Chapter 9

City Natural Gas Metering

Liji Huang

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/45809

1. Introduction

Natural gas as a city energy supply is well established in the developed countries while in the developing countries the usage of natural gas in city utility industry has significantly increased in recent years. The "town gas" or the "water-coal gas" generated from the process manufacturing of coal is vastly being replaced by natural gas. 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. The amount is almost doubled compared to that in 2003. This is not only from the requirements of environmental pollution control but for a better life style as natural gas is normally directly delivered to the residence providing much cleaner energy with higher efficiency. Metering the usage of natural gas is therefore a basic requirement for gas companies so that tariff can be fairly applied to customers and in return the revenue can further support gas company operation. This is particularly important today as current energy costs have skyrocketed. Some governments of Eastern European countries that were used to subsidizing or even providing free natural gas for residents are now starting to install gas meters under their new tariff system.

The first metering system for gas companies in history could be traced back to the very beginning of the 19th century when the gas was made for street and home lighting. The charges were initially based on contract and the usage was calculated on an hourly basis regardless of the actual consumption. Later gas charges were billed by the approximate numbers of gas burners counted by gas company workers touring streets every night. The first real dry gas meter that provides quantitative measurement was invented in 1843 in UK by William Richards and improved by Thomas Glover who established the first gas meter company in 1944. The meter was constructed with sheepskin diaphragms and a sliding valve enclosed with steel. Gas that enters into and fills up the first diaphragm chamber is pushed out for delivery while gas is filling the second chamber. The meter is hence named "diaphragm meter". This great invention provides excellent measurement range and is operated by pure mechanical structure without additional power. The invention virtually saved the gas companies and made them profitable for their services and continued growth. The dramatic increase of the gas meter business however started ironically after the invention of electricity bulbs in 1879 that took away the lighting business of the gas companies who were forced to develop new business for home cooking and heating in order to survive. Ever since almost all gas meters made for city residential gas metering are based on the same volumetric principle, although several attempts have been made but none proved good for mass deployment. Gas meters installed at residential place often experience many unexpected conditions including privacy constrains that make it very difficult for repair and maintenance. In addition, the pure mechanical character of the meter makes it almost impossible for *in situ* adjustment of measurement with respect to the change of environmental factors, i.e., temperature and pressure that in fact have great impact to the volumetric capacity of gas. The mechanical gas meters also require the direct human intervention for the data collection, which is often inconvenient as most of the meters are installed inside residential private area. To develop an alternative gas meter, it must have the capability of long life time, sustained accuracy, no service requirement during its life time and operation without external power. Despite the challenges, the advancement of the electronics and infrastructure as well as the ever increasing energy cost has undisputedly led gas companies into the urgency of a better gas management system.

In addition to the diaphragm meters for residential gas metering, commercial and industrial users are the other two types that most of the gas companies have to deal with. For commercial applications, rotary meters are commonly used as the diaphragm meters cannot withstand high gas pressure and handle the required high gas flow rate. Most of the diaphragm meters currently available are designed for measurement of a flow below 100 cubic meters per hour and a pressure below 100kPa. In addition, the size of the diaphragm meters for higher flow rate becomes very bulky creating many logistical difficulties. Rotary meters are also used as positive displacement (volumetric) gas meters and are built based on the lobed impeller principle proposed by Roots Brothers in 1846. The rotary meters are sometimes also called Roots meters. The first rotary meter for gas appeared in 1920s and became popular for commercial gas metering about 60 years ago. The rotary meters have better accuracy, higher pressure rating and smaller in size. In particular they can be equipped with a flow computer for temperature and pressure compensation for better performance. For industrial users with even higher pressure and larger flow rate that rotary meters cannot handle, turbine gas meters are often used. Unlike the rotary meters, the turbine gas meters are "inferential meters" as gas flow rates (volume) are calculated from the measurement of gas flow speed. The word "turbine" was derived from Latin word meaning spinning. The first turbine meter was invented by Reinhard Woltman in 1790, but the applications in utility industry only happened in late 1950s, it is likely because that turbine gas meters cannot handle the earlier manufactured gases with high humidity and impurity, only perform well in clean and dry natural gas. Turbine gas meters can be applied to high pressure and are acknowledged as primary standard with temperature and pressure compensation for custody transfer. However, they have a small dynamic measurement range and are not suitable for commercial or residential gas metering.

Since 1980s, many efforts toward the above mentioned objectives have been made for the development of all-electronic gas meters that can provide solutions to the drawbacks of the mechanical metering scheme for the city gas applications (Kang, 1992; Otakane, 2003; Matter, 2004; Kono 2006; Huang, 2010). The development and deployment of ultrasonic gas meter starting in late 1980s has yet to overcome the cost barrier and the progress has been slow. 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 is already evident. In this chapter, we will review the existing technology, current market demand and focus on the current city utility gas meter technology with MEMS mass flow sensing as well as the future outlook of the technology.

2. Market demand and smart gas meters

Current utility gas markets are driven by multiple factors. The global energy shortage makes the energy cost constantly increasing; global warming calls for usage of clean energy and reduction of carbon dioxide emission that city coal energy is one of the major contributors; success in electricity smart meter system (replacing the mechanical meter by electronic meter with networking) adds the pressure for the current man power based management system in utility gas industry; privatization and ever reduction of government subsidization forcing a more accurate tariff system. As such, better natural gas management is critical for gas companies. In the past few years, particularly after the world economic crisis starting in 2008, governments worldwide have made many initiatives to promote a better city energy system including those for natural gas management.

One of the initiatives related to the utility meters is the "smart metering infrastructure" that provides instant data access and management of the actual usage of electricity, water and gas. As of today, the electricity smart metering projects have proven to be effective, and wide replacement of the mechanical electricity meters with all electronic electricity meters has been executed worldwide. The "smart gas meters" are however still the diaphragm meters with an electronic data process device that converts the mechanical index into digital value and transmits to the data centre. According to the "smart meter project map" compiled by the UK Energy Retail Association, there are approximately 311 smart metering projects or initiatives worldwide as of 2011, among which only 37 or 11.9% are smart gas metering projects or initiatives. Table 1 and 2 summarizes the data from the above mentioned resources. The data indicate that the smart meters are still in their infancy and opportunities are huge as the market is now ready for taking new technologies. From the data one can notice that most of the projects or initiatives are in North America and Europe. Data summarized from the same database further indicated that the gas and water smart meter installation are less that 12% of the total smart meters in the fields. From the annual market data reported by the ABS Energy Research in 2008, there are 396 million gas meters installed in the world while the demand for new installation and replacement in 2012 was estimated over 35 million units with an annual growth of 4.0%. The fast growth of the new installation market is in Russia and China where the natural gas usage was previously subsidized by government or limited by resources. The growth rate in China is expected to be 8.7% as the country is converting the "town gas" into a much cleaner natural gas energy. Another high growth market with approximately a 15% growth rate would be in India where the construction of the natural gas delivery system is in progress. In North America and Europe the market is dominated by the replacement demand, where the US market is expected to have a 5.5% growth rate as promoted by the demand of AMR (automatic meter reading) or the AMI (automatic metering infrastructure). Because of the high replacement cost, difficulties in maintenance and long meter life time, gas companies waiting for replacement are aggressively searching for new technologies for the best cost structure and future management considerations. This could also be part of the reasons that the current smart gas meter installations are less than 2% of the total meters in the field. With the current existing technologies, the smart metering projects are also limited by the actual values that can be added.

	Gas		Electricity		Water	
	Projects	%	Projects	%	Projects	%
North America	16	43.2	103	47.9	40	67.8
Europe	19	51.4	78	36.3	13	22.0
Others	2	5.4	34	15.8	6	10.2

Table 1. World smart metering projects (2011), data can be found from Google map search.

	Gas	Electricity	Water
Smart meters	7.4	60.2	1.2
Total meters	396	1,584	736
% of smart meters	1.9	3.8	0.2

Table 2. Current worldwide field installed smart meters as of 2011(units in million).

As discussed above, current smart gas meter is simply the addition of an electronic device to the existing diaphragm meters in most cases. There are no changes in the actual metering technology itself. By nature, it facilitates elimination of the meter reading labour cost. However, the current electronic convertor and transmitter is very costly, even much higher than that of the meter itself, which is also a serious drawback for the deployment of the smart gas meters. The overall cost would not result in any savings while the labour elimination fosters unemployment as a side effect. Unlike the electricity smart meters that can provide hourly data, the transmitted gas data are an average of a few days of usage that greatly reduced the viability for analysis of customer consumption pattern. It also cannot compensate the undesired gas volumetric changes due to environmental condition variations. Reports of high installation errors for the smart gas meters in some earlier US deployments, as well as, some erroneous meter performance even initiated local referendum against the smart gas meter installations. Some experts also expressed concerns about the security readiness for data transmission with the current smart meter system and call for the current government initiatives as "money trumps technology".

The market demand for a better utility gas meter to meet the current challenges opens the golden doors for new technologies in this very traditional industry segment.

3. All-electronic gas meters for city natural gas metering

With the advancement of the electronics in late 1980s, development of all-electronic gas meters for utility industry was initiated. For obvious competition reasons for gas meters, the new technology must excel the old ones before it can be massively deployed. The diaphragm meters have their well acknowledged performance in large measurement range, long term reliability, reasonable accuracy, applicability for various gas compositions, low cost to manufacture, as well as, operation without external power. It is nontrivial to outperform these features for any of the existing gas measurement technologies.

The first prototype of an all-electronic gas meter for residential applications was reported by Kang et al. in 1992. The thermal time-of-flight measurement technology was used to build the prototype. A thermal pulse was sent from the transmitter while the pulse carried by the gas flowing through the transmitter was received by the receiver that was placed precisely at a pre-set distance from the transmitter downstream. A venturi structure was used for enhancing flow stability and boosting sensitivity at low flow range. The measurement of the travel time of the pulse can then determine the flow speed of the gas. The time-of-flight measurement scheme is by theory a pure flow speed detection that shall be independent of the gas composition as it is one of the variables that must be considered for the influence on measurements. The reported data indeed showed that the prototype calibrated in air can be readily applied to measure argon as well as natural gases with variable compositions. This prototype was however limited by the electronic technology in late 1980s, and the complicated construction of the transmitter and receiver with very thin hotwires which made it impossible for demonstration of reliability in field and capability in mass production regardless of its cost considerations. Nonetheless, this prototype successfully demonstrated the feasibility of an electronic gas meter for natural gas applications.

In addition to the above mentioned features of the mechanical meters that need to be matched by new technology, the all-electronic gas meters are expected to provide the capability of data safety, remote data transmission and management, and elimination of environmental conditions such as temperature induced metrology variations. In recent years, the efforts are made with ultrasonic and MEMS thermal mass technologies.

3.1. Ultrasonic gas meters

Ultrasonic flow meters were first introduced in 1963 by Tokyo Keiki and were used for industrial natural gas measurement in late 1970s by Panametrics (Yoder, 2002). There are two fundamental measurement principles in the ultrasonic gas meter technology, transit time or time-of-flight and Doppler shift. Either one is classified as the inferential measurement similar to that for the turbine meters. In the time-of-flight measurement configuration, a pair of transmitter/detector was placed at a distance apart inside the flow channel and close to the channel wall in most cases. The time difference between the signal transmitted from upstream to downstream and the one from downstream to upstream is proportional to the gas flow rate. For the meters employed with the Doppler shift principle, the ultrasonic signal sent via the ultrasonic transmitter across the flow channel is deflected by the particles inside the flow stream. The measured Doppler frequency shift is proportional to the flow speed of the particles that are traveling at the same speed along with the flow stream. Most of the ultrasonic gas meters are made with the time-of-flight technology as "particles" in many gases may not even be present to reflect the ultrasound for measurement.

With more technical understandings of the ultrasonic gas meters in natural gas industry, and particularly after the development of the multipath ultrasonic sensing measurement technology that two, four or even six pairs of the ultrasonic transducers are installed inside the same pipeline and the averaged data significantly enhanced the measurement accuracy. These advancements helped substantial increase of the ultrasonic meter deployment in utility gas industry. In the second half of 1990s, both Europe and USA have started to establish the standards for the technology, and subsequently published regulations for use of the technology in natural gas custody transfer applications. Both the Technical Monograph 8 by European Association of Natural Gas (GERG) and AGA-9 by American Gas Association are the milestones for ultrasonic meters for natural gas applications. However, due to the high cost and difficulties for the transducers configured in small gas pipelines, the ultrasonic gas meters were largely limited to the usage in large pipelines replacing turbine meters or orifice flow meters for custody transfer.

The first attempt to use ultrasonic meter for residential applications started in 1991 in UK. About 200 meters manufactured by Siemens and Gill Electric R&D were installed together with newly calibrated diaphragm meters in serial connection throughout the country. These meters were about half the size of that for the diaphragm meters with same flow range. The meters were powered by a battery with the anticipated life of 10 years and equipped with a safety shut-off valve. The measurement range of these ultrasonic meters was comparable to that of diaphragm meters and the accuracy was slightly better. In addition, these meters were also readily applicable for AMR and pre-payment schedule. The new technology hence showed good improvements for their performance as compared to those of the diaphragm meters. Japanese major gas companies including Tokyo Gas, Osaka Gas and Toho Gas led the way for the development of ultrasonic gas meters for residential applications in 2001, and field tests of 100 meters similar to that in UK started in 2003 and concluded in 2005 without showing any inferior performance as compared to those diaphragm meters in series. US meter manufacturer Sensus introduced the ultrasonic meter for residential applications in the same period of time. Both UK and US models only covered G4/G6 in equivalence to diaphragm meters while Japanese models do include the very low flow range models of G1.6/G2.5. In 2007, European Committee for Standardization (CEN) published the EN14236-2007 for ultrasonic meters for residential applications that significantly boosted the usage of the technology. However, due to substantially higher cost compared to those for diaphragm meters, residential ultrasonic meters are very limited in field installation and are mostly in the developed countries (approximately 1.3M in UK; 0.03M in Japan and 1.2M in USA). For more than 15 years after the first deployment, only less than 0.7% of the total existing meters worldwide are now ultrasonic meters in the regime of residential applications.

Ultrasonic gas meters for city residential or commercial gas metering by principle measure directly gas speed. With the current electronic technology, it has the advantage of readiness for data transmission, data safety, remote access and management. In addition, the measurement is independent of gas composition. On the other hand, the ultrasonic meters also have the same disadvantages of temperature and pressure dependence and thus bear the similarity of the volumetric measurement character that are currently adopted by city gas industry. Therefore it would have less public sensitivity when even partial replacement of the existing meters in a specific area takes place. Customers would not notify any differences in principle if both the diaphragm meters and ultrasonic meters are installed in the same neighbourhood. Although the advantages of the ultrasonic meters seem very compelling and attractive to gas companies, their high cost is nonetheless a huge barrier for the market penetration. Moreover, the desired compensation for the environmental variations could only be achieved with the addition of temperature and pressure sensors which not only add to the cost that is already higher acceptance but also it will introduce additional metrology errors.

3.2. Differential pressure gas meters

Differential pressure gas meters are the oldest technology for gas flow measurement. They utilize the differential pressure sensor to measure the pressure drop across the designated gas pipeline and calculate the corresponding flow rate. It is therefore also an inferential type of flow meter. The performance of this type of meter depends on the accuracy of the differential pressure sensor incorporated, as well as the design of the pressure dropper inside the flow channel that shall serve as the source of the accuracy for the measurement. The higher pressure drop will be easier for the pressure sensor to resolve the differences. Pressure sensors with high accuracy and large measurement range are often costly and not readily available on market. Consequently, the differential pressure gas meters usually could not have a wide measurement range, in most cases with a turn-down ratio (maximum detectable flow rate over minimum measurable flow rate) smaller than 5:1. With additional temperature compensation, these meters can provide fairly accurate measurement and hence they are traditionally used in gas stations for custody transfer together with a large pump since the flow rate is relatively stable at the gas stations. This type of meter is therefore not suitable for city gas distribution purpose. The mandatory presence of the pressure dropper or orifice within the flow channel creates additional pressure loss other than the normal ones due to pipeline transportation, which is very much undesirable for the city gas distribution where the commercial pipeline gas pressures are often within a few kilopascal. High pressure loss is detrimental to the gas delivery capability for the end user applications.

In recent years, gas meters for residential applications based on the differential pressure sensing principle have been developed. One of the products currently available on market was manufactured by Betar Meters of Russia. As of today, there is only one model available that is equivalent to the model of the smallest diaphragm meter G1.0 with a maximum flow rate of 1.6m^3/hr. The meter body was made of casted metal while the flow channel was constituent of several stamped aluminium plates that make the meter very compact and very low cost. It is the smallest available gas meter on market. Because the silicon based differential pressure sensors consume very low power, the battery powered differential pressure gas meters are expected to have life of over 10 years. The silicon pressure sensors can be mass produced with excellent consistency that can be an advantage in meter manufacture cost reduction. However, because of the sensitivity of the pressure sensor, this meter has a small turn-down ratio of 40:1 that is far inferior to the 160:1 of the current diaphragm meter technology. In addition, the market share for such a small flow ranged gas meter model is small, and such model has actually already been phased out in many countries. Furthermore, compensation of environmental variations such as temperature for this type of meter adds significantly to cost as well as metrology errors.

As discussed above, meters with the differential pressure sensing technology are not the best solution for the city gas distribution applications for its small measurement range and sensitivity to the environmental conditions. Differential pressure measurement in a larger pipeline may not be useful due to the presence of large undesirable pressure loss.

3.3. MEMS gas meters

It is generally recognized that MEMS technology was born after Christmas in 1959 when Richard Feynman delivered his speech, “There is plenty of room at the bottom”, at the American Physical Society Meeting, which inspired and promoted the technology worldwide. However, the terminology of “MEMS” only appeared in 1987 when a series of workshops on microdynamics was held in California. The European society is used to name the technology as “microsystems” while the Japanese scientists call it “micromachines”. But today MEMS is widely accepted by the international community. MEMS utilizes the device process technologies similar to those used in integrated circuitry to build a comprehensive microsystem that can execute designated electronic, mechanical, optical, magnetic and/or thermal functionality. They can perform multitasks in a small form factor with minimal requirements of energy consumption at a nominal cost. As of today, devices made by MEMS technology have penetrated into our everyday life - TV sets, automotive, computer and peripherals, cell phones, projectors, medical devices, scientific instruments, just to name a few. These devices have significantly changed the way we live, saved thousands of lives and enhanced our understandings to the world surrounding us.

MEMS gas meters utilize the MEMS mass flow sensing technology to measure gas flow rate. With the state-of-the-art electronics for the signal process, MEMS gas meters have extended dynamic range, enhanced data safety and are easy for network and remote data transmission. The measured flow rate has automatic temperature and pressure compensation and it

	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 and commercial	Small residential	Commercial and industrial
Markets	UK, US, Japan	Russia	China, Japan, Italy
Calorific value	No	No	Possible
Integration	No	No	Yes
Cost	Medium to high	Low	Low

Table 3. Comparison of current all-electronic gas meter technologies.

is also possible for direct calorific value measurement. These meters also have a substantially smaller form factor for better logistics. These features are ideal for the current demand of better gas energy management. In Table 3, the current all-electronic gas meter technologies are compared with respect to their characteristics.

The actual deployment of MEMS mass flow meters in utility industry started in mid 2000, and limited shipment of the commercial models to UK has started since 2011 that aims to replace the small turbine meter currently installed. Residential models of the MEMS mass flow meters made by MEMS AG had been extensively sampled in many European countries since 2003 while actual installations are few. One model of this meter for measurement of flow rate up to $6m^3/hr$, equivalent to G4 of diaphragm meter is available from Diehl Gas Metering.

In the following sections, we will discuss in detail the all-electronic gas meters made of MEMS mass flow sensing technology.

3.3.1. MEMS mass flow sensing technology

Using the silicon planar technology to make mass flow sensing devices was first proposed by Hutton in 1971 and the first device made on a 50 μm thick silicon substrate was reported in 1974 by Putten et al. The sensing principle of this sensor was energy dissipation (anemometer) and the sensing elements were made of diffused p-type resistors close to the four edges of a 1.5x1.5 mm silicon surface. Using the Wheatstone bridge circuitry it conceptually demonstrated that the sensor can be used to measure the gas flow. This novel device would be the proximity of the MEMS mass flow sensor commercialized some 15 years later. Current commercial MEMS flow sensing products are made based on the principles of calorimetry, energy dissipation and thermal time-of-flight measurement. Others are most in the stage of research. A review of these research activities can be found in the published book chapters (Haasl 2008, Bonne 2008).

The calorimetric flow sensors (Gehman 1985, Bonne 2008) have a microheater at the middle and two temperature sensors are placed symmetrically with respect to the microheater. The temperature difference, ΔT, is a measure of mass flow rate, q_m , thermal capacitance, C_p , and thermal conductivity, ξ , of the fluid: $\Delta T \propto P(\xi)/q_m \times C_p$. The thermal conductivity can be measured from consumed power, P, of the microheater. The calorimetric flow sensors are best for low flow rate as the sensing is also limited by the boundary conditions.

The construction of the anemometric sensor (Bruun 1995; van der Wiel 1993) is relatively simple as it only needs to measure the energy dissipation of the microheater when the flow fluid passing through the microheater. Therefore, the measured ΔT between the microheater and that of the gas temperature is proportional to the dissipated energy P and the mass flow rate of the fluid: $\Delta T \propto P(\xi)/(q_m)^k$, where k is the factor that related to the meter design. The heat dissipation is usually insensitive at low flow rate and therefore it is best for applications for high flow rate measurement.

The time-of-flight (TOF) flow sensors (Ashauer, 1999; Shin 2006) have the similar configurations to those of anemometric sensors, but the operation mode is not to measure the power of the microheater. The upstream thermistor sends out continuous pulses while the downstream thermistor measures the time of the heat that the pulse carried from the upstream to downstream. As the distance can be precisely made or can be further precisely calibrated, the flow speed of the fluid can then be precisely determined. Obviously this technical is best for very small flow rate. In practice, the frequency phase shifts between the two thermistors are measured for enhanced accuracy and easy data process.

A typical structure of a commercially available MEMS flow sensor is shown in Figure 1. As shown in the figure, the sensing elements and the microheater are built on the membrane that is normally made of silicon nitride or silicon oxide and silicon nitride combination. The underneath cavity provides excellent thermal isolation that shall boost the sensitivity at a low operational power. This cavity is made by front wet chemical etch in some of the earlier products, but later with the invention of deep reactive ion etching (DRIE) technology, backside opening of the cavity was applied for better yield and efficiency. The slots on the membrane shall provide the pressure balance to minimize the deformation due to internal gas pressure. Many materials that have a high temperature coefficient of resistance (TCR) can be used to make the sensing elements and the microheater, but for long term reliability, the most commonly used materials are platinum or doped polycrystalline silicon. The thermistor placed on the silicon substrate is used for measurement of environmental temperature that can provide feedback to microheater such that a constant temperature or constant power operation mode can be maintained for the performance. The elongated design of the sensor is to place the interface connection pads away from the sensing elements and the connections via wire bonding can be subsequently sealed with package materials to ensure no shortage or damages from possible deposits of conductive materials or impact of particles carried in flow fluid. The space between the sensing element and the interface is also designed to be large enough so as to ensure that the flow profile disturbance due to the package is minimized.

The design shown in Figure 1 can be used for either calorimetric, or anemometric or time-of-flight flow sensors, but most of the current commercially available sensors are using

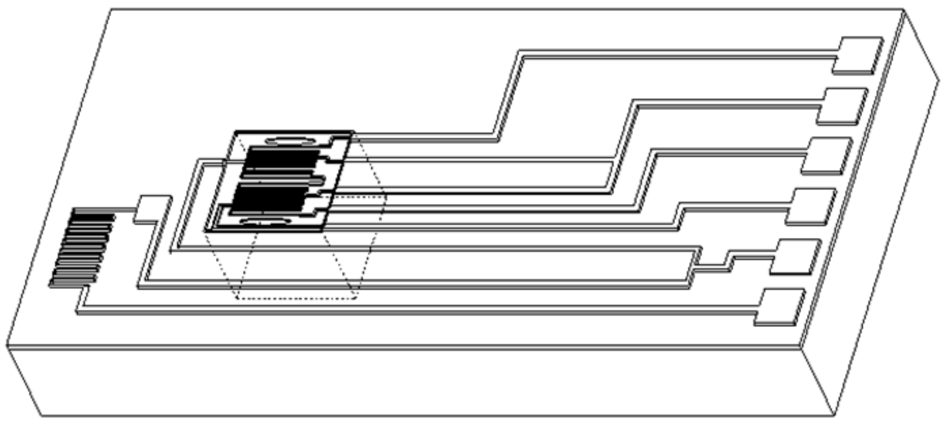

Figure 1. MEMS flow sensor designed by Siargo.

calorimetric measurement principle. Among the current commercial product suppliers, the first MEMS flow sensor was manufactured by Honeywell (Higashi 1985) in the late 1980s. Honeywell's MEMS chip utilizes the calorimetric principle having a footprint of approximately 2x2 mm. Its suspended membrane with openings was made by front wet chemical etch. The sensing elements were made by FeNi alloy or platinum. Because of the sensor size, the wire bonded at the interface is exposed to the fluid. This has limited the applications of its AWM series of flow sensors to clean and dry gases only. In mid-1990s, Bosch (Hecht 1997) released the MEMS air flow sensor for automotive applications. This sensor has also utilized the calorimetric sensing but with independent thermistor to measure the temperature of microheater. This sensor has no openings on the membrane which would however not a problem for the designated applications in automotive electronic control unit. In late 1990s, Sensirion (Mayer 2004) released a MEMS flow sensor that integrated the mass flow sensing elements with the control electronics on a single chip. This design uses doped polycrystalline silicon thermal piles as the up- and downstream thermistors featuring very low power consumption and good sensitivity. The sensor's membrane was similar to that of Bosch's made by back side DRIE process without open slots which results in a limitation for higher pressure applications. In additional, since it is undesirable to place the exposed integrated circuitry to the fluid, the sensor has to be packaged to a tiny channel that in return limits its applications in high flow rate. Yamatake (Azbil) shared the patents with Honeywell (Nishimoto 1991) and thus the sensor structure is very much the same. Omron (Fujiwara 2005) introduced its mass flow sensor products in earlier 2000s, the sensor chip has a similar footprint as that of Honeywell but its sensing elements were provided by polycrystalline silicon thermal piles. The MEMS mass flow sensors by Siargo (Wang 2009; Huang 2011) were designed for use in utility gas flow meters with a wide dynamic range to cover requirements from residential to industrial applications in city gas distribution. The sensor integrated calorimetric and anemometric sensing technology, and further enabled the self-cleaning capability. The openings on the membrane ensure the buffer to withstand medium gas pressure in industrial applications. There are a few other MEMS flow sensor manufacturers, but none of them are directly applicable to natural gas metrology.

3.3.2. Current MEMS gas meters

The first MEMS gas meter for city gas applications was developed by MEMS AG using Sensirion's MEMS flow sensor in 2000 (Matter 2004). This meter was designed to replace diaphragm meter G4 for residential applications. The compact all-electronic gas meter was a sensation for the industry and field tests were conducted extensively. However, as previously discussed, the bypass design would always be a concern for reliability although the manufacturer had data to show the otherwise. There may be additional concerns about the gas composition dependence as well as lack of industrial standards that shall be a barrier for the custody transfer applications. Further the one model product shall be difficult for the customers to manage their tariff system. In 2007, the product was transferred to Swiss Metering for sales and marketing but today it is available under its parent company, Diehl Gas Metering. This one model meter had a different appearance but at least the gas composition dependence as indicated by the user guide would have the same limitation. (www.diehl-gas-metering.com) As some critical hazardous protection ratings are still pending, this product at current remains a prototype. Yamatake released its "μF" series of MEMS gas meters for industrial applications in 2004 that was powered by external supply. A battery operated correspondence with the same performance was released in 2007. (www.azbil.com) The design of the meter utilized due chip package that enhanced the dynamic range. Due to its MEMS chip design as discussed earlier in this chapter, the meters have to have excessive protections at the inlet of the flow resulting in huge pressure loss which is very much undesirable in the city gas distribution. For a higher pressure, however, its maximum flow capability is rather disappointing. Further, missing of the hazardous protecting would add additional concerns for city gas metering. In 2011, Metersit announced its four models of MEMS gas meters matching to the equivalents of diaphragm G4, G6, G16 and G25, these models are particularly in response to Italian government's smart gas meter initiatives and regulations. They however have the same gas composition limitation as the same MEMS sensor by Sensirion was used. (www.metersit.com) Siargo since 2007 introduced its series of MEMS gas meters for both industrial (4 series, 10 models) and commercial (4 series, 7 models) gas metering applications. The products have been shipped to four countries as of 2011. (www.siargo.com) The MEMS gas meters manufactured by Siargo have the excellent dynamic measurement range by integration of the calorimetric and energy dissipation sensing elements onto a single MEMS chip. These battery powered models have an Ex ia IIC T4 rating that satisfies the city gas metering requirements. Table 4 compares the key performance parameters of the current available MEMS gas meters designed for city natural gas distribution by different manufacturers.

In this table, C means calorimetric and E is for energy dissipation. LF stands for "low flow model" while HF stands for "high flow model". Siargo's LF models include residential and commercial applications. Detailed ranges will be discussed later. Gas group H is based on European standard EN437; 12A/13A are two gas types in Japanese supply system. Siargo's meters can be used for most of the natural gases with optional automatic composition variation compensation. The pressure loss listed in the table is for low flow models. For higher flow, the pressure drops are in line with the counterparts of corresponding diaphragm meters or rotary meters. In the following sections, we will discuss the detailed design, performance and reliability of Siargo's gas meters.

	Diehl	Yamatake	Metersit	Siargo
Release date	2003	2004	2011	2006
MEMS sensor provider	Sensirion	Yamatake	Sensirion	Siargo
Technology	C	C	C	C+E
Max. flow (LF) (m^3/hr)	-	160	6	4/160
Max. flow (HF) (m^3/hr)	6	1600	40	3600
Min. pressure (mbar)	-	100	-	-
Max. pressure (mbar)	100	9800	150	3000/7000
Pressure loss (mbar)	200	>1200	200	200*
Gas Group	Group H	12A/13A	Group H	Any
Hazard rating	tbd	n/a	tbd	Ex iaIICT4

Table 4. Comparison of key performance parameters of current MEMS gas meters.

3.3.3. MEMS gas meter design

To accommodate the current requirements in city gas metering, the meters are designed into three series that cover the industrial, commercial and residential applications. Ideally the design shall have all current features of their mechanical counterparts while the new functions shall add significant values. In particular, the followings are among the design considerations:

- Similar or better dynamic flow range
    - To achieve this, calorimetric and energy dissipation sensing elements are integrated onto a single MEMS chip. The detection limit was then extended down to 0.008 m/sec and up to 75 m/sec. The theoretical dynamic range for this MEMS sensor shall have a turn-down ratio over 2000:1, which in principle is far better than the 160:1 turn-down for the diaphragm meters. And this single MEMS sensor chip can then be used to cover all dynamic ranges in city gas metering. The meter algorithm shall automatically determine the transitional point where the measurement scheme shall be switched from calorimetric to energy dissipation. The larger dynamic range shall require a longer manufacture (calibration) cost, therefore the actual dynamic range shall be a balance of performance and cost.
- Temperature and pressure compensation
    - This is certainly the advantages for the mass flow sensing principle as it does not require additional sensing elements to separately measure temperature and pressure. The additional measurement elements shall also incur additional metrology errors. This however requires the design for pressure balance on both MEMS sensor chip and the package.

- Leakage detection for enhanced gas safety
  - As the chip can measure very low flow rate, the algorithm can determine whether a leakage could be present if a predetermined constant low flow rate is to be measured continuously for a certain period of time, and an alarm can then be displayed or transmitted via the communication port to the data center.
- Stand-alone operation without external power
  - The beauty of mechanical metering technology is that it is operated by mechanical movement without external power. The all-electronic gas meter has to be powered by electric sources. Therefore the key would be that the power required must be low enough that a single battery can be used for sustained operation through its whole product lifetime.
- Data safety
  - With today's stat-of-the-art electronics, three individual data storage units are designed and placed on the electronic control board. Programmable data record is provided as an option for desired data safety regulations. And the data record will automatically trigger when the unexpected interrupt of the control sequence takes place such as battery failure or sensor fault.
- Build-in communication and network capability
  - The standard build-in communication protocol is Modbus (RS485) that is ready for external network and/or wireless modules such as GPRS. Optical port shall be an option, as well as other internal communication ports such as I^2C or SPI.
- Calorific value assessment and compensation
  - The integrated elements can measure the relative value of thermal conductivity and thermal capacitance from which the calorific value can be assessed. Detailed discussions can be found later in this chapter.
- Compact design for cost reduction
  - As the MEMS sensor chip is miniature, the sensor assembly including the electronic control board can be designed into a compact form that is substantially smaller than the mechanical counterpart. This will provide additional benefits for the reduction of the cost not only in manufacture but for overall gas distribution management.
- Hazard rating
  - As the applications demand, the design must meet minimal requirements for hazardous protection to ensure safety.

The series of the current products are shown in Figure 2. The flanged meter series (a) are designed for applications in the gas pipeline with medium pressure up to 1.5MPa with a pipe diameter from 25 to 150mm and maximum measurable flow rate from 125 to 3600 m^3/hr. The meters for commercial applications have a pipe diameter of 20 to 80mm covering maximum flow rate from 6 to 160 m^3/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 2.5 to 4 m^3/hr. The residential series have a maximum working pressure rating of 0.3MPa. The flow rates for all these meters are calibrated at the standard conditions of 101.325kPa and a customized temperature of 0, 15, or 20°C.

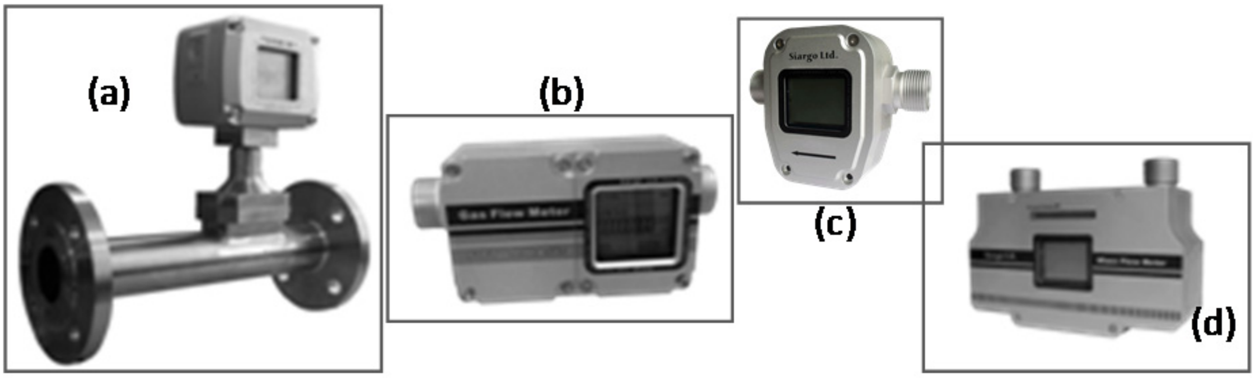

Figure 2. MEMS gas meter series manufactured by Siargo. (a) industrial applications; (b) commercial applications; (c) residential applications and (d) residential applications with pre-paid card reader option.

The meters are powered by a lithium ion battery of 19Ahr for a life time of four (industrial), six (commercial) and twelve (residential) years. For all models, both the instant mass flow rate and accumulated flow rate at the standard conditions (101.325kPa, 0/15/20°C) are displayed simultaneously. The battery indicator on the LCD will flash approximately three months before the end of the battery life. The battery pack was placed in a separate chamber that enables the integrity of the metrology during change of the battery. For data safety purpose, the meters have three separate nonvolatile memories to record the operation status of time, instant flow rate and accumulated flow rate 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 users for their specific application requirements. For remote data transmission, RS485 with Modbus protocol provides connections to the local concentrator and further transmission could be via wired or wireless network. Optical communication port is an option.

3.3.3.1. MEMS gas meter mechanical design

For all models, the sensors are inserted at the center of the flow channel that is manufactured with a venturi structure for flow stability. Figure 3 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 safety while the electronics itself is designed to be intrinsic safe. The meter body is either made of stainless steel or aluminum alloy. The flow conditioner assembly is placed at the inlet of the flow which adds to a maximum pressure loss of less than 200Pa 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 dimensions and package.

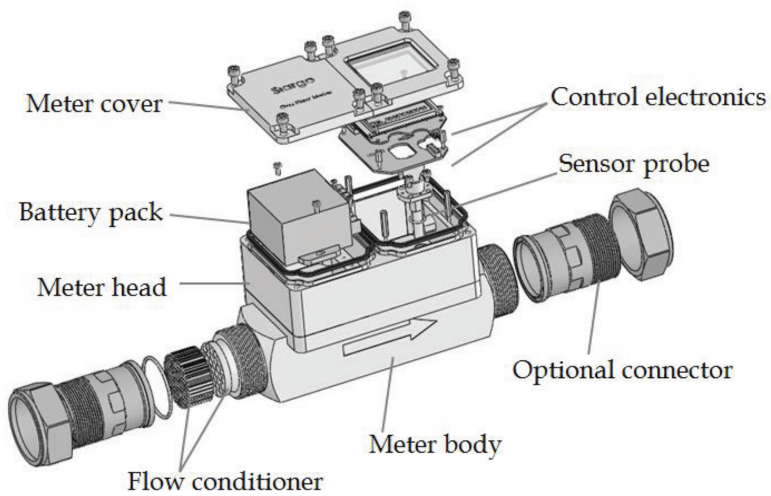

Figure 3. Component schematics of the commercial gas meters

3.3.3.2. MEMS sensor assembly

The sensor probe assembly is shown in Figure 4. The sensor probe is made of stainless steel. For large flow applications and meters with diameters more than 50mm, dual or tri-sensors are packaged on the same probe so that the mass flow value can be averaged from multipoint measurements resulting in an enhanced accuracy. The probe is shaped into a plate with a thickness about 1 mm that shall form a boundary layer in the flow channel. The sensor/plate surface is parallel to the gas flow directions such that a redistribution of the gas forces the flow into a laminar formality across the sensor probe. This laminar flow shall be helpful for maintenance of gas conversion and flow stability for the sensing signals. When the dual or tri-sensors are on the same probe, the installation of the probe will ensure that the sensor at the tip is placed at the center of the flow channel (master sensor) and the other ones (slave sensors) will be placed at one fourth (dual sensors) and one third (tri-sensors) of the flow channel diameter, respectively. As the sensor surface direction is in parallel to the flow direction, the edge of the probe is made with a sharp slope so that any particle impact onto the sensor assembly will have a good chance to be impelled away from the sensor surface reducing the head-on collision induced sensor reliability.

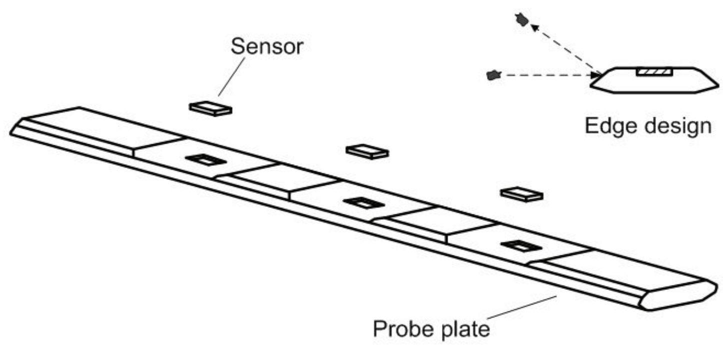

Figure 4. Schematics for sensor probe assembly.

3.3.4. MEMS gas meter performance

3.3.4.1. Permissible errors

The meters were 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% and traceable to a national standard. The measured permissible errors 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 5 shows the measured data that indicated the maximum permissible errors of the meters are well within the general requirements for city gas distribution, benchmarking to those by the traditional mechanical meters with temperature and pressure compensator.

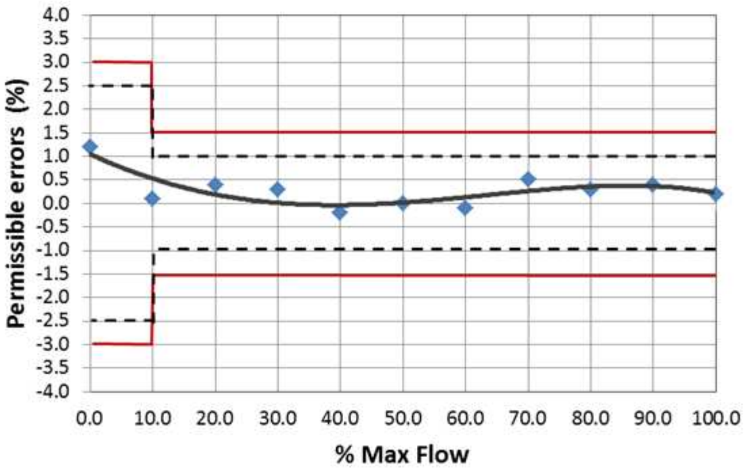

Figure 5. MEMS meter permissible error measurement.

While the MEMS meters by principle are automatically 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. This is due to that the sensor chip has a free standing membrane with a cavity underneath. If the sensor design and its assembly cannot provide the pressure balancing configuration, pressure variations in the flow channel may lead to minor membrane deformation that would be sufficient for altering the sensor accuracy. Therefore in the sensor chip (Figure 1) and the assembly design, pressure balance via the openings on sensor chip as well as via the openings on the support and below the sensor cavity is made to eliminate the pressure change induced by sensor membrane deformation. In addition, high pressure could also introduce measurement errors as the thermal properties of the gas under high pressure may be substantially different from those at ambient calibration conditions. Another factor that would impact the meter performance is the temperature compensation of the electronic circuitry as it could produce additional errors due to the component temperature performance deviations. However, this could be removed by additional temperature calibration, and normally a temperature coefficient of 0.015%/ºC could be achieved that shall be in line with the city gas distribution requirements.

3.3.4.2. Pressure loss

Pressure loss is one of the major undesirable factors for the city gas metering as the pipeline pressure is often low when reaching to end users. A higher pressure loss will not only introduce additional energy consumption for the distribution system but may lead to customer issues, *e.g.*, the gas may not be sufficient for burner operation or even may fail to fire residential ranges.

In the current 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 inlet and outlet of the flow channel. Additional flow stability provided by the venturi structure of the meter body in the design also would not introduce additional pressure drop as it has been well demonstrated in literature. Figure 6 shows the measured pressure loss in air at 20ºC and 101.325kPa for the commercial models. These values are compatible with those by the diaphragm meters. For the actual usage in natural gases, the pressure loss shall be even smaller for about 40% as for the differences in the densities of air and natural gases.

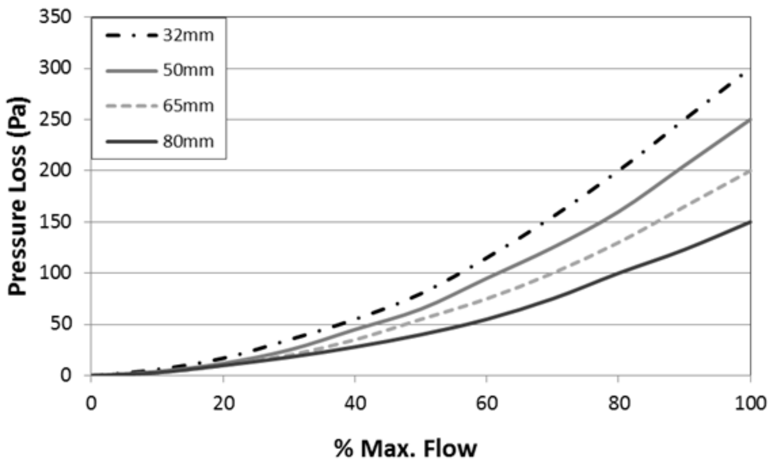

Figure 6. Pressure loss for the commercial gas meter models measured in air.

3.3.4.3. Installation conditions

For mechanical meters particularly for turbine meters, it is necessary to have enough long straight pipe lines before and after the meter installed so that the flow stability can be ensured and the measurement permissible errors can be within the requirements for city gas distribution. This limitation makes the installation costly and sometimes it simply cannot be met due to field space restrictions. In the current MEMS meters, a pair of flow conditioners (a combination of a flow straightener and a flow profiler) is designed to create a controllable flow profile regardless of the flow conditions. The plate design of the sensor assembly and its position in the flow channel result in the boundary conditions making a laminar redistribution, which again help the stability and reproducibility of the flow measurement. Therefore the straight pipeline requirement in these meters would not be a crucial factor for flow measurement uncertainties. Figure 7 shows the test and verification results by placing different bended pipes before the inlet of the flow meter. The meter was connected to a sonic nozzle system as the reference as shown in the figure. At each condition, permissible errors were taken against the original calibration, and Figure 7 is the summary of all data in this experiment. It can be observed that a straight pipeline with a length of 5 times of the pipe diameter would be sufficient for the specified permissible error (±1.5%) at all different pipe connection/conditions before the inlet of the meter. This length is much shorter than that required by turbine meters.

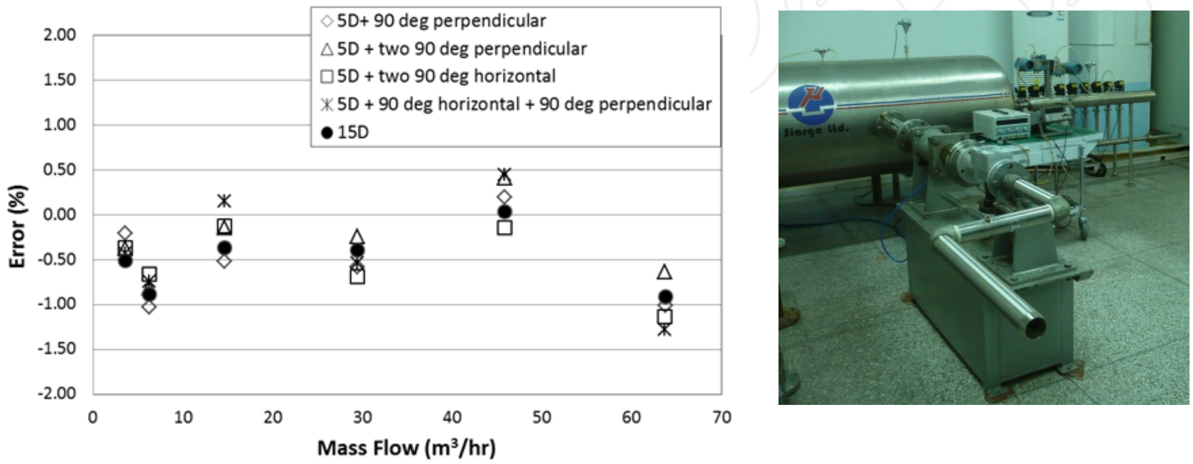

Figure 7. Measured permissible errors for different installation conditions.

3.3.4.4. Calorific value assessment and compensation

In USA, natural gas sold to residential customers is billed by "therms" that is based on the volumetric metering from the installed diaphragm meters and the monitoring of the gas properties at the central gas station. Each month a different factor shall be applied to gas bill to match the gas company's totalized data. In this case, it is almost impossible for customer to challenge the bill by looking at the record of the installed diaphragm meter as the monthly factor is set by the gas companies and varies. 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 (Otakane 2003), 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 permissible errors can be controlled irrespective of the gas compositions except for inclusion of high concentration of non-calorific gases such as nitrogen. However, the report neither specifies which calorific values were used to correlate output nor provide solutions to compensate the composition variation induced deviations so that the current acceptable tariff standards can be met as the volumetric value is still the base in most of the countries' tariff system. This could also be the reason for the limited applications for the existing products in Europe, for which a particular gas group has to be specified as discussed earlier in this chapter. For a wider spectrum of applications, a compensation scheme has to be provided for the purpose of fairness unless all meters with the same metrology capability can be changed overnight. The calorific value measurement at present shall only serve as an added-value for reference or for future tariff system development.

The current capability of the calorimetric MEMS meters for 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. 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. Since the flow rate is proportional to the gas thermal conductivity and thermal capacitance, and both of them are related to the thermal values. Therefore, if the thermal conductivity and the thermal capacitance can be measured independently, it would be possible to differentiate the gas calorific value or gas composition induced mass flow rate variation. The compensation scheme can then be applied to the measured mass flow rate. Consequently, the measurement could be adjusted *in situ* to be in consistent with the current tariff system. For this purpose, additional two thermistors were integrated onto the previously discussed MEMS sensor chip, both located on the membrane for better thermal isolation. These two thermistors can measure the thermal conductivity and thermal capacitance of the gases. To demonstrate the capability of the MEMS mass flow meters incorporated with the integrated sensors, natural gases with five different compositions or thermal values were selected for tests by the meters that are pre-set with the gas calorific value compensation scheme and calibrated with air. Table 5 lists the selected gas compositions, thermal values and other data to be discussed.

	CH_4	C_2H_6	C_3H_8	N_2	GCF	HHV	R. Gravity	P/C_p
A	89.29	7.57	2.29	0.25	0.7959	44.12	0.6138	20.85
B	94.65	0.05	0.02	5.25	0.8735	37.89	0.5773	21.86
C	89.00	8.00	3.00	0.00	0.8199	39.18	0.6511	21.19
D	80.71	6.68	1.90	0.00	0.7815	39.59	0.7137	20.68
E	97.55	0.43	0.06	1.02	0.8778	36.81	0.5761	21.92

Table 5. List of the test gas properties and measured data.

In this table, only the concentrations for major constituent components of the gases are listed. Other minor constituents make up to the remaining concentrations of each gas. The HHV stands for high heating value with a unit of MJ/m^3. The HHV values were obtained using gas chromatography-mass spectrometer (GCMS) and hence are not *in situ* values. The relative gravity (R. Gravity) values were referenced to that of air and are also measured *ex situ*. GCF is the gas conversion factor that was obtained by referencing to the volumetric values in air. The meters calibrated in air were connected to a high precision standard volumetric rotary meter with the maximum permissible error of ±0.5%. The correlation between the readings of the two types of meters, if it is linear, shall establish the gas conversion factor. Figure 8 shows the measured data for gas A from MEMS gas meter with a maximum flow rate of $4m^3/hr$ (G2.5). The excellent linearity further established that the real gas calibration would not be required in this type of meter. This allows a substantially reduction in manufacture. In other words, the GCF varies with the gas composition confirms that the meters could not be simply applied to the existing tariff system without knowing the gas compositions, but if the specific GCF is preset in MEMS mass flow meters, it 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. Compared to the traditional thermal mass flow technology, the MEMS gas meters have the advantage that a unique gas conversion factor can be established for each gas with respect to air. Specifically, after applying the gas conversion factor to the meter, it will retain the accuracy in the full measurement dynamic range. The data shown in Figure 8 and the verifications justified the proposed applications in the existing tariff system. It is expected that the GCF is not a universal factor but meter design dependent. Different manufacture may have slightly different value for each gas conversion factor.

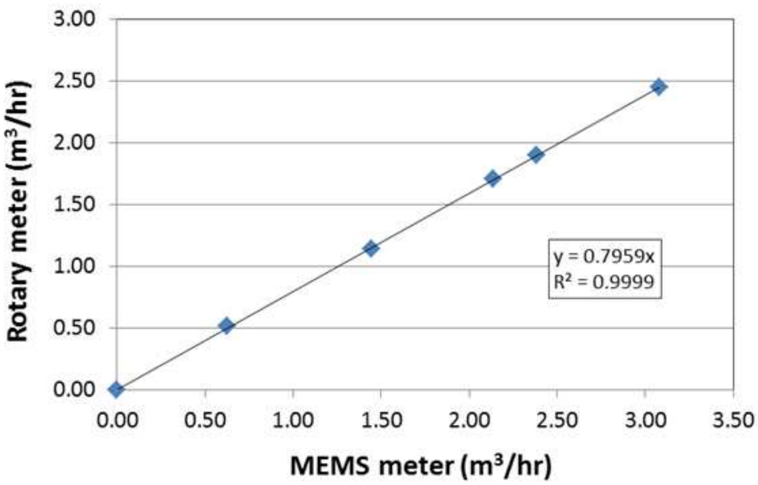

Figure 8. Gas conversion factor measurement.

The values P/C_P 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 which makes it possible for an instant compensation scheme. In the previous report (Otakane 2003), the actual calorific value was not reported, and the data show strong dependence on nitrogen inclusion. From the data in Table 5, it can be observed that the GCF can be correlated to the gas thermal value (Figure 9) and the nitrogen inclusion seems less important compared to that in the previous report if the current thermal values are used for correlation since one of the gases (Gas B) has 5% nitrogen inclusion. The linear correlations of the *in situ* measured data, P/C_P, with the GCF (Figure 9) suggested that these values can be used for dynamic compensation of the gas thermal value (composition) variation. To verify this assumption, a MEMS gas meter incorporated with the compensation algorithm that is calibrated based on Gas D (which was pre-calibrated in air and applied GCF) was used for the measurement in Gas A. One can observe from Figure 10 that a large error was found without implementing the compensation scheme, while the compensation could be successfully eliminating the thermal value or composition induced errors based on current volumetric tariff system. On the contrary, one would suggest that the meter has the capability for thermal value measurement and the positive deviation shown in Figure 10 was due to that Gas A has a higher thermal value, but in order to compliance with the current tariff system such compensation scheme must be implemented.

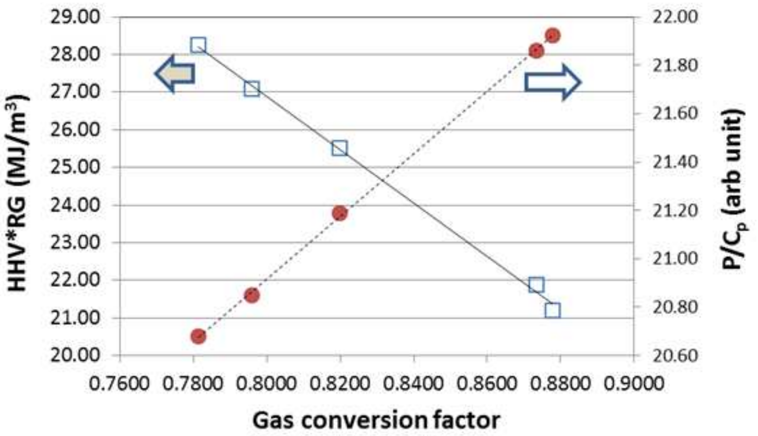

Figure 9. Correlation of the gas high heat thermal value HHV*RG (relative gravity) and *in situ* measured thermal value with respect to the gas conversion factor.

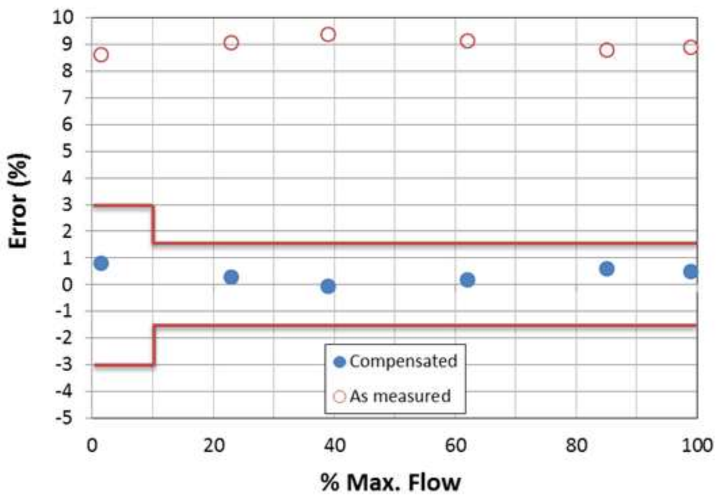

Figure 10. Comparison of as measured and compensated errors for a MEMS gas meter calibrated with Gas E but applied for measurement of Gas A.

3.3.5. MEMS gas meter field tests

3.3.5.1. Long term stability

One of the key concerns for the electronic meters is the reliability for long term operation. Figure 11 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 a preheat process and then heat-up with medium fire followed by large fire for shaping and then slowly reduced the heat for cooling down. This gas usage pattern was a typical application that requires a meter with large dynamic range in order to accurately record the gas consumption. With the existing mechanical meters, the metering during the preheat process can be completely missed, costing revenue for the gas suppliers. It is however an excellent application for the present MEMS meters. In this particular case, a DN50 flanged medium pressure meter with the flow range of 0~400Nm^3/hr was installed. From the data shown in Figure 11, no performance degradation or accuracy deviation could be observed, since one can reasonably assume that the process of the ceramic making would consume pretty much the same amount for each run. For further validation, the meter was re-verified after the one-year installation by measuring its maximum permissible errors and the results confirmed the above observation.

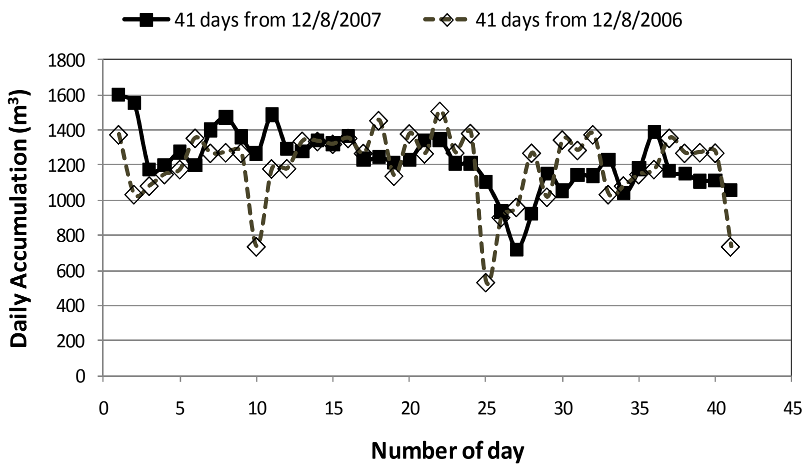

Figure 11. The daily accumulated flow apart from one year for a meter installed at a factory.

3.3.5.2. Project for distribution accuracy enhancement

To avoid inaccurate metering for small flow, a gas supplier had installed seven diaphragm meters (G25) at a public school where the gas consumption was much less in the morning as only breakfast was served. In the evening the gas consumption substantially increases due to gas burner operation for supply of hot water and other heating requirements. The seven diaphragm meters could meter a maximum flow of 280 m^3/hr that was well covered by a DN50 flanged MEMS gas meter for industrial applications for current design (0~400Nm^3/hr). Since the local standards required the meter set at 20°C and 101.325kPa at 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 during summer time but when temperature dropped, the MEMS meter recorded the gas consumption more accurately since the diaphragm meter could not be compensated with environmental temperature change.

Figure 12. One MEMS meter can replace seven diaphragm meters with better accuracy.

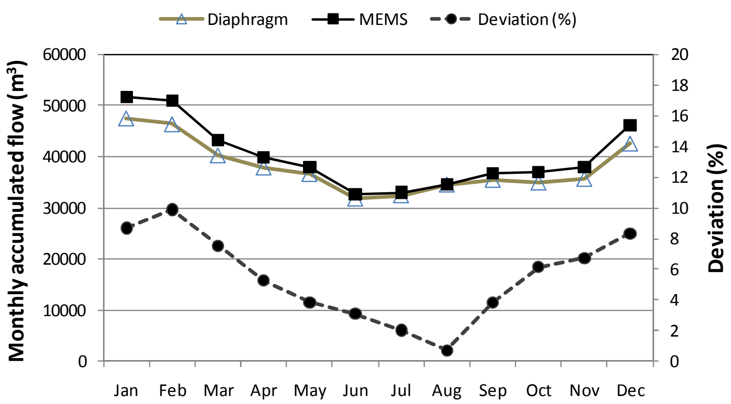

Figure 13. MEMS meter can better record the data while temperature varies.

4. Future development

Among the current all-electronic gas meter technologies for city gas metering, MEMS mass flow sensing technology would be the best candidate for future development and enhancement. It provides much better gas data acquisition and management. The MEMS mass flow meters feature a large dynamic range with automatic temperature and pressure compensation. Its capability in gas safety with leakage detection, readiness in data safety and remote data management adds significant values to current energy management. The small form factor provides significantly reduction in manufacture cost and logistic cost. The technology is also promising for direct calorific value measurement without any additional cost.

For the existing issues, one of the key improvements in near future would be further power consumption reduction. Although the current designed lifetime for residential meters was claimed for as long as 15 years with battery by Metersit, few battery manufacturers would provide such a warranty. Battery life itself shall be dependent on many environmental factors which might significantly reduce the specified lifetime. Once the power fails, the all-electronic meter will stop working although such failure will not create detrimental results for end users but for gas companies it is a concern. Remote data logging shall help to monitor each meter's status, a remedy to power failure is however still very much desired. One of the promising directions could be the current energy harvesting activities utilizing the flow energy inside the pipeline to generate electricity to power electronics. MEMS harvesters for vibrational energy have been emerging for commercialization. Similar approaches for flow measurement (Schmidt 1997; Kim 2000) would suggest the clues in this aspect. Another issue for gas metering is the unexpected gas composition variations or *in situ* gas composition information. MEMS flow sensing chip definitely has rooms for integration of gas sensors that would very likely provide such value. Additional desired functions shall include *in situ* calibration or verification, self-cleaning of possible additives on sensor surface and onsite exchange of the metrology components during maintenance.

The MEMS TOF technology can be integrated with the calorimetric MEMS flow sensors. This would help to simplify the leakage detection electronics as it has the advantage in ultralow flow sensing. The TOF technology shall also further simplify the gas composition compensation scheme since it could provide pure gas flow speed measurement without the process of decoupling gas calorimetric value from gas speed. The frequency measurement might provide better contamination resistance as signal attenuation would be easier to take place for the amplitude measurement by calorimetric sensing. Therefore it is expected that TOF sensing scheme might have better reliability in case of presence of contaminants.

The future development and massive deployment of the MEMS gas meters for city gas metering also require establishment of internationally acceptable standards. Current guideline could come from gas meter recommendation by International Organization of Legal Metrology, OIML R137-2011. European standards for residential ultrasonic meters EN14236-2007 also provide valuable references to the MEMS gas meters especially for the electronics of the meters. However, the MEMS gas meters have many features/functions that are missing in the above mentioned standards for the measurement schemes and principle, particularly for the calorific value related measurement. For a gas meter used for city gas metering or gas distribution, a well-defined standard is necessary.

MEMS gas meter for city gas metering is at its very earlier stage. The history of this industry asks for patience and persistence. With more and more manufacturers to participate in the development and commercialization process, and with today's state-of-the art electronics and advancement of the MEMS technology, a comprehensive gas energy management system based on the MEMS flow sensing technology shall eventually emerge and assist us for better natural gas resource management and conservation that ultimately benefits not only gas suppliers but all gas consumers.

Author details

Liji Huang
Siargo, Inc., USA

Acknowledgement

The author would like to thank his colleagues Chih-Chang Chen, Gaofeng Wang, Yahong Yao, Sugang Jiang, Jack Xuan, Yong Feng, Wenhong Deng, Xiaozhong Wu, Jianwei Fang, Xiang Lan, Changming Jiang, Xiangyou Yang, Jiliang Ruan, Rui Liu, Min Ao, Hong Luo, Rongzhong Yang, Min Du, Pei Zhou, Yaling Tao, Xueming Huang, and many others for their dedication to the very challenge process of MEMS gas meter commercialization. Financial supports from Entrepreneur Investment and Acorn Campus are also greatly appreciated. Special thanks to Mr. Richard Qu, David Tsang, Ga-Lane Chen and Chester Wang for their continued supports and inspiration. Mass production of the current products and future residential meters will be provided by Meter Technologies Limited.

5. References

ABS Energy Research (2008). World Gas Meter Report 2008. www.absenergyresearch.com. Data can also be found in www.meterpedia.com.

Ashauer, M.; Glosch, H.; Hedrich, F.; Hey, H.; Sanmaier, H. & Lang, W. (1999). Thermal flow sensor for liquids and gases based on combination of two principles. Sensors and Actuators, Vol. 73, pp. 7-13.

Bonne, U. (1992). Fully compensated flow microsensor for electronic gas metering, *Proceedings International Gas Research Conference*, Orlando, November 16–19, Vol. III, pp. 859 – 862.

Bonne, U. (2008). Gas Sensors, *Comprehensive Microsystems*, Vol. 2, Chapter 8, Elsevier Science, pp. 375-427. ISBN 978-0-44452-194-1.

Bruun, H.H. (1995). Hotwire anemometry: principle and signal analysis, Oxford University.

Fujiwara T. & Sasaki, Sho. (2005). Flow sensor and flow rate measuring method, US Patent 6,871,538, March 29, 2005.

Gehman, R.W.; Bohrer, P.J.; Johnson, R.G. & Higashi, R.H. (1985). Design and packaging of a highly sensitive microtransducer for airflow and differential pressure sensing applications, *Third International Conference on Solid State Sensors*, Philadelphia, June 11-14, pp. 207-211.

Haasl, S. & Stemme, G. (2008), Flow Sensors, *Comprehensive Microsystems*, Vol. 2, Chapter 7, Elsevier Science, pp. 209-272. ISBN 978-0-44452-194-1.

Hecht, H.; Tank, D. & Konzelmann, U. (1997). Method for correcting the output signal of an air mass meter, US Patent 5,668,313, September 16, 1997.

Higashi, R.E.; Johnson, R.G. & Bohrer P.J. (1985). Flow sensor, US Patent 4,501,144, February 26, 1985.

Huang, L.J.; Chen, C.; Yao, Y.; Wang, G.; Feng, Y.; Wei, K.; Deng, W.; Jiang, C.; Ruan, J. & Jiang, S. (2010). All-electronic MEMS flow meters for city gas applications. *Proceedings of 15th International flow measurement conference 2010*, Taipei, October 2010, pp. 376-383. ISBN 978-1-61782-472-2.

Huang, L.J.; Chen, C.; Yao, Y. & Wang, G. (2011). Micromachined thermal mass flow sensor with self-cleaning capability and methods of making the same, US Patent 7,878,056, February 1, 2011.

Hutton, S.P. (1971). Flow metering and future aims. *Proceedings of conference on modern development in flow measurement*, Harwell, September 21-23, pp. 401-405. ISBN 978-0-90122-330-2.

Kang, S.S. & Nutt, W.E. (1992). Development of a compact flow meter for residential natural gas metering, *Final Report,* Creare Incorporation.

Kim, D.; Kang, S.; Sim, J.; Shin, J.; Choi, P. & Lee, J. (2000). Characteristics of piezoresistive mass flow sensors fabricated by porous silicon micromachining, Jpn. J. Appl. Phys. Vol. 39, pp. 7134-7137.

Kono, K.; Nagai, N.; Yuasa, K.; Fujimoto, T.; Suzuki, M. & Fujii, Y.; Hiroyama, T. (2006). Development of intelligent domestic ultrasonic gas meters, *23rd World Gas Conference*, Amsterdam, 2006.

Matter, D.; Kramer, B.; Kleiner, T.; Sabbattini, B. & Suter, T. (2004). Microelectronic domestic gas meter with new technology, *Technisches Messen*, Vol. 71, pp. 3-22.

Mayer, F. & Haeberli, A.M. (2004). Method and device for measuring the low of a fluid, US Patent 6,763,710; July 20, 2004.

Nishimoto, I.; Kurosawa, T. & Yamamoto, T. (1991). Microbridge flow sensor, US Patent 5,050,429, September 24, 1991.

Otakane, K.; Sakai, K. & Seto, M. (2003). Development of the thermal flow meter, *SICE Annual Conference in Fukui*, August 4-6, pp. 2031-2034.

Putten, A. F.P. van & Middelhoek, S. (1974). Integrated silicon anemometer. *Electronics Letters*, Vol. 10, No. 21, pp. 425-448.

Schmidt, H.J.; Holtkamp, F. & Benecke, W. (1997). Flow measurement in micromachined orifices, J. Micromech. Microeng. Vol. 7, pp. 189-192.

Shin, W.C. & Besser, R.S. (2006). A micromachined thin-film gas flow sensor for microchemical reactors, Journal of Micromechanics and Microengineering, Vol. 16, pp. 731-741

US Energy Information Administration (2011). International Energy Outlook 2011. *US Department of Energy Report* DOE/EIA-0484, September 2011.

Wang, G.; Chen, C.; Yao, Y. & Huang, L.J. (2009). Micromachined thermal mass flow sensors and insertion type flow meters and manufacture methods, US Patent 7,536,908 May 26, 2009.

van der Wiel, A.J.; Linder, C.; de Rooij, N.F. & Bezinge, A. (1993). A liquid velocity sensor based on the hot-wire principle, Sensors and Actuators, Vol A37-38, pp. 693-697.
Yoder, J. (2002). Ultrasonic flowmeter market. www.Flowresearch.com.