurement errors as demonstrated in the experiment described in the previous section. Simple calculation shows that even a 0.5% measurement error for a 12-inch turbine meter operating at 500 psig may cost a gas company or its customers several million dollars in a six-year recalibration cycle [9]. Properly defining the calibration specifications for a turbine meter application eliminates one of the significant sources of flow measurement error.

Natural gas and atmospheric air are by no means the only gas media for testing turbine meters. Carbon dioxide gas has been used successfully for the same purpose [1, 9]. Calibrating turbine meters in carbon dioxide gas has many advantages. Carbon dioxide is non-combustible and much safer to handle than natural gas in a test facility. It can be compressed and circulated in a test loop to generate high Reynolds number flow at a considerably lower operating pressure. Experimental results have confirmed that calibrations of turbine meters at a carbon dioxide test facility were indistinguishable from those calibrated at a high pressure natural gas test facility [10].

Since calibration is so important to flow measurement accuracy, many regulatory agencies and professional organizations have recommendations for good gas turbine meter calibration practices. The International Organization of Legal Metrology (OIML) R137-1-2006 document [11] recommends that turbine meters be calibrated at or close to their operating conditions. In Europe, the European Committee for Standardization (CEN) EN12260-2002 [12] specifies that turbine meters operating at or below 60 psig (4 bar) may be calibrated at atmospheric pressure, while turbine meters operating beyond 60 psig must be calibrated close to their field conditions. The American Gas Association (AGA) has similar recommendations that have been discussed in a previous section of this paper. Measurement Canada does not require turbine meters to be calibrated at their operating pressures at this time. However, they have stated on a number of occasions their intention to mandate the requirement to calibrate turbine meters at a pressure that is commensurate with their intended use.

Conclusion

Turbine meter is the workhorse of the natural gas measurement industry for more than fifty years. It is easy to use, reliable, rugged, and accurate. It is necessary to pay attention to certain design and operational details of a turbine meter in order to get the best error performance. This paper briefly highlights some of the factors that affect the error performance of a turbine meter installation. Observing the guidelines presented in this paper will help a turbine meter user to achieve and maintain a high level of flow measurement accuracy.

REFERENCES

[1] A.G.A. Transmission Measurement Committee Report No. 7, "*Measurement of Natural Gas by Turbine Meters*", American Gas Association, Washington, D.C., April 2006.

[2] Miller, R.W., "*Flow Measurement Engineering Handbook*", McGraw-Hill Book Company, March 1996.

[3] Mattingley G. E. and T. T., Yeh,' *Effects of pipe elbows and tube bundle on selected types of flow-meters*', Flow Meas. Instrument., 2, pp. 4-13, 1991.

[4] Honchar, P.,' *Fundamentals of Turbine Meters*', Canadian Gas Association, Gas Measure School, Ottawa, 2007.

[5] Reid R.C, Prausnitz J.M, Sherwood T.K.,"*The Properties of Gases and Liquids*", McGraw-Hill Book Company, 1977.

[6] George, D. L., GRI Topical Report GRI-01-0226, "*Metering Research Facility Program: Turbine Meter Research in Support of the Planned AGA Report No. 7 Revision*" Gas Research Institute, Des Plaines, Illinois, January 2003.

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

[8] George, D. L., GRI Topical Report GRI-03-0172, "*Metering Research Facility Program: Effects of Line Pressure and Gas Density on Turbine Meter Measurement Accuracy at Conditions from Atmospheric Air to 700 psig in Natural Gas*". Gas Research Institute, Des Plaines, Illinois, August 2004.

[9] Tang, P.W., "*Improving Turbine Meter Measurement by Alternate Fluid Calibration*", Canadian School of Hydrocarbon Measurement, Calgary, Alberta, March 2007.

[10] George, D.L., Fraser, H.L., Nored, M., Tang, P.W.,"*Carbon Dioxide as a Test Fluid for Calibration of Turbine Meters*", American Gas Association, Operations Conference 2004, Phoenix, Arizona, May 2004.

[11] International Organization of Legal Metrology (OIML), "*R137-1 International Recommendation – Gas Meters Part 1: Requirements, Section 7.5.5*", Edition 2006 (E).

[12] European Committee for Standardization (CEN), "*EN12261 Gas Meters – Turbine Gas Meters, section 5.2.1.2 - Test*", 2002(E).