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Pressure Effect on Turbine Meter Gas Flow Measurement

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Abstract: *Pressure sensitivity of turbine gas meters is a well observed phenomenon since the inception of these devices for use in the natural gas industry. However, very little published experimental data was available for study until recent years. Due to the ever increasing emphasis on fair trade, the natural gas industry is paying much more attention to improving the accuracy of natural gas flow measurement. Regulators in many countries either mandated or recommended turbine gas meters to be calibrated close to their intended operating pressures in order to minimize measurement error caused by pressure effect. This paper explains the pressure dependency of gas turbine meters, and the calibration approach to minimize measurement error caused by line pressure effect.*

1. Introduction

A turbine meter is essentially a device that converts the kinetic energy of a flowing fluid into the rotation of the blades on a rotor. The rotational speed of an ideal turbine meter should be exactly proportional to the volumetric flow rate of the flowing medium. However, a real turbine meter operating under field conditions is far from ideal. Observation of the calibration shift of a turbine gas meter due to line pressure fluctuation is a well established phenomenon. To understand the pressure effect on a turbine meter, one must start with the understanding of the concept of fluid flow and Reynolds number. This concept will be explained in more detail later in this paper. Generally speaking, the Reynolds number of gas flow increases with the increase in line pressure. A turbine meter can be considered as 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 operating pressures which characterizes these meters' performance when they are placed in service. However, the current revision of the AGA No.7 Report [3] emphasized that the *k*-factor of a turbine meter should be determined by matching Reynolds number to the field operating conditions. We shall examine the pressure dependency of turbine meters first by explaining the theory of operation of these instruments.

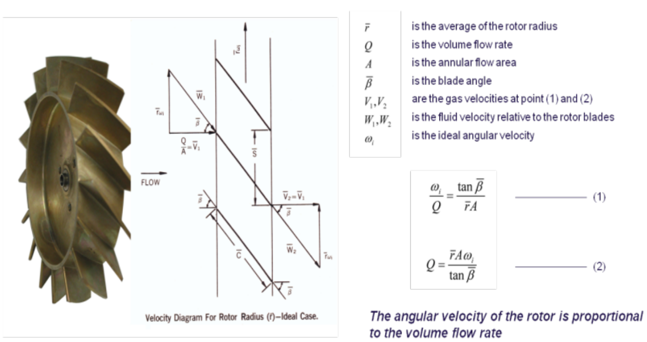

Figure 1 Angular velocity of a turbine meter rotor

2. How Turbine Meters Work

Turbine gas meters are inferential meters. A turbine meter measures gas flow volume indirectly by registering the number of revolutions accumulated when its rotor is subjected to a stream of flowing gas. At a given flow rate Q, the rotor of the turbine meter would spin at an angular velocity ω_i which is proportional to the flow rate as shown in Figure 1. The relationship between the volume flow rate and the angular velocity of the turbine meter can be expressed as follow:

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

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

Expression (2) shows a linear relationship between the volume flow rate Q and the angular velocity ω_i of an idealized turbine gas meter. However, a real turbine gas meter is affected by many additional factors that complicate the process of accurate gas flow measurement. The angular velocity of the rotor in a non-ideal turbine meter in reality is only roughly proportional to the volumetric flow rate of the flowing fluid. A slippage of the 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 individual and combined contribution of these factors to the overall performance of a turbine is shown in Figure 2.

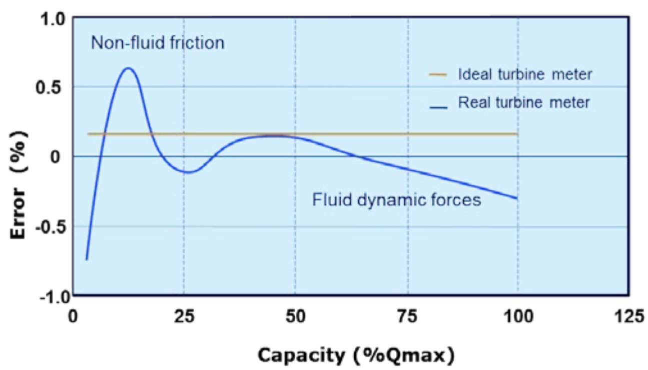

Figure 2 Effect of fluid and non-fluid retarding torques on gas turbine meter performance

3. Reynolds Number

Reynolds number is a dimensionless number which is a function of the gas flow velocity, the pipe diameter, and the physical properties of the gas medium. For a gas of density ρ, dynamic viscosity μ, flowing through a meter run of diameter D, and at velocity v, the Reynolds number of the flow is given by

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

Reynolds number can be interpreted as a ratio of the inertia force versus the viscous force in a fluid flow. A small Reynolds number (Re < 2000) indicates that viscous force dominates and therefore the flow is laminar in nature. Laminar flow is characterized by layered fluid movement. The velocity of a laminar flow exhibits a parabolic cone shaped profile across the pipe diameter as shown in Fig 3. As the Reynolds number increases, the flow velocity profile becomes more uniform throughout the whole pipe diameter. Fluid flow with large Reynolds number (Re > 4000) is known as turbulent flow. Unlike laminar flow, the flow velocity profile of a turbulent flow takes on a much blunter appearance, with exception to the area in close proximity to the pipe wall. The fluid flow is said to in a transitional state when the Reynolds number is between 2000 and 4000. The profile of a transitional fluid flow is typically complex and unstable.

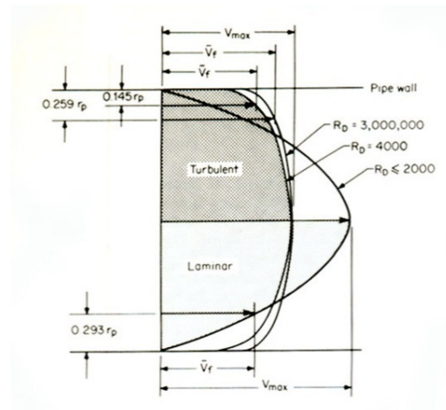

Figure 3 Velocity Profiles in Laminar and Turbulent Pipe Flow. (Source: Flow Measurement Engineering Handbook – R.W. Miller, McGraw-Hill)

Reynolds number is a very important parameter in the concept of dynamic similarity of fluid flow. The principle of dynamic similarity specifies that when an object is exposed to a fluid flow with the same Reynolds number, 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 gas at the same Reynolds number, regardless of the composition, pressure, or temperature of the gas. Dynamic similarity makes it possible for engineers to test scaled models in a wind tunnel or flow channel to simulate the corresponding behavior of a full size object. It also allows measurement engineers to characterize the performance of a turbine meter under very different flow conditions.

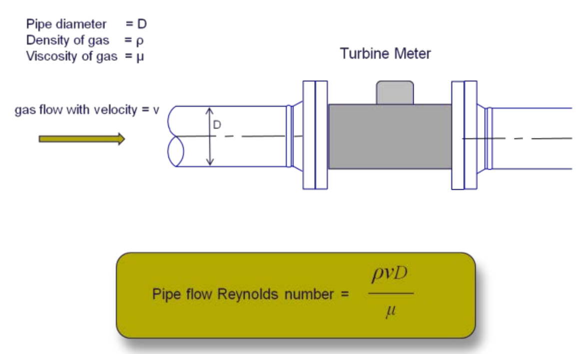

Figure 4 Turbine meter operating in pipe flow

Let us use a pipe flow example shown in Fig 4 to demonstrate the relationship between Reynolds number and line pressure. Assuming that the diameter of the pipe *D* remains constant, then equation (3) stipulates that the Reynolds number of the flow is influenced by the density ρ, dynamic viscosity μ, and velocity v of the flowing medium. For most gases, classical kinetic theory and experimental results show that their viscosity will change very little up to a pressure of 1,500 psia. Viscosity changes are not considered significant in most natural gas flow measurements because the operating pressures typically do not reach this value. Based on the understanding of the ideal gas law, it can be said that the density of a gas is directly proportional to its pressure assuming there is no change in temperature. It is therefore possible to examine the effects of Reynolds number, and hence the operating pressure, on the performance of a turbine gas meter.

4. Pressure Effect on Turbine Meters

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 would be necessary. The American Gas Association's (AGA) Turbine Meter Task Group and the Gas Technology Institute (GTI) sponsored a series of studies on the pressure effect of turbine meters in the early 2000's. The objective of these studies was to provide test data to support the planned revision of the American Gas Association turbine meter standard, the AGA No. 7 Report. In the first set of tests conducted in 2002 at the Meter Research Facility (MRF) of the Southwest Research Institute (SwRI), a sample of commercially available turbine meters of various designs was tested in natural gas at line pressures ranging from 30 to 700 psig. The test result shown that line pressure changes did affect the metering errors of all of the turbine meters used in this experiment. Although most of the sample meters reported less than ±1.0% calibration shift over the entire pressure range, three of the nine meters tested did exhibit calibration shifts more than ±1.0%. This set of tests confirmed that the metering error caused by calibration shift of some turbine meters under changing line pressures is significant.

Since a large number of turbine meters used in the natural gas industry were calibrated and sealed using data generated by atmospheric tests, it would be valuable to investigate the potential calibration shift of these meters when they are used in applications at higher pressures. In 2003, the Gas Research Institute sponsored a second set of tests to do just that. Eight turbine meters used in the 2002 pressure effect study were selected for these tests. The samples included turbine meters of different manufacturers and designs. These tests were conducted both at the Southwest Research Institute (SwRI) and the Colorado Engineering Experiment Station, Inc. (CEESI). The objective of this study was to supplement the 2002 study with gas flow test data at Reynolds numbers and densities ranging from atmospheric air conditions to the lower limit of test conditions at the Meter Research Facility (MRF). The maximum K-factor shifts of the sample meters at flow rates over 20% of the maximum rated flow rates (Qmax) of these meters were within ±2.5%. However, the maximum *k*-factor shift for one of the sample meters tested at flow rates lower than 20% of Qmax was found to exceed 7%.

The test results and analysis of the two studies were published by the GTI as topical reports [4, 5]. These reports provided valuable references for the AGA Task Group R7 in revising the Transmission Measurement Committee Report No. 7 "*Measurement of Natural Gas by Turbine Meters*"[3] published in April of 2006.

5. Matching Reynolds Number with Dissimilar Fluids

Using the principle of dynamic similarity, it is possible to create a flow condition of equal Reynolds number at different pressures and temperatures using different fluids. From equation (3), the Reynolds number of a pipe flow was shown to be directly proportional to the product of the density-viscosity ratio (ρ/μ) of the flowing fluid and the velocity of the flow (v). Since the density or the viscosity of a fluid of a known composition is defined by the equation of state (EOS) of that fluid at the prevailing temperature and pressure, one can make a turbine meter to behave the same way in a pipe flow of different fluids by manipulating the composition of the fluid, the temperature, pressure, or the volumetric flow rate.

An example of Reynolds number matching for dissimilar fluids is given in Figure 5. In this example, an 8-inch turbine meter was first calibrated in air at atmospheric

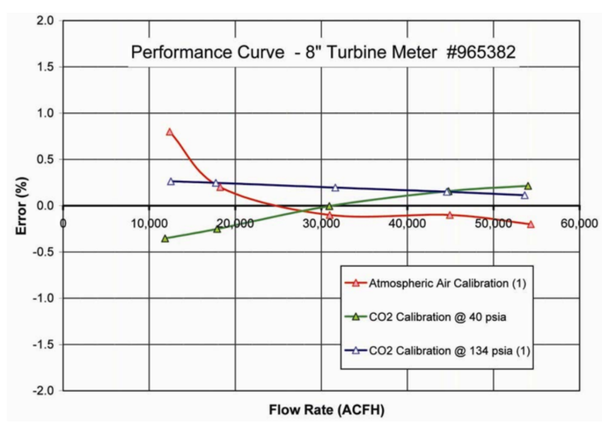

Figure 5 Turbine meter performance in different fluids plotted against flow rate

pressure. Pure carbon dioxide gas was then introduced, and the same turbine meter was calibrated at both 40 psia and 134 psia respectively. Figure 5 shows the error performance curve of the meter over the full flow range, operating both in atmospheric air and carbon dioxide gas at the two different pressures. The vertical axis of this chart was expressed in percent error, while the horizontal axis was indicated in volumetric flow rate in ACFH.

The atmospheric air test curve, shown in red in Figure 5, is typically supplied by the meter manufacturer when a turbine meter is purchased. In many jurisdictions, the *k*-factor derived from an atmospheric air calibration of a turbine meter is allowed to be used for higher pressure applications. The other two curves, shown in green and blue, are the performance curves of the meter in pressurized carbon dioxide gas. It can be seen on this chart that each one of these three curves has very distinct and different characteristics. Should these calibration curves be shown individually, one would not be able to easily identify and visualize the physical relationship between them. Furthermore, it is evident from this chart that any one of these three calibration curves does not represent the behavior of the meter operating under the other two sets of operating conditions.

In order to gain some theoretical insights about the test data in Figure 4, it is necessary to reconsider them in terms of Reynolds numbers. Applying the principle of dynamic similarity, one would expect the turbine meter under test to behave the same way at the same Reynolds number even though the flowing fluids and the operating conditions were different. To demonstrate the turbine meter test data from the Reynolds number perspective, the data points

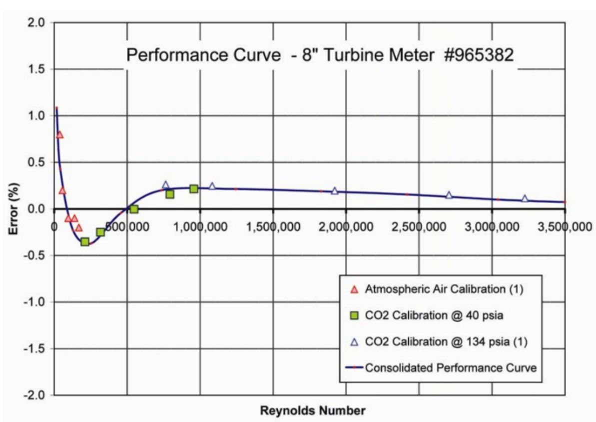

Figure 6 Turbine meter performance in different fluids plotted against Reynolds numbers

shown in Figure 4 were consolidated and the error curves redrawn and plotted against Reynolds numbers in one single line. In this case, the 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 6 looked very much like the theoretical curve expressed in Figure 2. Observing the data points with overlapping Reynolds numbers, it is also apparent that the data points with similar Reynolds numbers exhibited the same error characteristics. This experiment confirmed the validity of the AGA 7 recommendations that the *k*-factor of a turbine meter should be determined by matching Reynolds number to the field operating conditions.

6. Inter-facility Comparison

It is important for flow laboratories to compare their performance with other recognized test facilities in order to maintain a high level of quality control. A special artifact was designed and fabricated for this purpose [6]. The participants of this program were the MFR of the SwRI, the TransCanada Calibrations (TCC) Facility, and the FortisBC Triple Point Facility. The test fluid was natural gas at the first two facilities and carbon dioxide gas at the third. Figure 7 shows the test data collected in the

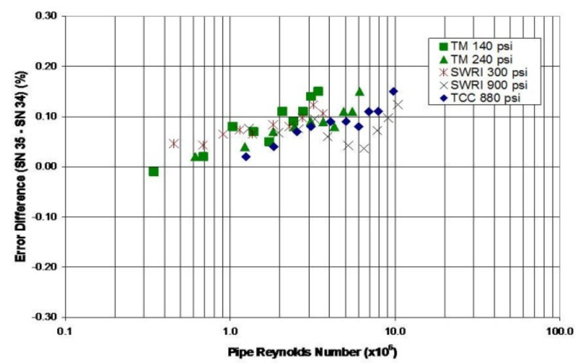

Figure 7 Inter-comparison of an artifact's error performance at Triple Point (TM), MFR (SwRI), and TransCanada Calibrations (TCC). The results show good agreement between the three flow laboratories with different test fluids

2009 round robin. While the test fluids and test pressures were different at these three facilities, the agreement of metering error was better than ±0.1% between the three participating facilities. These test results provided further evidence to support the validity of the Reynolds number matching method.

7. Conclusion

Pressure sensitivity is an important contributor to measurement error for turbine gas meters. This type of error can be accounted for and reduced by calibrating turbine meters at Reynolds numbers comparable to those anticipated at pipeline operating conditions. The Reynolds number method is valid for different flowing fluids and line pressures. The experimentation described in this paper is a successful demonstration of the Reynolds number matching method for turbine meter calibration.

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