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

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Abstract

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

How Turbine Meters Work

Turbine gas meters are inferential meters. They measure gas flow volume indirectly by counting the number of revolutions when a rotor is subjected to a gas flow. A gas turbine meter is essentially a machine that converts the kinetic

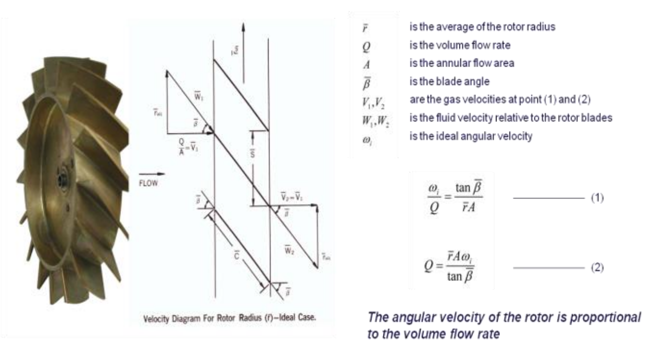

Figure 1 Angular velocity of a turbine meter rotor

energy of a moving gas into rotational energy. At a given flow rate Q, the rotor of the turbine meter would spin at an angular velocity ω_i as shown in Figure 1. With an idealized turbine meter, the rotational speed of the rotor would be directly proportional to the volumetric flow rate of the flowing medium. The relationship between flow rate Q and the angular velocity ω_i can be expressed as follow:

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

From equation (1), one can deduce that

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

The real performance of a turbine gas meter is far from ideal. It is affected by several additional factors that complicate the process. In reality, the angular velocity of the rotor in the turbine meter is only roughly proportional to the volumetric flow rate of the flowing fluid. A slippage of the

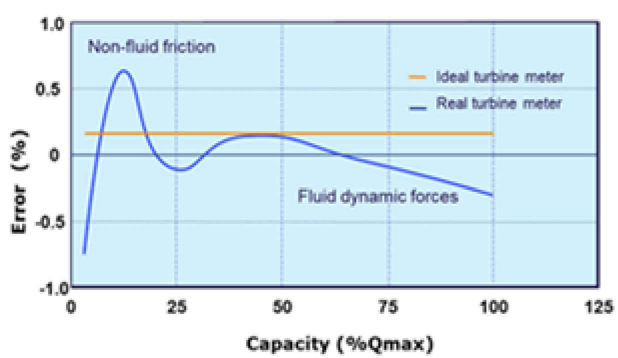

Figure 2 Effect of fluid and non-fluid retarding torques on gas turbine meter performance

rotational speed occurs due to the development of a 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 forces - caused mainly by fluid drag and turbulence.

The non-fluid retarding forces are introduced by the friction of rotor bearings and the mechanical loading of the drive train in the flow indicating registers. The fluid retarding forces are made up of fluid drag which is a function of the Reynolds number of the flow, and turbulence which is a function of the flow velocity. The contribution of these factors to the overall performance of a turbine is shown in Figure 2.

Performance of Turbine Metering System

Turbine meters are velocity sensing devices. They can only make accurate flow measurement when applied to a flow with properly defined flow profile. Careful consideration must be given to the design of the piping immediately upstream and downstream of the meters for this reason. It is important to eliminate situations that may cause flow profile distortion. An effective way of dealing with flow profile distortion is to provide sufficient length of straight pipe upstream and downstream of a turbine meter. Long straight

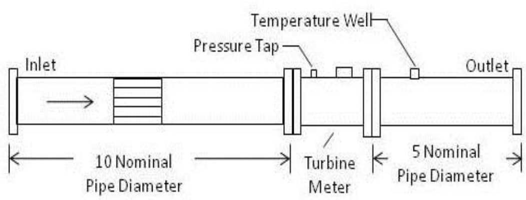

Figure 3 AGA 7 recommended meter run configuration

upstream piping ensures that all of the energy of the disturbance is dissipated before the flow reaches the turbine meter. A great deal of research 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 calls for a minimum of 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 this country, 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 [2] related problems.

The most common types of flow profile distortion are swirling and jetting brought on by placing a meter in close proximity to control valves or reducer fittings, and/or improper placement distance of elbows along a meter run. Given sufficient pipe length upstream and downstream of a turbine meter, these types of disturbance will settle down, and the flow will return to its normal well-developed profile in due course. Unfortunately, most metering stations do not have the luxury of ample space and long meter runs. Many metering stations were designed only to meet the minimum pipe length requirements. It is therefore crucial to pay attention to the auxiliary equipment used to mitigate flow profile distortion problems. The conventional flow profile correcting devices are 19-tube bundle straightening vanes or flow conditioning plates as shown in Figure 4. Tube bundles are effective at removing swirl conditions [3], however they have the tendency to freeze the velocity profile of a flow. Experimental results shown that tube bundles are not particularly effective in removing jetting flow problems. A different type of flow conditioning device is the conditioning plate. These are plates perforated with special patterns designed to isolate the flow in order to form an optimal profile for the meter.

Conditioning plates are very effective in eliminating swirling and jetting. However, they have the unfortunate side effect of introducing more pressure loss than the tube bundles. Several manufacturers have incorporated the design of a flow conditioner in their meters resulting in products that can be used in close-coupled installations where space is at a premium.

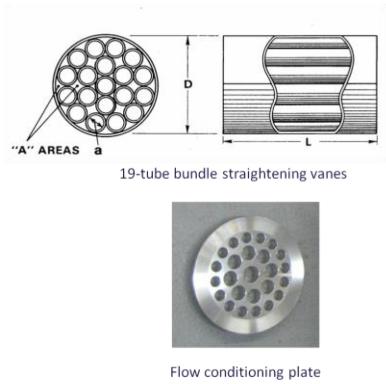

Figure 4 Tube bundle and flow conditioning plate

While swirl and jetting problems are typically created in the vicinity of a turbine meter, measurement errors caused by pulsating flow may originate some distance from a meter. Pulsating flow is longitudinal waves caused by unsteady flow conditions, the presence of reciprocating compressors, or unstable pressure regulators upstream or downstream along the pipeline. Well designed turbine gas meters use good bearings to minimize mechanical friction. They also use rugged rotor bodies to withstand the stress exerted by the force of the moving gas. Unfortunately, the same physical attributes that make a good turbine meter also cause it to display an asymmetrical transient response characteristic to a flow. A turbine meter can respond quickly and track an accelerating flow very well. The same meter, however, will not be able to slow down as fast when the flow is quickly reduced or interrupted. Figure 5 illustrates a turbine meter's response when it was subjected to a pulsating flow. While the meter could correctly capture 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 total flow volume for the measuring duration being overestimated. The transient response characteristic of 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 would have a longer time constant. Flow pulsation can be reduced to a certain extent by deploying surge filtering devices to minimize flow measurement error. However, such filtering devices are expensive and their presence adds unnecessary complexity to a metering station. It would be more desirable to identify pulsation flow problems in advance and avoid the placement of a turbine metering station at such locations.

Many internal factors influence the accuracy of a turbine meter. A turbine meter is a piece of precision instrumentation. A well built, well calibrated turbine meter is capable of measuring flow volume with less than ±0.25% error. However, maintaining such level of performance requires due care. A common field problem experienced by turbine meters can be attributed

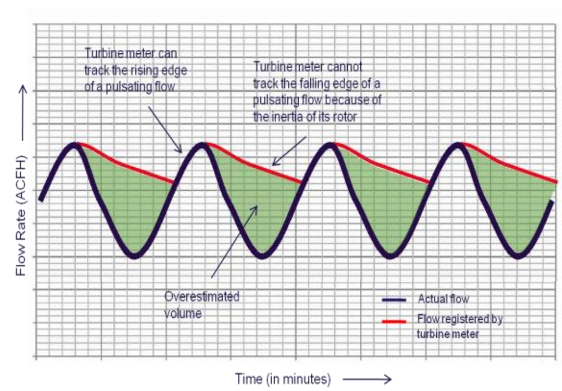

Figure 5 A turbine meter's response to a pulsating gas flow

to 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 lack of maintenance can cause a turbine meter to slow down substantially, and eventually burn out the bearings as shown in Figure 6.

The spin test is a very effective way of determining the health status of a turbine meter module. Most well designed turbine meters have a consistent spin time that is repeatable within a few seconds out of several hundreds. Comparing field spin time with factory provided figures provides a good estimate about the condition of a meter. A shorter than expected spin time for a turbine meter module is typically a warning sign for potential bearing problems and would cause the meter to run with reduced rangeability. Failed spin time tests may also indicate a mechanical problem within the drive train mechanism of the top plate. In most cases, a change in spin time is also a signature for indicating a change in the meter's calibration. A spin time test can be performed either on a bench or in situ. The detailed procedure for performing a spin test can be found in most turbine meter manufacturers' maintenance manuals.

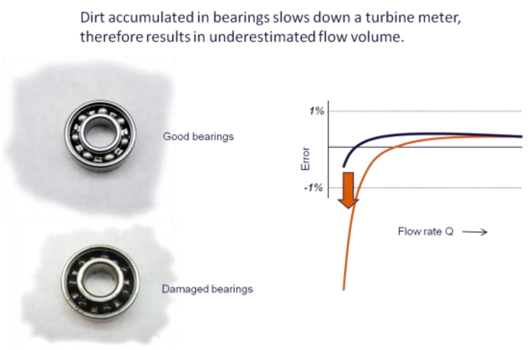

Figure 6 Error impact of bearing damage on turbine meter

One of the often overlooked sources of turbine meter measurement errors is the flow path within the meter. Operating with a changed meter body or a damaged flow conditioning element will alter the fluid dynamic characteristic of the meter. For example, even minute damage or deformation on the nose cone flow straightening element can caused an unacceptably large error. Figure 7 shows the nose cone of a turbine meter with a small corner of one of the straightening fins broken off. Laboratory test results revealed 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.

Conventional turbine meters have only a single rotor. The dual rotor turbine meters were developed much later by meter manufacturers to address several of the turbine meter error problems discussed earlier. The secondary rotor is typically used for checking the measurement integrity of the primary rotor. In certain more 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 in the previous paragraphs [4]. This type of turbine meter has been shown to be effective in preserving measurement accuracy under hostile application environments. To demonstrate this fact, the damaged nose cone previously shown in Figure 8 was installed in a dual rotor turbine meter body and recalibrated at the same facility. The adjusted flow measurement error was reduced to less than 0.5%. This magnitude of measurement improvement seemed to substantiate the manufacturer's claim about the product's immunity to aerodynamic disturbance.

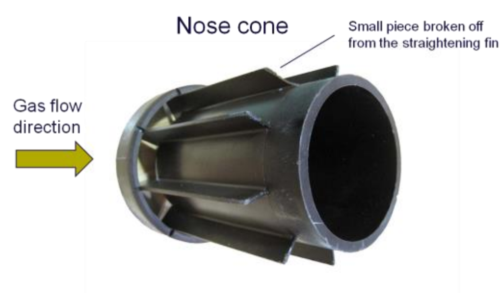

Figure 7 Laboratory tests showed that small damage on the nose cone resulted in a measurement error of nearly 2%

Secondary Parameters

Since nearly all gas flow measurements are not made under standard conditions, secondary parameters must be used to convert the subject flow to a standard volume flow. The computation of standard volume flow requires the application of the Gas Laws and the Equation of State [5]. The Gas Laws express the relationship between volume, temperature, and pressure of a gas. The Equation of State describes the physical state of the gas under a given set of temperature and pressure conditions and a known composition. The Equation of State is typically used to calculate the density and compressibility of the gas medium. The accuracy of temperature and pressure measurements has direct bearing in the accuracy of flow measurement calculations. As a rule of thumb, a measurement error of +1 °F near ambient temperature can results in the under estimation of flow volume by approximately 0.2%. The measurement of temperature and pressure at a turbine meter run must be taken with due care. The installation specification section of the AGA Report No. 7 [1] provides good guidelines for the placement of the temperature well and pressure tap on a turbine meter run.

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 ν, the Reynolds number is given by

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

Reynolds number can be interpreted as a ratio of inertia force versus viscous force. A relatively small Reynolds number (Re < 2000) indicates that viscous forces dominate and therefore the

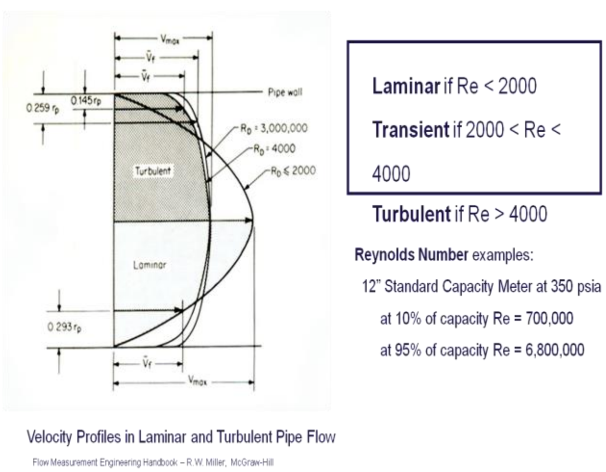

Figure 8 Flow profiles at various Reynolds numbers

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 large Reynolds number (Re > 4000) results in turbulent flow. The fluid flow is in a transition 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 the concept of dynamic similarity of fluid flow. The principle of dynamic similarity stipulates that when an object is exposed to the same Reynolds number environment, it would display the same behavior. For example, the rotor of a turbine meter would rotate at the same angular velocity when it is subjected to a flow of fluid at the same Reynolds number, regardless of the composition, pressure, or temperature of the fluid. 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.

Pressure Effect on Turbine Meters

The pressure dependency of a turbine meter is a well-known phenomenon. Figure 9 shows a series of typical turbine meter errors versus Reynolds numbers plotted at three different operating pressures. Both atmospheric air and pressurized

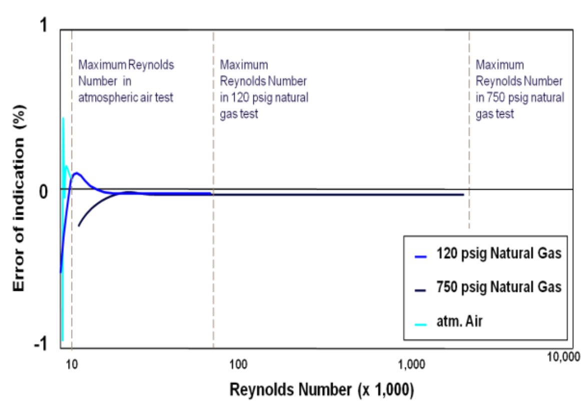

Figure 9 Turbine meter error vs Reynolds number

natural gas were used in this example in order to span a wider Reynolds number range. This example shows that the flow rate and operating pressure has significant effects on the 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 commonly expressed in terms of its metering errors versus the corresponding volumetric flow rates. In order to characterize the error performance of a turbine meter at different pressures or in different fluids, a family of curves

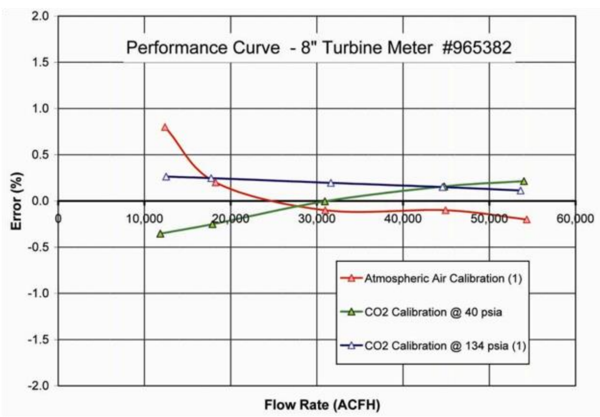

Figure 10 Line pressure effect on a turbine meter

would be necessary. An example is given in Figure 10. In this example, an 8-inch turbine meter was first calibrated in air at atmospheric pressure. 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 has very distinct and different attributes. Given this set of curves, one would not be able to easily visualize the physical relationship between these curves. Furthermore, it is quite evident from Figure 10 that any one of the three calibration curves does not represent the behavior of the meter operating under the other two sets of conditions. In this example, most of the error differences did not exceed 1% when the operating environment was changed. However, research work published recently by AGA and also by the Gas Research Institute [6, 7, and 8] reported that metering errors of this magnitude or higher are not uncommon, and accurate turbine meter calibrations can only be obtained when a calibration program is tailored to a specific flow regime. 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*".

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 test fluids. The performance

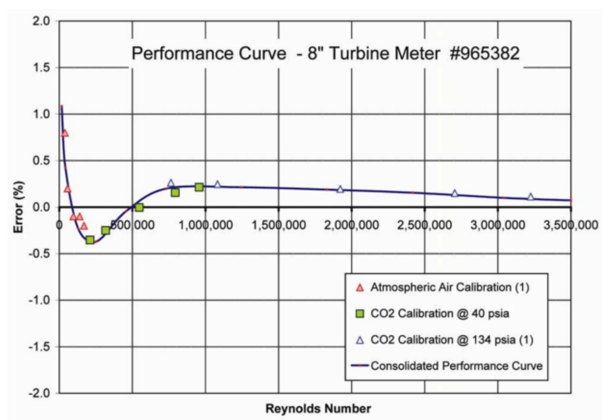

Figure 11 Calibration curve in Reynolds number

curve thus obtained showed a new level of elegance and simplicity. The shape of the new curve shown in Figure 11 looked very much like the theoretic curve expressed in Figure 9. Observed carefully, 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].

Calibration of Turbine Meters

Proper calibration is the key for ensuring good measurement accuracy for a turbine meter. Calibration is a process of comparing one measurement device with another of known correctness. This process either validates or provides correction for the device under test based on the comparative result with the reference device. The reference device is referred to as a calibration 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 an alternate gas is an acceptable 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 purchased and 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. The number of turbine meters used in the natural gas industry operating at such a low Reynolds number range is very limited. As demonstrated in Figure 10, using atmospheric air calibration factors for high pressure natural gas applications runs the risk of making excessive measurement errors. 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 calibration cycle [9]. Specifying the proper calibration 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. In the last few years, carbon dioxide gas has been used successfully in gas flowmeter proving loops [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 revealed 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. While Measurement Canada does not require turbine meters to be calibrated at their operating pressures at this time, it has previously stated on a number of occasions its intention to mandate the requirement to calibrate turbine meters at a pressure that is commensurate with their intended use.

Conclusion

Turbine meters have been a workhorse of the natural gas measurement industry for more than fifty years. They are proven to be easy to use, reliable, rugged, and accurate. In order to get the best performance out of a turbine meter installation, it is necessary to pay attention to certain design and operational details. This paper briefly highlights some of the factors that influence 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.

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