Calibration and Verification of MEMS Mass Flow Meters for Custody Transfer

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Abstract: Thermal mass flow meters are commonly of full scale accuracy and not considered for applications where custody transfer is required. Recent advancement of MEMS mass flow technology in city natural gas metering has demanded a better calibration and verification procedure so that the custody transfer can be justified with regard to the traditional thermal mass flow meter technology. The thermal mass flow sensor could be impacted by the humidity, gas composition and temperature. Calibrations with one standard may often be not applicable to the others if each of the factors is not fully accounted; even the meter itself has been well designed and immune to the variables. In this paper, we will discuss the calibration procedures and measurement uncertainties of the MEMS mass flow meters. The results indicated that with the MEMS meter designed for processing the variables, the MEMS thermal mass flow meters either with calorimetric and/or energy dispersion principle can be applied for custody transfer with a generally acceptable accuracy of ±1.5% or better.

Keywords: MEMS flow meter, Custody transfer, Calibration methodology

1. Introduction

The demands for better management of the city gas have been seeking new metering technologies in addition to the communications via remote data transmission and networking, since the current technologies of diaphragm, rotary and turbine that have been serving the industry for more than a century could not effectively provide the satisfactory solutions. These technologies are respectable for their simplicity, proven reliability and accuracy, which are the basic requirements for custody transfer. Nevertheless, the current technologies all have some fatal problems to meet the requirements for today's management infrastructure. Adding an electronic converter to the diaphragm meter has been troublesome not only for its high cost but its high chance of inconsistency between the electronic data and those in its mechanical recorder, in addition to the difficulties for incorporation of temperature and pressure compensation devices. The turbine meters do not have enough resistance to the pulse flow and the small dynamic range would often under-measure in custody transfer resulting in irrecoverable loss for the gas companies. Turbine meter installations have been decreasing recently in city gas applications.[1,2] Rotary meters have been competing with turbine meters and gained its market shares in recent years, but the risk of clogging by particles or debris in the pipeline that will shut off the gas supply could be catastrophic in many industrial process such as ceramic process line. Such damages could even lead to legal liability and demands for retroactive reimbursement.

For the gas metering technology, thermal mass technology is among the few that provide the direct mass flow measurement without additional temperature and pressure compensation. However, in the flow range for city gas applications, the traditional thermal mass flow utilizes heat transfer to measure the flow that often comes with full scale uncertainties and the offset (zero point) has large instability making it unsuitable for the custody transfer. In the last few years, Tokyo Gas and MEMSAG [1-3] have demonstrated the new thermal mass gas meters using MEMS technology for city gas applications. These all-electronic meters met the requirements of accuracy and reliability for custody transfer but high pressure loss and other aspects preventing them from commercialization. In this paper, new design of MEMS mass flow meters are discussed for their performance as well as the critical issues of meter calibration and verification for custody transfer.

2. MEMS Mass Flow Meter Design

The MEMS sensor chip is placed into a pre-manufactured cavity at the center of a 0.8mm thick stainless steel plate and the sensor surface is aligned with the surface of the support so that the assembly forms a sharp plate inside the fluid. Then the sensor assembly is inserted at the center of the flow channels that are of a venturi structure for flow stability. The lithium ion battery pack provides the power for the meter at the separate chamber for the purpose of explosion proof while the electronics itself is intrinsic safe. A combined flow conditioner assembly with a flow straightener and a profiler is placed at the entrance of the flow channel to achieve better repeatability. Because the sensor chip is designed for robustness against the impact of particles and wire connection is sealed from exposure to the fluid, no additional protections are required that result in a low pressure loss matching to those typically by diaphragm meters. The detailed description for the meter design can be found elsewhere.[4]

3. Reference Standard and Calibration

2.1 Calibration System

For the thermal mass flow meters, the conventionally used calibrators are either sonic nozzle or turbine meter that could be traceable to Bell Prover or PVTt or mt standard. For the manufacture purpose, turbine meter would have higher efficiency as it is usually less time-consuming for flow to be stabilized during the calibration. However, turbine meters as calibrator do not have large enough turndown. For the desired dynamic range of the MEMS mass flow meters, at least two turbine meters need to be applied. The switching between the two turbine meters is not only impractical but could introduce additional uncertainties at the transition point during manufacture. Further, turbine meters for small flow would not have the same reliability as it is in the large flow applications. A sonic nozzle system is then chosen for the calibration of the MEMS mass flow meters. The sonic nozzle is considered a stable system with a recertification period of no less than 3 years while for turbine meters the recertification is usually 6 months for traceability requirements. The extended uncertainty of the system is ±0.2%. The sonic nozzle system is further traced to a Bell Prover with an uncertainty of ±0.05%.

2.2 Calibration Procedure

In the custody transfer applications, repeatability is the essential requirement. As MEMS mass flow sensing is a new technology for custody transfer, there are no established international or local standards available for the conformity assessment. For the city gas applications, most of the commercial meter applications would not be over 150,000m^3/year while for industrial applications, the gas consumption would be within 10M m^3/year. Hence, for the best practices applied to the current technologies,[5,6] the turndown should be at least 50:1 with an accuracy no less than ±1.5% of reading. In our current meter design, for commercial applications (maximum DN=80 with a maximum flow of 160 m^3/hr) the accuracy was designed for ±1.5% with a turndown of 100:1 while for industrial applications the accuracy was designed for ±1.5% with a turndown of 100:1 for meters of DN equal to 50mm or less and for ±1.0% with a turndown of 50:1 for meters of DN equal to 65mm or above. All meters, nevertheless, have a dynamic range over 200:1. The errors in dynamic range beyond the specified turndown normally have 2 times of the specified accuracy.

As the MEMS sensor chip is manufactured with the state-of-the-art processes similar to those in today's IC industry, the sensor to sensor variation is very small. The consistence of the meters is then mostly coming from the meter assembly for which several precise molding could assist to reduce the variations during manufacture. In practical, we found that the meter calibration curve can be approximated with a smooth polynomial of 4^{th} power, and the specified turndown accuracy can be maintained using 21 point calibration while the dynamic range can be achieved with additional 3 calibration points towards the lower end. It is believed with continued efforts in the manufacture process, the necessary calibration data points can be further reduced. The measured uncertainties for the meters are obtained by another independent sonic nozzle system that has the same uncertainty of the one used for the meter calibration. Figure 1 shows the typical calibration curve of a meter used for commercial applications.

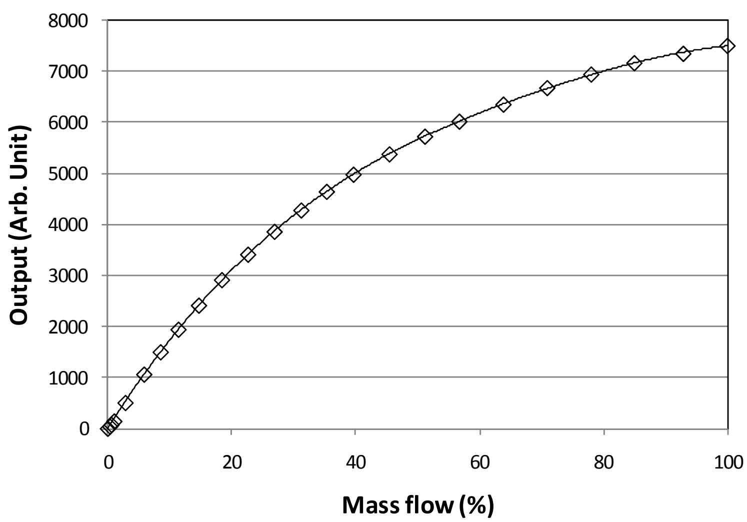

Fig. 1 Typical calibration curve of a MEMS mass flow meter for commercial application

2.3 Verification by Natural Gas

One of the advantages for the volumetric meters is that the meter calibration could be normally done with air at the pre-defined standard environmental conditions. When the same meter is used for natural gas measurement, the performance of the meter is the same as those in air and the deviation could be well within control. For traditional thermal mass flow meters such practice would not be available particularly for the accuracy requirements of custody transfer. However, it would be impractical to use real gas calibration to manufacture the meters used for city gas applications. This is not only because the natural gas composition could be varied, but the manufacturability would not allow it. Therefore, if the MEMS mass flow meters are to be massive deployed for the natural gas applications, one of the key issues to be verified is to demonstrate the accuracy in natural gas for the same meter calibrated in air would not be deviated. It has been proposed [7] that for the MEMS mass flow technology, a gas conversion factor can be applied when applying the meter to different gases. Hence the following experiments are designed for such verification.

2.3.1 Verification on Natural Gas Calibrator

Table 1 shows the data obtained from the natural gas calibrator by the sonic nozzle system that was duplicated from Colorado Experiment Engineering Station, Inc. (CEESI) and installed at the China Petro Verification Branch of Natural Gas Flowmeters at Chengdu, China. At the time of verification, the system was running with the natural gas (97.549% CH_4; 1.019%N_2; 0.912%CO_2; 0.423%C_2H_6 and other trace chemicals) at a temperature of 25.22±0.64ºC and a pressure of 94.18±0.02kPa. The gas line pressure was maintained at 0.84±0.01MPa during the verification tests. The MEMS meter had a pipe diameter of 80mm and was pre-calibrated with air on a sonic nozzle system described earlier in this paper for the dynamic range of 0~800 Nm^3/hr. Before the meter was verified in the pipeline, a gas correction factor of 0.7845 based on previous experimental data was applied to the meter. The similar data had been obtained for another meter with pipe diameter of 50mm using the same practice. It can be observed from the table that within the test range, the MEMS meter could be readily applied to the natural gas custody transfer measurement.

Table 1 Test data for the MEMS meter with DN=80mm

	Standard (m^3/hr)	Test Meter (m3/hr)	Repeatability (%)	Accuracy (%)
1	633.60	631.33	0.18	-0.36
2	311.47	310.33	0.18	-0.37
3	137.71	137.41	0.23	-0.22
4	44.35	44.56	0.08	0.49
5	502.97	504.09	0.16	0.22
	Meter uncertainty (%)		Meter repeatability (%)	
	±0.49		0.23	

2.3.2 Comparison with Turbine and Rotary Meter

As both turbine and rotary meters are commonly used in custody transfer for city gas applications, additional verifications and/or comparison of the MEMS mass flow meters were carried out using turbine meter and rotary meters (see Figure 2 for the installations). The MEMS mass flow meter was installed in serial to a turbine meter as shown in Figure 2. The line pressure was 3 bar during operation. Both these meters had a pipe diameter of 100mm. The turbine meter had an accuracy of ±0.5% with a dynamic range of 60~1200 m^3/hr at 3 bar while the MEMS mass flow meter had an accuracy of ±1.0% and a dynamic of 15~1500m^3/hr. The natural gas composition was the same as that discussed above for the calibrator verification. The data shown in Figure 3 indicated that the relative errors were within the ±1.5% in dynamic range of 20:1 that was consistent with the turndown of the turbine meter. Whereas beyond the turbine dynamic range towards the small flow, the errors were all becoming positive that was also in agreement with the performance characteristics of the turbine meter and suggested that the MEMS mass flow meter would have the advantages in the small flow ranges for the custody transfer purposes since turbine meter could not function well in such range. The slightly worse repeatability would come from that the actual error of the turbine might be larger as the system required additional temperature and pressure compensation. Very similar data were obtained from the comparison with the rotary meters. Rotary meter has a larger turndown compared to the turbine and less demanding on the installation. The observation is also in agreement with the previous work by Kono and co-workers that the MEMS mass flow meters were stable for the natural gas measurement.

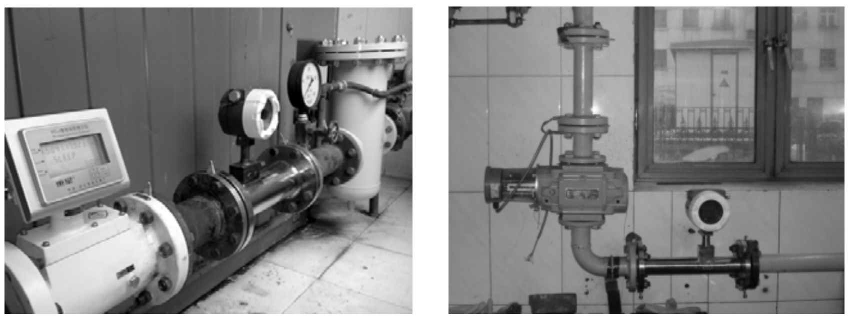

Fig. 2 Comparison/Verification with turbine and rotary meters

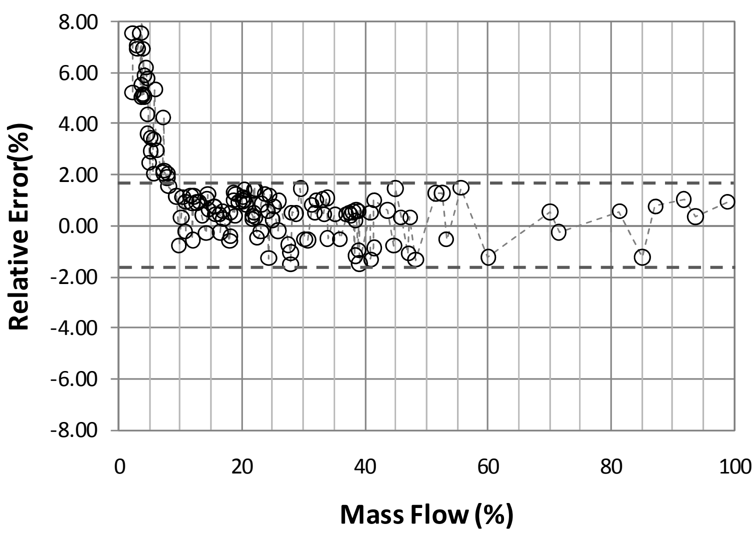

Fig. 3 Comparison/Verification data with a turbine meter

3. Meter Performance

3.1 Repeatability and Reproducibility

In addition to the importance of repeatability for a custody transfer meter, long term stability is also critical as any deviations from the calibration would possibly involve the monetary disputes. For example, for a typical commercial application in a pipeline of 50mm diameter, the dynamic range would be within 0~65m^3/hr and have a typical flow of 25m^3/hr. Assuming a normal working day of five hours such as in a cafeteria, one year gas consumption would be within

45000 cubic meters. The value of 1% of such amount could be well over the cost of the meter. Therefore demonstration of the stability over the time before next maintenance could further validate the technology. In the present work, a meter with the pipe diameter of 50 mm was chosen to investigate the reproducibility under continuous operation at the upper flow limit of $65m^3$/hr in an air pipeline with the air source provided by a blower. The meter was verified before and after the 30 day continuous air-flow that resulted in about $46850m^3$ accumulated air flowing through the meter, which would be equal to over one year's normal operation. Figure 4 shows the measured repeatability and reproducibility data for the meter before and after the air flow tests and the data indicated that the performance was well within the specified accuracy of the product.

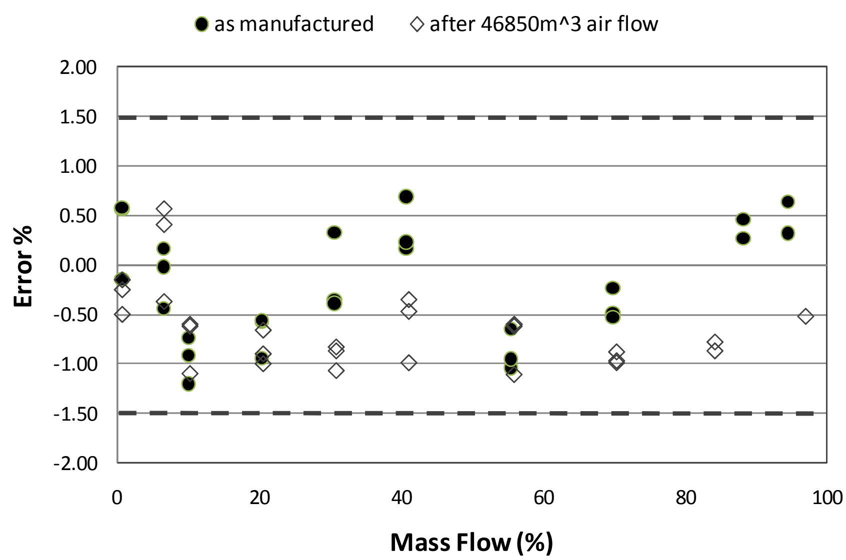

Fig. 4 Repeatability and reproducibility for a MEMS mass flow meter

3.2 Ambient Temperature

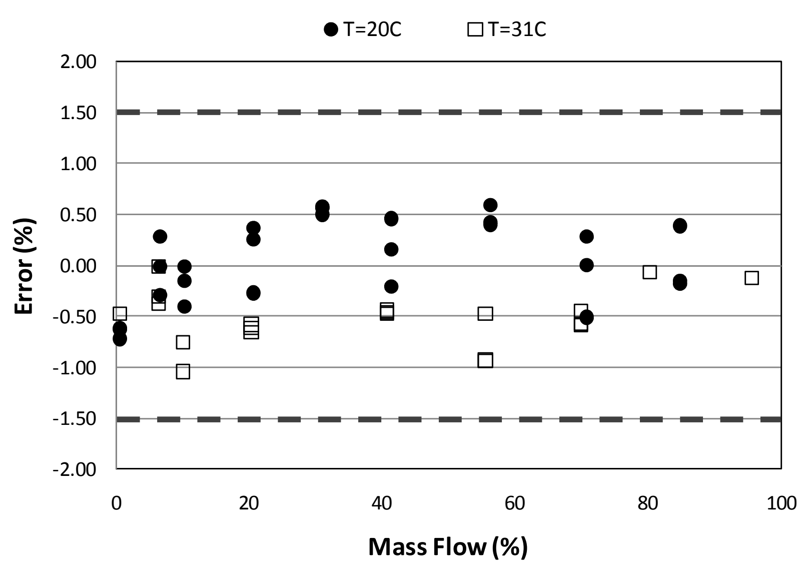

Fig. 5 Measured accuracy at different ambient temperature

Because most of the gas meters for city gas applications are installed outdoor, another important factor for the meter performance is the ambient temperature variation. The impact of the environmental temperature would mostly from the meter electronics as the current standard usually only specify the fluid temperature compensation.[8] Figure 5 are the measured results from a MEMS meter tested with a sonic nozzle system with the ambient temperature varied over 10ºC. Although the errors at the elevated temperature had the trend that shifted slightly towards the negative, such changes were within the specification and the averaged errors based on the above data would not be over 0.015%/ºC which therefore would not add any meaningful errors to the performance within the normal operation conditions from the ambient changes.

3.3 Installation Conditions

For custody transfer applications, the mechanical meters particularly the turbine meters require long straight pipe line before and after the meter at the installation to ensure the accuracy. In many practical cases, such requirement often cannot be met leading to concerns for the applications. To verify such effects and demonstrate the function for the flow conditioning design, one MEMS mass flow meter was place on a sonic nozzle system with various pipe conditions as indication in the figure. At each condition, accuracy data were taken against the original calibration, and Figure 6 is the summary of all data in this experiment. It can be observed that a straight pipe with a length of 5 times of the pipe diameter would be sufficient for the specified accuracy at all different pipe connection/conditions before the meter.

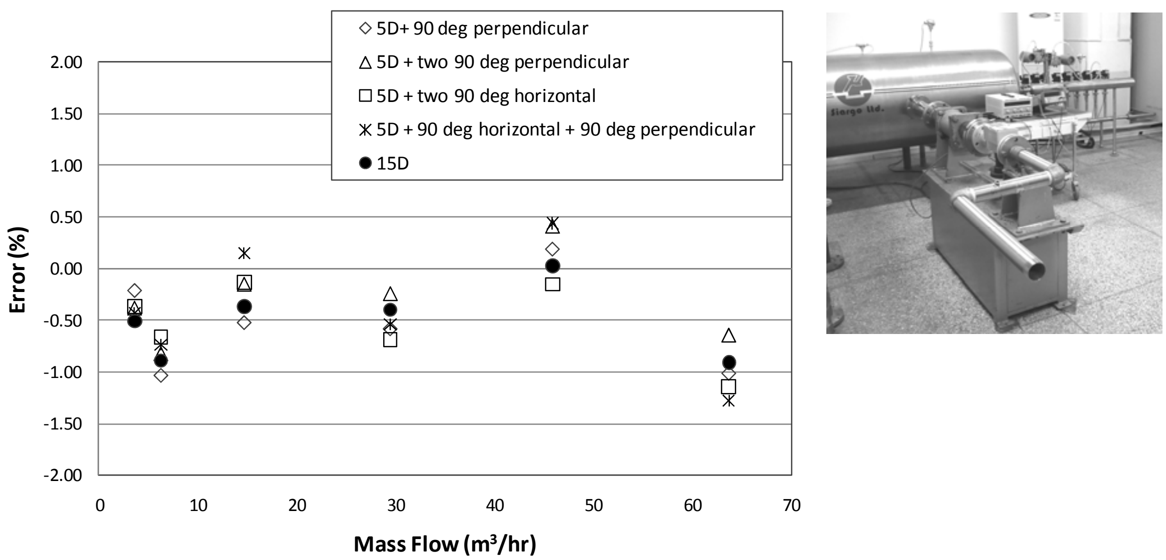

Fig. 6 Measured data for different installation conditions

4. Application Restrictions

As the thermal mass flow principle restricts, the MEMS mass flow meter cannot be applied to gases with variable gas compositions such as water gas. The manufacture process of water gas sometimes would incorporate certain amount of nitrogen which has large impact on the gas thermal properties. When the gas composition varies, the thermal conductivities of the gas usually will change as well leading to the deviation of the heat transfer and altering the sensing output from the MEMS sensor chip including the changes of the sensor offset. This will result in uncontrolled errors. However, in the city gas applications, most of the gas composition remains stable as the natural gas supply normally from stable gas sources from which the composition would be a constant. Other gas supply from liquefied natural gas (LNG) or liquefied petroleum gas (LPG) also in most cases has fixed composition and dominated by CH_4 or C_3H_8, respectively. Experiments with these two sources showed the similar results that a gas conversion factor would be good enough for custody transfer measurement as those for natural gases.

Other restrictions for the applications of the MEMS mass flow meters come from the requirement of no condensation in the gas pipeline which sometimes does occur particularly close to the supply sources when the process of dehumidification is not completed. The condensation in the pipe line and hence will pass on the sensor chip. It will dramatically change the thermal conductivity of the medium resulting in large measurement error although it could recover when the condensed moisture was removed.

5. Conclusion

The data in this work indicated that the MEMS mass flow meters can be readily used for custody transfer for city gas applications as long as the gas composition maintains the constant. The MEMS mass flow meters have a significantly larger dynamic range, easier data management for remote data network, and substantially lower cost. Adding to these advantages are savings from logistics and materials.

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