

All Electronic MEMS Flow Meters for City Gas Applications

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Abstract: City gas metering has been dominated by diaphragm meters for over a century. In the past 30 years, development of all-electronic meters for better energy management has been pursued by many companies using ultrasonic, thermal time-of-flight, and MEMS calorimetric principles. Installations and trials have been reported but mostly in small quantity. The challenges for such meters come from reliability and cost requirements. While ultrasonic technology has been better developed, the cost and gas composition dependency are often the barrier for the market acceptance. In this paper, we discuss cost effective and battery powered MEMS mass flow meters for city gas applications with the battery life over 5 to 10 years depending on operation conditions. The meters consist of a specially designed MEMS mass flow sensing chip with multiple sensors that offers the capability of large turn-down ratio over 200:1. The package technology enables applications with pipe diameters ranging from 15 to 150mm, and with an accuracy of $\pm 1.5\%$ or better. The long term reliability including resistance to particle impact and oil/moisture contaminations is ensured by chip design. The meters are ready for various remote communication protocols and the actual installations will also be discussed.

Keywords: MEMS flow meter, City gas, All electronic flow meter

1. Introduction

The global energy shortage has been demanding for better energy management. For more than three decades, the electricity industry has phased out the mechanical meters by electronic meters and is now pursuing the smart grid system aiming a total network solution via the existing grid to significantly improve electricity usage. In contrast, over 99% of the world gas and water meters are still operated with the century old mechanical meter technologies making the management of those energies very challenging. For the city gas measurements, current technologies have been dominated by diaphragm, positive displacement (roots meters) and turbine for more than a century. In this industry, reliability requirements often offset the accuracy particularly for residential applications as the meters installed would not be easy for repair or replacement. The diaphragm meters have been used for residential and commercial customers but are bulky and incapable of temperature and pressure compensation. Various current digitized devices for the diaphragm meters are yet to demonstrate their accuracy making it difficult for effective management. Reliability of the roots meters and turbine meters in small pipe (<1" in diameters) have serious reliability issues, in addition to their cost, and cannot be used for residential applications. For medium pressure industrial applications, roots meters have excellent performance but the additional requirements of temperature and pressure compensation often reduce their accuracy. In particular, the high cost of maintenance as well as the risk of clogging during operation by impact of particles prevents their applications in critical process line. Turbine meters are ideal for custody transfer as they can be of high accuracy, but the dynamic

measurement range of the turbine meters usually is difficult to be over 20:1 making the accumulated data inaccurate because of the deviation in low flow totality.

Since 1980s^[1-4], many efforts have been made for the development of the all-electronic gas meters for the city gas applications. The concept of the time-of-flight residential gas meters by Kang et al. provided a solution but the reliability of the sensors did not allow the commercialization in addition to the complicity of temperature and pressure compensation. Ultrasonic technology has been well established for the natural gas measurements and has been promoted by many companies such as Panasonic, Siemens, Elster, Invensys and Actaris but the cost sets the barrier for its entrance into the residential gas meter market. Earlier build of the residential and commercial gas meters with the MEMS thermal mass flow sensors by ABB/MEMS^{AG} and Yamatake, respectively, provided a direct mass flow measurement scheme at a much lower cost suggesting an excellent potential for the applications. However, the residential meters has a bypass configuration that might lead to clogging with the presence of fine powders while the commercial meters have a high pressure loss that might not be suitable for the city gas applications where the pipeline pressure is often at the low end.

In 2006, Siargo introduced a series of MEMS gas meter products designed for working at the city gas operation conditions that traditionally covered by diaphragm, roots and turbine meters. These battery powered models have been since fully commercialized and deployed in four countries where China has the major installation base. In this paper, we will discuss the design, performance and installation of these products with suggestions for further improvements.

2. Meter Design

The structure of the MEMS sensor is described elsewhere.^[5] The chip size is about 2x4mm with the bonded wire covered by anti-corrosive sealant. The surface of the MEMS chip was further passivated with thermal conductive silicon nitride film which prevents the sensor from degradation or damage by moisture or other aggressive materials in the flow medium. Both the calorimetric sensing elements and the energy dispersion sensing elements were integrated onto the same sensor chip offering extended dynamic mass flow range. Therefore the applicable dynamic flow range will be dependent on the calibration, and a balance between the turndown and the manufacture cost would be judged at the time of production.

The meter series cover all ranges for the city gas end user applications, as showed in Figure 1. The flanged meter series can be applied for the gas pipeline with medium pressure up to 2.5MPa with a pipe diameter from 25 to 150mm and maximum measurable flow from 125 to 3600 Nm³/hr. The meters for commercial applications have a pipe diameter of 20 to 80mm covering maximum flow rate from 6 to 160 Nm³/hr and maximum working pressure of 1.0MPa. The residential gas meter series have a pipe diameter of 15 to 20 mm for a maximum flow rate of 4 Nm³/hr and a maximum working pressure of 0.5MPa.

The meters are all powered by a lithium ion battery of 19Ahr for a life time of six (medium pressure models), eight (commercial) and ten (residential) years. For all models, both the instant mass flow rate and accumulated flow rate at the standard conditions (20°C and 101.325kPa, other conditions can be set at the time of calibration) are displayed simultaneously. The battery indicator on the LCD will flash approximately three months before the end of the battery life. For data safety purpose, the meters have three separate nonvolatile memories to record the operation status of time, instant flow and accumulated flow as well as the alarm status. The clock is maintained by a crystal and can be remotely synchronized as well as adjusted if daylight-saving time should be accounted. Each memory can store up to 3000 items that are programmable by the

users for their specific application requirements. For the remote data transmission, RS485 with Modbus provides connections to the local concentrator and further transmission could be via wired or wireless network. Figure 1 shows current models offered by Siargo: (from left to right) medium pressure applications for industrial users; low pressure applications for commercial users; residential users and residential users with a pre-paid card.



Fig. 1 Siargo gas meter series for city gas end user applications.

2.1 Meter Components

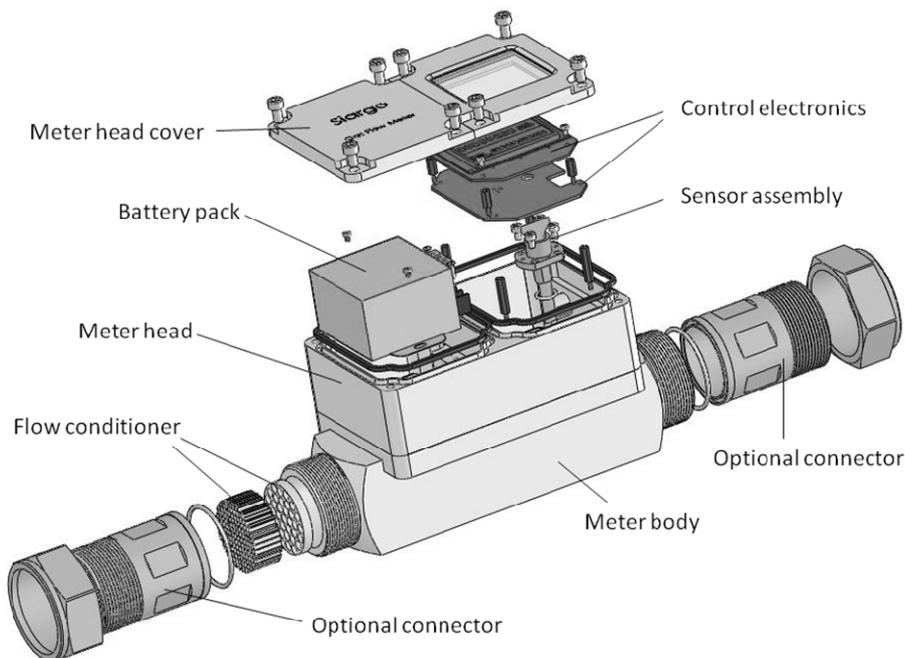


Fig. 2 Component schematics for the commercial gas meters

For all models, the sensors are inserted at the center of the flow channels that are manufactured with a venturi structure for flow stability. Figure 2 shows the assembly structure of a commercial gas meter. 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. The meter body is either made of stainless steel or aluminum alloy and allows a maximum working pressure of 1.0MPa. The flow conditioner assembly is placed at the entrance of the flow which leads to a maximum pressure loss of less than 300Pa for the smallest pipe diameter at the ambient working conditions. The optional connectors usually shipped with the meter provide easy connection to

the existing pipelines. For the medium pressure flanged series and the residential series, the components that formed the meters are basically the same except for a different package formats and dimensions.

2.2 Sensor Assembly

The sensor assembly is shown in Figure 3. The sensor insertion pole is made of stainless steel. For large flow applications and meters with diameters more than 50mm, dual sensors are packaged on the same insertion pole so that the mass flow value can be averaged from multipoint measurements resulting in an enhanced accuracy for the measurement. When the dual sensors are presented on the same insertion pole, the installation of the pole will ensure that one of the sensors is placed at the center of the flow channel (master sensor) and the other one (slave sensor) will be placed at one fourth of the diameter of the flow channel. As the sensor surface direction is in parallel to the flow direction, the edge of the pole is made with a sharp slope so that any particle impact onto the sensor assembly will have a chance to be impelled away from the sensor surface and reducing the head-on collision and thus reduce the possibility of the foreign materials induced sensor reliability.

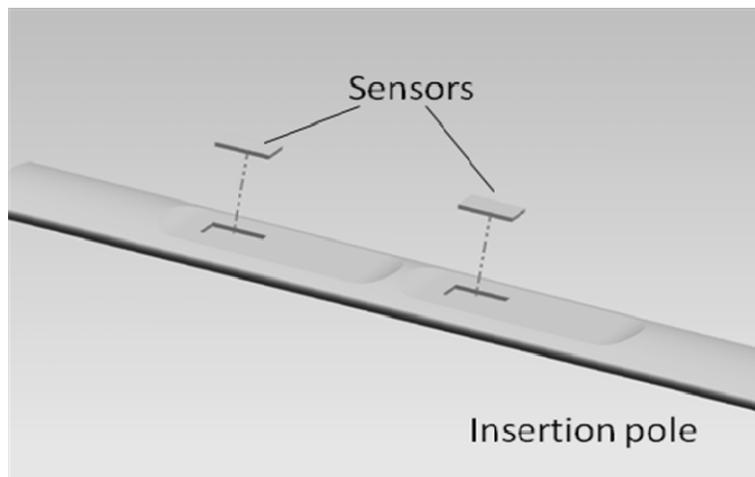


Fig. 3 Schematics for dual sensor assembly

3. Meter Performance

3.1 Uncertainties

The meters were all calibrated by a sonic nozzle system that has an uncertainty of $\pm 0.2\%$. The uncertainty of the sonic nozzle was custody transferred via a Bell Prover with an uncertainty of $\pm 0.05\%$. The verified uncertainties for the meters were obtained by another independent sonic nozzle system that has the same uncertainty of the one used for the meter calibration. Figure 4 shows the measured data that indicated the uncertainties of the meters are within the general requirements for the custody transfer, benchmarking to those by the traditional mechanical meters with the flow computer or temperature and pressure compensator.

While the MEMS meters by principle have automatically been compensated for variations of temperature and pressure, the design of the sensor assembly may however introduce additional effects from the pressure changes in the pipeline as well as flow induced pressure variations. This is due to that the sensor chip has a free standing membrane with a cavity underneath. If the sensor assembly cannot provide the pressure balancing configuration, the flow induced pressure

variation may lead to the minor membrane deformation that would be sufficient for altering the sensor accuracy or uncertainties. Therefore in our sensor assembly, a pressure balance design was implemented via the openings on the support and below the sensor cavity. Another factor that would impact the meter uncertainties is the temperature compensation of the electronic circuitry as it could produce additional errors to the meter. However, this can be done relatively easy as quite a few solutions are available as the design guidance. With this design enhancement for temperature effects, we are able to achieve a temperature coefficient of 0.015%/°C.

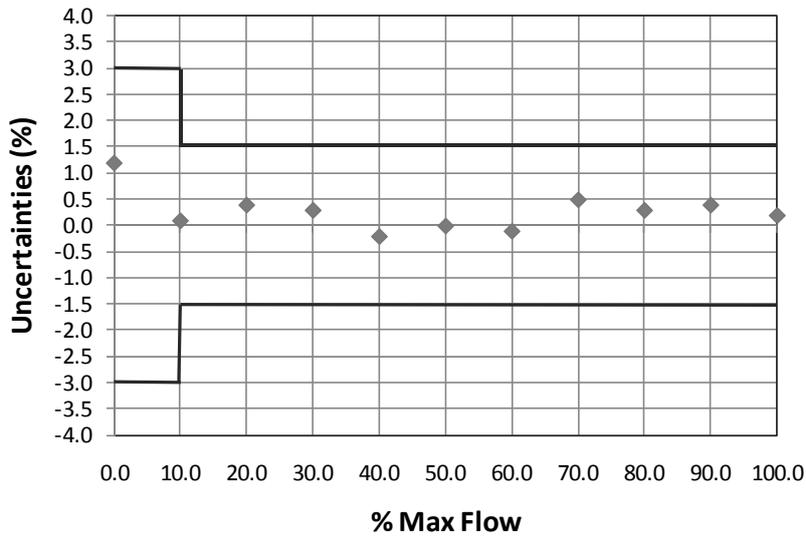


Fig. 4 MEMS meter uncertainty measurement

3.2 Pressure Loss

Pressure loss is one of the major concerns for the city gas applications as the pipeline pressure is often low when reaching to the end users. A higher pressure loss will not only introduce additional energy consumption but may lead to problems such that the gas may not be able to provide sufficient supply for burner operation. This is actually one of the problems for the previous work that prevented the massive deployment.

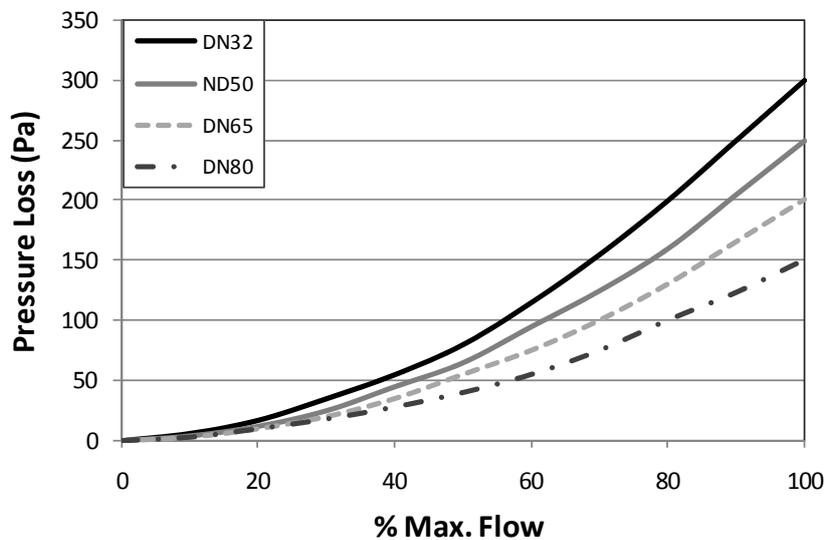


Fig. 5 Pressure loss for Siargo's MEMS commercial gas meters

In our design, the sensor probe is directly inserted at the center of the flow channel instead of a bypass configuration that requires a pressure dropper between the entrance and exit of the bypass channel. Additional flow stability provided by the venturi meter body in our design also would not introduce any pressure drop as it has been well demonstrated before. Figure 5 shows the measured pressure loss at 20°C and 101.325kPa for our commercial gas meters that are compatible with those by the diaphragm meters.

3.3 Pipe Connection

For mechanical meters particularly for turbine meters, it is necessary to have long straight pipe lines before and after the meter installed so that the custody transfer can be ensured and the requirement for the length of the straight line before the meter usually is much longer than that after the meter. This limitation makes the installation costly and sometimes it cannot be met due to the field space restrictions. For the current MEMS meter design, the sensor and the sensor support assembly are formed as one perfect plate such that the sensor assembly itself would serve as a conditioner as the boundary layer will force the distribution of the fluid across the package plate into a laminar flow. Therefore the straight pipe line requirement would not be very critical for the MEMS meters. Figure 6 shows the picture of a test setup for verification of the straight pipe line before and after the meters. A medium pressure flanged meter is installed at the bottom entrance pipe while two commercial meters are installed at the downstream split from the entrance pipe with valves to control the flow. Further to the left, two residential meters are installed. A blower is used to generate the flow and the readings of each meter are recorded. In this configuration the minimal straight line before the meter could be less than 3 times of the pipe diameter. As it is indicated in the picture all readings match well within the specified meter accuracy of $\pm 1.5\%$ of reading.



Fig. 6 Test setup for verification of the straight pipe line requirements at the installation.

3.4 Field Tests

3.4.1 Long Term Stability

One of the key concerns for the electronic meters is the reliability at long term operation. Figure 7 shows the comparison of the 41 day's daily accumulated flow data recorded one year apart. The meter was installed at a ceramic manufacturer where natural gas was used by the kiln for making

ceramics. The process for the kiln required small fire initially for preheat and then heat-up with medium fire followed by the large fire for shaping and slowly reduce the heat for cooling down. This gas usage pattern was a typical application that requires a meter having large dynamic range in order to accurately record the gas consumption, which in turn presents an excellent application for the MEMS meters. In this particular case, a DN50 flanged medium pressure meter with the flow range of 0~400Nm³/hr was installed. From the data shown in Figure 7, no performance degradation or accuracy deviation could be observed, as one can reasonably assume that the process of the ceramic making would consume pretty much the same amount for each run. For further validation, we re-verified the meter after the one-year installation by measuring its uncertainties and the results confirmed the above observation.

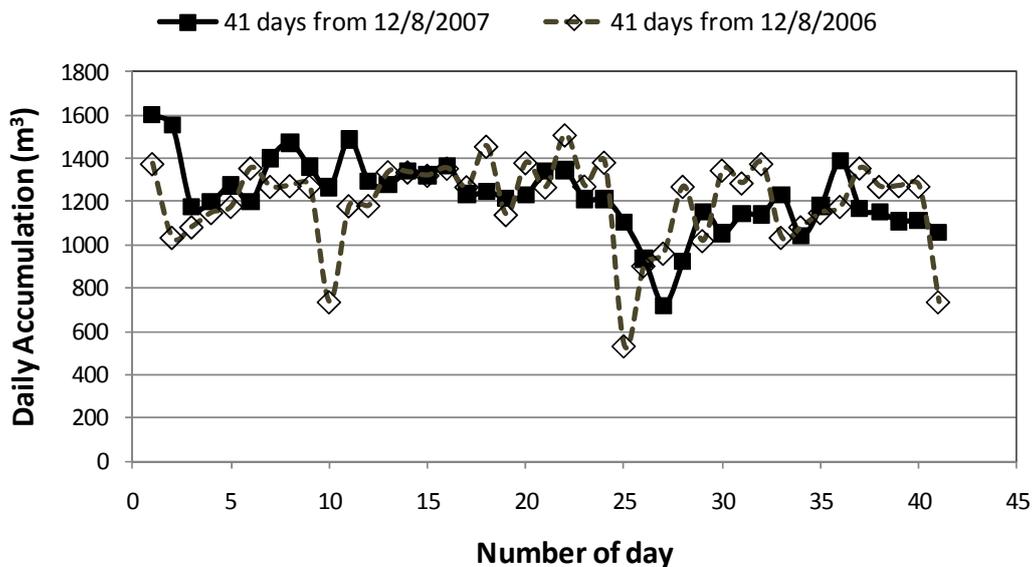


Fig. 7 The daily accumulated flow apart from one year for a meter installed at a factory.

3.4.2 Comparison with the diaphragm meter cluster



Fig. 8 One MEMS meter can replace seven diaphragm meters with better accuracy.

To avoid inaccurate metering for small flow, a gas company had installed seven diaphragm (G25) meters at a public school where the gas consumption was much less in the morning as only breakfast was served while in the evening when the gas burner starts to operate much more gas supply is required. The seven G25 diaphragm meters can meter a maximum flow of 280 m³/hr that is well covered by a DN50 flanged medium pressure meter manufactured by Siargo

(0~400Nm³/hr). Since the local standards required the meter set at 20C and 101.325kPa at the calibration, the data collected within one year indicated that the MEMS meter matched closely with the total gas consumption of the seven diaphragm meter cluster at the summer time but when temperature dropped, the MEMS meter recorded the gas consumption more accurately since the diaphragm meter could not be compensated with the weather change.

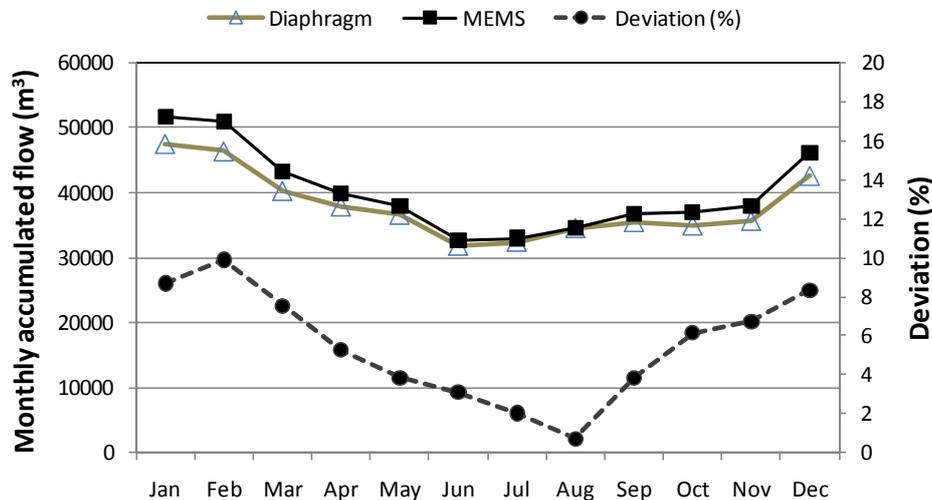


Fig. 9 MEMS meter can better record the data while temperature varies.

4. Concluding Remarks

MEMS mass flow technology is a very promising technology for city gas metering applications as it provides much better data safety and readiness for remote data logging/analysis. The MEMS mass flow meters feature a compact size and large dynamic range that excels the existing technologies with automatic temperature and pressure compensation, and significantly reduce the cost and the logistics. As discussed by the previous work, the technology is also good for providing direct caloric values without impacting the accuracy even with the gas composition varying to some extent. Combined with today's state-of-the art electronics and advancement of the MEMS technology, the advancement of the technology might be able to further reduce the power consumption of the MEMS sensor chip or even phase out the battery option with the self-harvesting within the system.

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