Cost Effective MEMS Mass Flow Meters

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Abstract: Cost effective flow meters are dominated by rotameters or variable area flow technology. These meters only measure instant volumetric flow rate with a low accuracy. In addition, the meters are not capable for temperature and pressure compensation as well as remote communication. With increasing demands on data communication and remote control in current industrial processes or gas measurement applications, development of new technologies would be necessary. We present a series of MEMS mass flow meters that are cost compatible with the variable area flow meters while providing all digital data process including accumulated flow rate measurements, user programmable flow alarm and flow data storage. These in-line meters provide packages in pipe diameter from 4 mm up to 100mm. It is powered with battery and can be used as a stand-alone potable option. The meter is also equipped with the industrial standard RS485 Modbus communication interface for easy networking and remote management.

Keywords: MEMS flow meter, Thermal mass flow, Portable flow meter

1. Introduction

One of the most frequently used variable area flow meters is the rotameter that utilize a float sitting in a tapered tube. When fluid passes through the tube, the float is elevated by the fluid and the distance the float travels is proportional to the fluid flow speed which can be used for volumetric flow measurement. The rotameters are easy for maintenance and very cost effective making it possible for installation at many applications where cost would be a concern. The world market estimated by various sources is over US$300M. The rotameters however cannot provide digital data output without incorporating some conversion devices. This has been an issue at today's applications that data transmission has become more and more important. In addition, the rotameter could be easily damaged at a high speed flow pulse that is practically the case when the valves to a pressurized source were turned on without additional cautions being applied.

In recent years, mass flow meters [1-4] using MEMS (Micro Electro Mechanical System) mass flow sensors manufactured with silicon micromachining technology have been developed and applied for various applications in medical, environmental and other industries for clean and dry gas mass flow measurement and control. The MEMS mass flow sensors on market mostly operate with the calorimetric principle and packaged in a bypass configuration which is very similar to those by the capillary thermal mass flow technology. However, the sensing elements of the MEMS mass flow sensors are placed on a suspended membrane that is thermally isolated with the gas under measurement providing a much better stability than that in a capillary tube. The manufacture process of the MEMS mass flow sensors is similar to those for state-of-the-art integrated circuitry with which a mass production will substantially reduce the cost. Furthermore, the MEMS mass flow meters containing the MEMS mass flow sensor and control electronics can be operated at a power as low as sub milliwatt with the average current consumed in a few hundred microamperes. It can then be packaged into the intrinsic safe formality. The thermal mass flow meters powered by battery also become possible with the MEMS flow sensors. Nevertheless, the current available products are often costly and only for dry and clean gases, which prevents their deployment from applications where low cost is a critical factor.

In this paper, we present the design of the MEMS mass flow meters that are cost-compatible to those by low cost rotameters while providing significant advantages in performance, data communication and installation.

2. Meter Design

The meters are designed for general purpose industrial gas measurement and monitor. Several models cover the mass flow ranges from 0~10 to 0~1000 SLPM and the range can be customizable at the time of manufacture. The accuracy of all the models are designed to be ±(1.5% reading + 0.25% full scale) while higher accuracy can be achievable with calibration at manufacture as well as during installation with a longer straight pipeline to ensure a better flow stability.

Fig. 1 Explosive view of the meter components and picture of the actual product.

Figure 1 shows the explosive view of the meter components. The meter body is manufactured with copper or other metel materials to compatible with the requirements of gas safety such as oxygen. The connectors at both ends can be customized to match the pipe threads in the specific applications. The meter head cover is made of polycarbonate. The user interface is through a mini-USB connector providing RS485 Modbus communication and external power supply if desired. In the current design the meter can be powered with 4-AA batteries with an AC adaptor as an optional accessory. The meter can operate on battery for up to 2000 hours continuously before the power failure alarm gets on. At the operation, the meter will read instant flow and accumulated flow rate as well as the fluid temperature through the LCD display or the RS485 interface. The buttons under the display provide the password security for accessing the meter data, set flow alarm, and other functions that can be further explored with the enhanced software. Additional network software is also available for management of cluster of the meters. For convenience in installation, the meter head can be rotated 180º counter-clockwise and vice versa.

Figure 2 is the block diagram of the electronics control circuitry. The EPPROM provides the data storage and can be user programmed for storage intervals. Up to 3000 items of the data can be stored in the EPPROM and user can access the data via RS485. The total current consumed by the circuitry is about 200μA.

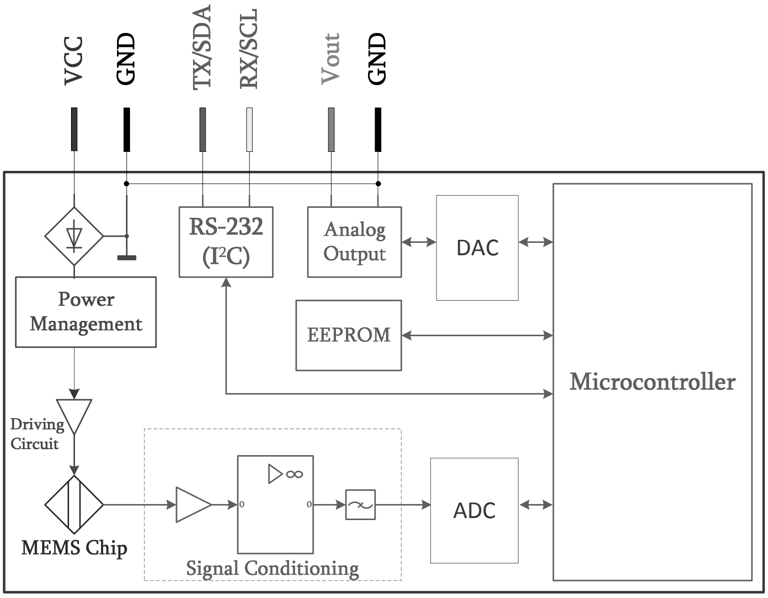

Fig. 2 Block diagram of the control unit

3. Test Results

3.1 Meter Performance

The meters were all calibrated by a sonic nozzle system that has an uncertainty of ±0.2%. The uncertainty of the sonic nozzle was custody transferred via a Bell Prover with an uncertainty of ±0.05%. 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 3 shows the typical output of the meter (calibration curve) for one model with the flow range of 0~300 SLPM (20ºC, 101.325kPa).

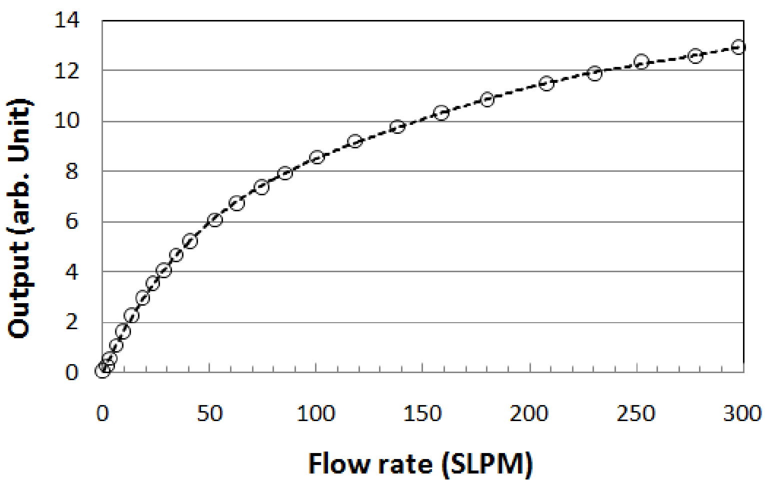

Fig. 3 Calibration curve for a mass flow meter 0~300 SLPM.

Calibration usually contributes to the most of the cost during the meter manufacture process, as it is very time-consuming if many data points have to be collected for each individual meter. Fortunately as the MEMS sensors are made from the process tools that are similar to those used in today's IC productions that provide good process uniformity resulting in high performance consistency from sensor chip to chip. Based on the manufacture database, we found that all of the sensors output similar curves that can be proximate with a fourth order polynomial. This then allows significantly reduction of the calibration data point leading to lower manufacture cost. Figure 4 shows the two measurements of the uncertainties for the same meters but calibrated with 7 and 28 data points, respectively. The error band boundaries are shown by the solid lines in the figure. One can observe that both calibrations have similar results that are well within the specified accuracy as mentioned above.

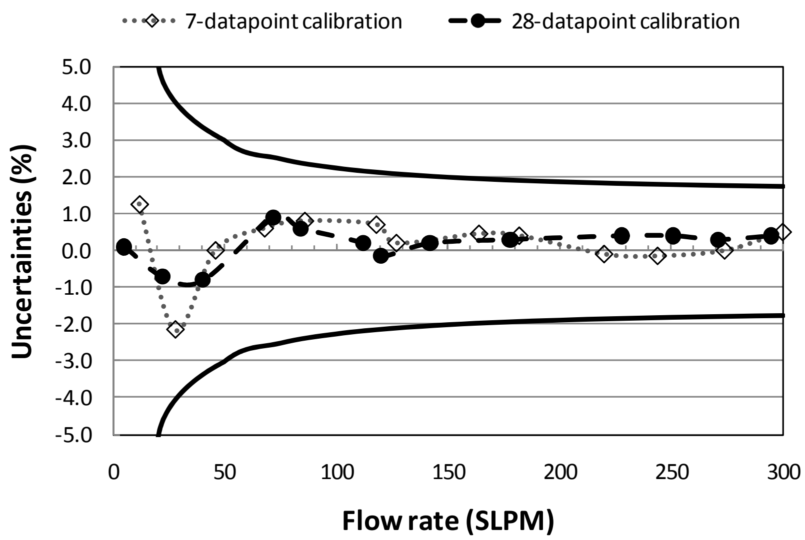

Fig. 4 Uncertainties measured for the mass flow meter of Figure 3.

3.2 Gas conversion factor

One of the advantages in the capillary thermal mass flow sensing technology is that a gas conversion factor can be applied as the flow channel of the meter can be designed such that the fluid flowing through the bypass and main channel bears the very similar properties (usually in laminar flow conditions). This enables the meter calibrated with one fluid can be easily applied for measurement of another without additional real gas calibration. This feature is very important for many industrial applications. The MEMS mass flow sensors, on the other hand, are manufactured on silicon wafer that could allow the sensor be packaged into a plate assembly. This sensor assembly using our insertion meter design is a plate with a thickness less than 1 mm and the plate surface is placed in parallel to the fluid flow direction. It therefore will possibly force the fluid redistributing from the plate edge of the sensor assembly into laminar flow according to the fluidic boundary layer theory. [5] If this is the case, this redistribution of the flow into the laminar flow at the MEMS sensor assembly will be independent of the initial flow formality and the fluid composition, which suggest that we might as well apply a gas conversion factor to the flow meter being calibrated for an arbitrary medium, e.g. nitrogen gas, when measuring another gas using the same MEMS meter.

To verify this assumption and obtain such factors for the MEMS meters in the present work, the meters were first calibrated with the nitrogen gas and then applied for measurement of the argon and carbon dioxide at the same temperature and pressure (20ºC, 101.325kPa). A differential pressure volumetric meter with ±0.5% accuracy was used as the reference meter. Figure 5 shows the data of the measurements. One can observe that when the gas is not the nitrogen (calibration gas), the outputs are deviated from the original volumetric value but are linearly against the reference volumetric flow value. Thus the experimental data demonstrate the gas conversion factor can be used for the current MEMS flow meters. It is noted that these factors are qualitatively similar but different in absolute values published in the application notes by Honeywell for its mass flow sensors on its webpage, and again slightly different from other MEMS mass flow sensor manufacturers such differences would come from the sensor design, package and control electronics.

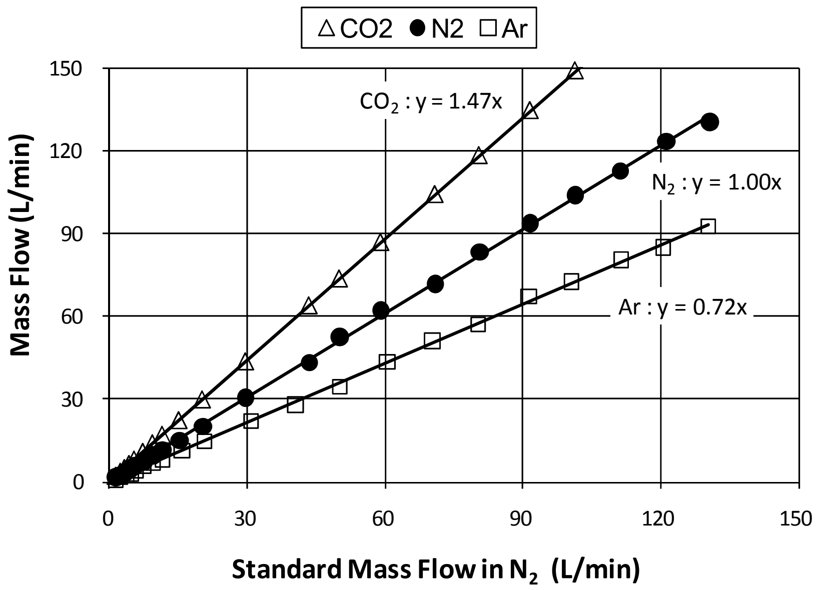

Fig. 5 Output of a meter calibrated with N_2 applied for Ar and CO_2, respectively.

3.3 Installation environments

As the meters are designed for general purpose industrial applications, the installation should be as easy as possible or a plug-and-pay installation would be preferred. Figure 6 shows the measured accuracy for a test configuration that the meter was plugged into one-touch connectors at both ends with the flexible plastic tube. The flexible tube can be bended at any arbitrary angles for tests of the flow stability through the meter body in which the flow channel is a venturi structure with a flow conditioner at the inlet. At the upstream of the meter, a standard differential pressure flow meter used as the reference which was connected to a straight pipeline of about 50x of the pipe diameter. At the 90 degree bending of the flexible tube the data shown in Figure 6 indicated that all the tested data are within the specified accuracy band, which further endorses the plug-and-play character of this meter.

Compared to the capillary thermal mass flow meters, the MEMS mass flow meters discussed in the present study also feature a significantly lower pressure loss that is comparable to that of the variable area flow meters. For example, for the 0~10L/min model, the pressure loss is about 380Pa at the maximum flow. This is particularly important for low pressure applications.

Because of the package advantages, similar pressure loss can also be achieved for higher flow models.

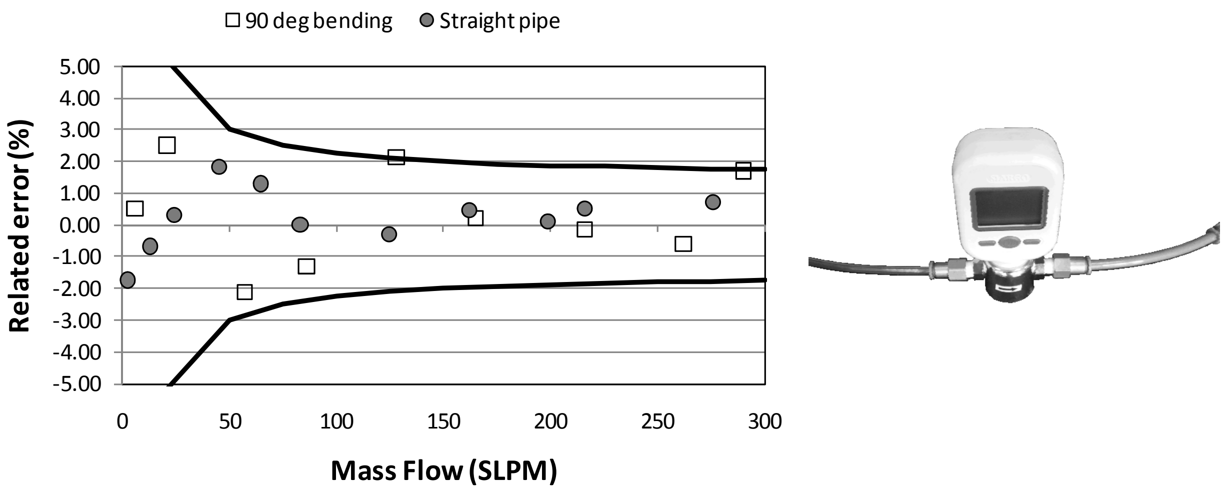

Fig. 6 Accuracy measurement for flexible pipe connection.

4. Conclusion

With the character of the manufacture process for the MEMS mass flow sensor and today's stat-of-the-art electronics, MEMS thermal mass flow meters can be manufactured at the cost that is similar to those for variable area flow meters while providing significant advantages in performance. In particular, capability of mass flow measurement, much better accuracy, compact size, low power consumption and portability, data safety and industrial standard communication protocols for networking. These features will surely enable an emerging market and massive deployment of the MEMS mass flow sensing technology into many industrial and even consumer flow applications.

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