MEMS MASS FLOW METERS
WITH *IN SITU* GAS COMPOSITION COMPENSATION

L.J. Huang and Y. Feng
M-Tech Instrument, Inc.
2041 Mission College Boulevard, Suite 250, Santa Clara, CA 95054 USA
E-mail: Liji@wisenstech.com

K.S. Ling, W.T. Wong and M.F. Sham
Meter Technologies Limited
363 Java Road, North Point, Hong Kong
E-mail: ks.ling@mtechmetering.com

Abstract

Thermal mass flow meters for gas metering with complicated gas composition are often a challenge as it requires the real gas calibration. In many cases, particularly for gases with dangerous or harmful components the calibration is very costly and sometimes even not feasible for re-calibration at field. It is even worse that at the time gas composition varies, the calibration would be erroneous. In this paper, the design, theory and experiments for a MEMS thermal mass flow meter that is capable to dynamically compensate the gas composition variation during measurement are discussed. The meter can also provide in situ measured gas thermal values.

Introduction

According to the worldwide energy consumption outlook released in 2011 by US Energy Information Administration, the worldwide annual natural gas consumption is at an average growth rate of 1.6% and will reach to 186.7 trillion cubic feet in 2035, almost doubled compared to that in 2003. This is not only the requirements of environmental pollution control but a better life style as the natural gas via the pipeline can be directly delivered to the residence eliminating the troublesome supply by tanked gases. Metering the usage of natural gas is therefore a basic requirement for gas companies such that tariff can be fairly applied to customers and the income can further support the gas company operation. The first dry gas meter that provides quantitative measurement was invented in 1843 by the British William Richards and improved by Thomas Glover who established the first gas meter company in 1944. These volumetric diaphragm meters are still the dominated players in the city gas metering.

Since 1980s, many efforts have been made for the development of all-electronic gas meters that can provide compensations to volumetric metering due to the impact of the environmental changes. The development and deployment of ultrasonic gas meter starting in late 1980s has not overcome the cost issue but the efforts have been nevertheless moving forward although slowly. MEMS (micro electro mechanical system) mass flow meters for city utility industry have been developed in several countries since late 1990s. With the dramatic advancement of the electronic technology in this century, the all-electronic gas meters become more and more close to reality and commercialization of such meters already emerges. As of today, three technologies have been employed to develop the all-electronic meters for city gas metering. Table 1 summarizes the major merits of these technologies.

Table 1. Comparison of current all-electronic gas meter technology

	Ultrasonic	Differential pressure	MEMS mass flow
Temperature compensation	Additional	None	Included
Pressure compensation	Additional	None	Included
History (as of 2011)	20+ years	3 years	18+ years
Models	Residential & commercial	Small residential	Commercial & industrial
Markets	UK, US, Japan	Russia	China, Japan, Italy
Caloric value	No	No	Possible
Integration	No	No	Yes
Cost	High	Low	Low

The differential pressure gas meters have limited application history and a small dynamic range. Therefore it will not be discussed further. The ultrasonic gas meters have a long history with established standard for deployment, but it is a volumetric meter without additional temperature and pressure compensation and the cost is also an issue for residential applications. MEMS thermal mass flow meters have the advantages of automatic temperature and pressure compensation, large dynamic range and a low cost. The field data also demonstrated its reliability. Nevertheless, the most critical issue for the MEMS thermal mass flow meters is the gas composition sensitivity.

In USA, natural gas sold to residential customers is measured by “thermo” that was based on the volumetric metering and the monitoring of the gas properties at the central gas gate station. Each month a different factor shall be applied to the gas bill to match the gas company’s internal data. These unilateral factors do not match to the fair play principle as the actual metering on site does not provide such. Although it is the fact that customers are consuming the thermal value of the natural gases not the volumetric value, it would be more reasonable if the installed residential meters can actually measure the thermal value of the natural gas instead of the volumetric value. In the previous report, it was found that the measurement of natural gases with different compositions by calorimetric MEMS gas meters shall have deviations but if the data were plotted against the calorific value, the accuracy can be retained irrespective of the composition except for inclusion of high concentration of non-calorific gases such as nitrogen. Hence this report suggested that the MEMS mass flow meters may provide an option for a better metrology system based on the thermal value metering. Nonetheless, to meet with the current tariff systems, the meters are required to be insensitive to the gas compositions. In other words, a compensation scheme has to be provided for the purpose of fairness unless regulation allows the phase in process differences while the calorific value measurement shall serve as an add-value for future tariff system.

In this study, we shall discuss the *in situ* compensation scheme for gas composition induced variation for the MEMS mass flow meters.

Experiment

A volumetric Roots (rotary) meter PTZ-40 with the flow range of 0~65m^3/hr and the uncertainty of ±1.0% was used for the reference that was connected in serial with a MEMS mass flow meter MF50GD designed for the utility applications. This MEMS meter had the same flow range but an uncertainty of ±1.5%. Both of the meters had a pipe diameter of 2 inches and a minimal of 10 inch pipeline was used for the in serial connections before and after the meter ends. Then natural gases with five different compositions were then flown through the meters separately with different flow rates in the full dynamic span to test the capability of the *in situ* gas compensation detection and develop the gas composition compensation scheme. The rotary meter is equipped with a digital interface that sent out the pulses corresponding to a volume at a specific time interval while the MEMS mass flow meter had a standard RS485 Modbus digital interface. Both of the meters sent the readings through the interface to a computer that collected the data and processed them for analysis. The compositions of the five natural gases used in this study are listed in Table 2.

Table 2. List of the test gas properties and measured data.

	CH_4	C_2H_6	C_3H_8	N_2
A	89.29	7.57	2.29	0.25
B	94.65	0.05	0.02	5.25
C	89.00	8.00	3.00	0.00
D	80.71	6.68	1.90	0.00
E	97.55	0.43	0.06	1.02

In this table, the listed compositions are for the major components of the gases. Other minor constituents shall make up to the 100% of each gas.

Results and discussions

Gas conversion

In order to achieve the gas composition compensation, it is critical that the MEMS mass flow meter maintains a singular or even better a linear correlation when metering the gases with different compositions. In other words, the gas conversion correlation should be established. The current capability of the calorimetric gas meters for the calorific value comes from its measurement principle. Therefore the measured flow rate shall depend on both the mass flow rate and the calorific values or the compositions of the gases. The gas conversion factor is the linear correction value that is obtained by referencing to the temperature and pressure compensated volumetric values in air or a specific gas. In most cases, the air is employed for obtain this value for easy accessibility. The detailed process for the MEMS meter calibration in air is reported earlier. The calibrated MEMS mass flow meter MF50GD was then placed onto the gas experimental bench that is equipped with a pressure and temperature compensated high precision volumetric meter rotary meter PTZ-40. The natural gas of type A was then flown through the gas pipeline of the test bench. Both of the reference rotary meter and the MEMS mass flow meter output the readings to a computer that recorded the data and performed the further process for the comparison. The correlation between the readings of the two types of meters, if it is linear, shall establish the gas conversion correlation. Figure 1 shows the data for gas A against air collected from the test bench.

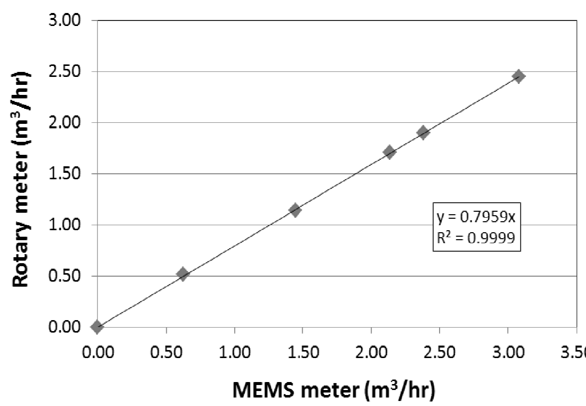

Fig.1. Measurement of gas conversion correlations against air using a rotary standard meter.

The data shown in Figure 1 indicated an excellent linearity for the correlation and hence suggested that the specific gas conversion was well established for the MEMS mass flow meters in natural gas against air calibration, or the MEMS mass flow meter can be used to measure the corresponding natural gas with the mass flow value that is equivalent to the temperature and pressure compensated volumetric value. The measured gas conversion factors (GCF) in this study are listed in Table 3. This gas conversion can then be pre-programed into the MEMS mass flow meter for the metrology applications. It should be noted that the gas conversion would be dependent on the design of the electronics for the MEMS mass flow meters, therefore different manufacturers may have a set of the different GCFs.

Table 3. The measured gas conversion for the five natural gases in this study

	CH_4	GCF	HHV	R. Gravity	P/C_p
A	89.29	0.7959	44.12	0.6138	20.85
B	94.65	0.8735	37.89	0.5773	21.86
C	89.00	0.8199	39.18	0.6511	21.19
D	80.71	0.7815	39.59	0.7137	20.68
E	97.55	0.8778	36.81	0.5761	21.92

In Table 3, the HHV stands for high heating value with a unit of MJ/m^3. The HHV values are obtained using gas chromatography-mass spectrometer (GCMS) and hence are not *in situ* values. The relative gravity (R. Gravity) values are referenced to air and are also measured *ex situ*. We will address these data in the following discussions.

Thermal value and gas composition

For the actual applications, there shall be the possibility that the gas composition will be changed from time to time due to the resources of supply. Once the gas composition changed, the gas conversion shall be changed and the metrology against the volumetric value will be deviated as the calorific factor will play the critical role for the meters' calibration against the volumetric values when this happens.

In order to decouple the calorific values from the flow rate measurement, additional sensing elements or schemes are then necessary for acquiring the relevant parameters while the mass flow rate is measured. The flow rate is proportional to the gas thermal conductivity and thermal capacitance in additional to the flow speed, and both of the thermal parameters are related to the calorific values. Therefore, if the thermal conductivity and the thermal capacitance can be measured independently, it would be possible to differentiate the gas calorific value that can be further correlated to the gas composition. Since the gas conversion is gas composition dependent, it is expected that if the calorific value can be determined for the specific gas, the MEMS mass flow meters calibrated based on a specific gas conversion can then be correlated. Such a correlation or a compensation scheme can be further applied to the measured mass flow rate resulting in a direct correlation to the pressure and temperature compensated volumetric value. Consequently, the measurement could be consistent with the current tariff system. For this purpose, additional two thermistors are integrated onto the previously discussed MEMS sensor chip, located on the membrane of the chip for better thermal isolation. These two thermistors can measure the thermal conductivity and thermal capacitance of the gases. To demonstrate the capability of the proposed MEMS mass flow meters, natural gases with five different compositions or thermal values as listed in Table 2 are selected for the meters that are pre-set with the gas calorific value compensation scheme and calibrated with air.

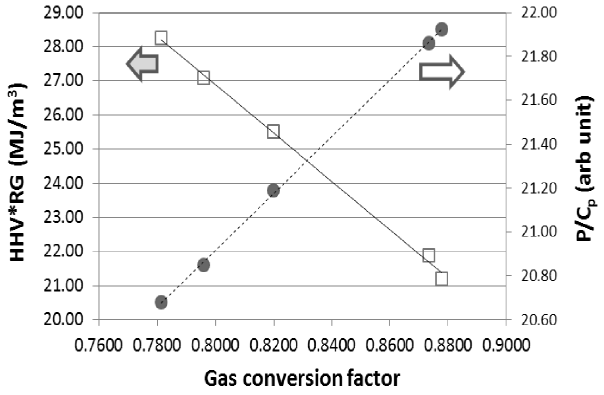

*Figure 2. Correlation of the gas thermal value HHV*RG (relative gravity) and in situ measured thermal value with the gas conversion factor*

Figure 2 shows the results that were *in situ* measured from the proposed MEMS mass flow meter. The values P/Cp are obtained from the *in situ* measurements of the thermal values via the additional thermistors integrated into the calorimetric MEMS flow sensor. These values can be measured either dynamically or statically. It can be seen that the natural gas compositions (gas conversion factors) are in direct correlation to the thermal value (thermal density) as well as the measured thermal conductivities over the thermal capacitance. The proposed MEMS mass flow meter is based on the calorimetric flow sensing principle that has a micro-heater at the middle and two thermistors are placed symmetrically with respect to the micro-heater. The temperature difference, *ΔT*, is a measure of mass flow rate, q_m , thermal capacitance, C_p , and thermal conductivity, ξ , of the fluid: $\Delta T \propto \frac{P(\xi)}{q_m \times C_p}$. Therefore the observed data confirmed the measurement principle and that the measurement can be used for the compensation of the relative changes of the gas composition based on calibration of any of the one gas composition, or air can be used as the base for the calibration whilst the measured P/Cp value can be used to adjust the mass flow rate readings when the gas composition changes during the service of the MEMS gas meter. The direct correlation between the heat density *HHV*RG* and the gas conversion factors suggest that the proposed MEMS mass flow meter can be further used for the direct measurement of the calorific value of the natural gases providing an option for the future advancement in metrology should a standard (base heat value) could be assessed and approved.

In the previous report, the actual calorific value was not reported, and the data shown strong dependence of nitrogen inclusion. From the gas composition value in Table 2 as well as the data shown in Figure 2, it can be observed that the gas conversion factor correlation to the gas thermal value had less impact by the nitrogen inclusion if the current thermal values were used for correlation since one of the gas (Gas B) has 5% nitrogen inclusion.

To further verify the assumption of the *in situ* gas composition compensation scheme, a MEMS gas meter incorporated with the compensation algorithm that is calibrated based on Gas D was used for the measurement in Gas A. It sees from Figure 3 that a large error was found without implementing the compensation scheme based on current volumetric tariff system, while the compensation could be successfully eliminating the thermal value or composition induced errors. One would suggest that the meter has the capability for thermal value measurement and the positive deviation is due to that Gas A has a higher thermal value, but for the current tariff system such compensation scheme would be a must.

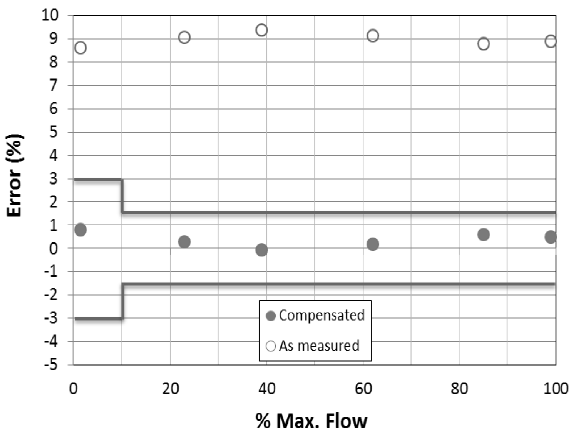

Figure 3. Comparison of as measured and compensated errors for a MEMS gas meter calibrated with Gas E but applied for measurement of Gas A.

Concluding remarks

The present study shows that the proposed MEMS mass flow meters for utility gas metering can measure the calorific value *in situ* in addition to the mass flow rate. The measured calorific values can be further used for adjustment to those that are equivalent to the pressure and temperature compensated volumetric flow rate. Hence the proposed MEMS mass flow meters for utility gas metering shall be ready to apply for the city gas metering with the current tariff system while the meters are opted for the future calorific value tariff system as well.

The major issue for the proposed MEMS mass flow meters compared to the current diaphragm meters is the use of a power source. As particularly the gas meters for residential applications requires a life time for over 10 years, the power failure would create additional service cost, and if it is in a large scale, it would be not acceptable for the gas utility providers. Although remote data logging shall help to monitor each meter's status, a remedy to power source is still very much desired. One of the promising activities could be the energy harvesting utilizing the flow energy inside the pipeline to supply the electronics. As MEMS sensing chip has the room for integration that would add value to the current technology, the additional functions ideally shall include *in situ* calibration or verification, self-cleaning of possible additives on sensor surface, and detailed gas composition information. Further, for the massive deployment of the MEMS mass flow meters in the tariff system, it is essential to establish the international standards that shall be particular for the technology as well as for the benefits of both the gas providers and the end users.

References

[1] R.E. Higashi, J.G. Johnson, P.J. Bohrer, "Flow sensor", US Patent 4,501,144, February 26, 1985.

[2] N. Ueda and S. Nozoe, "Flow rate measuring device", US Patent 7,559,256, July 14, 2009.

[3] T. Fujiwara, S. Nozoe and N. Ueda, "Flow velocity measuring device", US Patent 7,062,963, June 20, 2006.

[4] F. Mayer and M. Lechner, "Method and sensor for measuring a mass flow", US Patent 6,550,324, April 22, 2003.

[5] H. Hecht, D. Tank and U. Konzelmann, "Method for correcting the output signal of an air mass meter", US Patent 5,668,313, September 16, 1997.

[6] G. Wang, C. Chen, Y. Yao and L. Huang, "Micromachined mass flow sensor and insertion type flow meters and manufacture methods", US Patent 7,536,908, May 26, 2009.

[7] U. Bonne and E. Satren, "Sensor package for harsh environments", US Patent 6,911,894, June 28, 2005.

[8] F. Mayer, R. Hornug and S. Vanna, "Flow sensor", US Patent 6,813,944, November 9, 2004.

[9] K. Eirnsnf, K. Ullrich and M. Muziol, "Flow sensor element and its self-cleaning", US Patent 7,739,908, June 22, 2010.

[10] L. Huang et al., "All electronic MEMS gas meters for city gas applications", in Proceedings of the 15th Flow Measurement Conference, 2010, pp. 376-383.