MEMS Mass Flow Technology: Striving for 30 Years

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Abstract: Since late 1970s, MEMS mass flow sensors have been emerged for gas mass flow measurement providing cost effective alternatives. However, unlike the other MEMS technology, MEMS mass flow sensor market grows at a very slow pace dominating only in automobile air mass flow sensing. The MEMS mass flow meters have been few since year 2000 and are limited to low flow speed applications in dry and clean gases due to the vulnerability in design and adversity for moisture and particles. Siargo since 2003 has been dedicated to provide its patented MEMS mass flow technology excelling for the traditional counterparts and targeting as the alternatives to the century-old diaphragm utility technology and many others in industrial applications. A wide spectrum of product lines has been introduced to the market and has been well accepted by the customers. This paper presents a comprehensive analysis of the existing MEMS mass flow technology, products on markets, and the prospective of the MEMS mass flow technology in the coming years.

Keywords: MEMS flow sensors, MEMS flow meters, Flow sensing

1. Introduction

Flow technologies have been dominated by mechanical approaches. Most of the mechanical flow technologies are well established and have demonstrated their reliability over a century. Their self-sustained character with long life time sets huge barrier for any new comers. However, mechanical meters, particularly for gas flow, are not able to self compensate the environmental variations such as temperature and pressure, which is making the mass flow measurement a difficult task. What are even worse are their requirements for data storage and/or transmission matching to the advancement of other current technology. The development of thermal mass flow sensing elements using hot wires (anemometers) in the late 1950s initiated the capability of direct measurement of mass flow, and later the calorimetric capillary mass flow sensors have great impact to the development of semiconductor technologies. Nevertheless, the thermal mass flow technologies are limited by its stability at null flow, high power consumption and bulk package as well as expensive build. Applications where high accuracy is required such as custody transfer are still waiting for additional solutions, although ultrasonic approach has gained certain acceptance but limited by its cost and complicated algorithm as well. In addition, similar to mechanical metering technologies, ultrasonic approach can not apply to flow in a small channel or in microflow domain.

The MEMS pressure sensors had been applied for flow measurement using the differential pressure principle but have not become the mainstream. In earlier 1980s, Honeywell[1] pioneered MEMS (micro electro mechanical systems) mass flow technology using silicon bulk machining based on the calorimetric principle. The MEMS mass flow sensors manufactured by Honeywell have made it possible for low cost mass flow sensing particularly for clean and dry gases in low flow regime. The compact or even miniature size and low power capability eased the applications in medical and quite some other industrial applications. In 2003, MEMS^{AG}/ABB[2] first introduced the battery powered MEMS domestic gas meter prototype demonstrating the low power thermal mass flow technology for custody transfer. In 2006 Siargo[3] commercialized the first battery operated industrial utility meter and other industrial applications packaged both in-line and insertion. In this paper, various types of MEMS flow sensors developed ever since will be reviewed and compared. In particular, applications in large flow capability, custody transfer approach, massive deployment as well as the future advancement of the MEMS flow technologies will be discussed.

2. MEMS Mass Flow Products

MEMS mass flow products started to debut in late 1980s by Honeywell. The products provided by Honeywell however are applicable for gas only and the plastic packaged mass flow sensors with limited accuracy were targeting the medical and general purpose industrial applications. In addition, it requires the gases be dry and clean with a flow speed usually not exceeding 10 m/sec. Since then few companies[2-5] also offer MEMS mass flow sensor and meter products utilizing the same calorimetric thermal mass flow measurement principle with the similar restrictions in the applications. Bypass design or configuration is dominated in many of the product designs to avoid damages to the sensors or sensor packages. Siargo on the other hand manufactures integrated MEMS mass flow sensor with multiple technology platforms by supplying a much wider spectrum of products with the sensors directly inserted into the flow channel. In addition to the gas flow sensing products, Sensirion[7] and Siargo also offer liquid flow sensors using the same gas flow sensor chip while ISSYS[8] developed Coriolis MEMS flow sensor for liquid applications. Table 1 lists the MEMS mass flow Technology and the current MEMS flow sensing product manufacturers. According to various market data, the annual market for MEMS flow sensing products is about US$350M and MEMS automotive air mass flow sensors led by Bosch have the major market share among other MEMS flow applications as of today.

Table 1 Manufacturers of commercialized MEMS mass flow sensors and meters

Technology	Calorimetric	Calorimetric + Energy dispersion	*Time-of-Flight*	*Coriolis*
Sensors	Honeywell, Bosch, Azbil, Omron, Sensirion, Siargo etc.	Siargo	Siargo*	ISSYS*
In-line meters	Sensirion, Azbil, Siargo	Siargo	Siargo*	ISSYS*
Controller	Sensirion, Brooks, Bronkhorst, Burkert, Azbil etc.	--	--	--
Insertion meters	Siargo	Siargo	Siargo*	--
Custody Transfer	Siargo, Azbil, $MEMS^{AG}$ **	Siargo	--	--

*In the process of commercialization;
**$MEMS^{AG}$ offered prototype but not fully commercialized.

3. MEMS Mass Flow Technology

3.1 The Make of the MEMS Thermal Mass Flow Sensors

The MEMS thermal mass flow sensors are mostly made on a silicon wafer substrate on which a couple of micron thick low stress silicon nitride film is used as the supporting membrane where the micro-heater and up/downstream sensors are placed. The silicon nitride film usually is deposited with low-pressure chemical vapor deposition (LPCVD). The micro-heater centralized on the membrane usually is made of noble metal platinum or doped polysilicon while the up/downstream sensors can be made of the same materials or thermal piles. The additional temperature sensor is place in close contact with the substrate for better sensing of the environmental changes. Either wet chemical etching or dry etching technique of silicon micro-machining is applied to remove the silicon materials underneath the silicon nitride membrane. In order to prevent the direct contact of the resistors to the fluid, the MEMS sensor surface is usually passivated with low stress silicon nitride or sometimes with silicon carbide that will have good thermal conductivity and hardness for reliability. For better heat isolation, openings between the micro-heater and sensors are made on the supporting membrane. Some manufacturers also designed additional temperature sensor next to the micro-heater in order to ensure that the micro-heater temperature can be properly maintained during measurement.

3.2 Calorimetric Sensors

Most of the current MEMS mass flow sensors utilize calorimetric measurement approach. Compared to the traditional capillary mass flow sensors, the MEMS flow sensors often have an additional temperature sensor that can be used for environment temperature measurement to provide better feedbacks for heater/sensor temperature stability. The MEMS sensors also feature a miniaturized package, low power consumption and significant cost reduction. In addition, the up and down stream sensors can be made of thermal piles for further reduction of power consumption, improvement in sensitivity, and enhancement of offset stability, which enable the capability of low flow sensitivity down to 5 mm/sec or lower. Because of the size of the chips, the sensors can be packaged into a flow channel as small as 0.5mm in diameter. This pushes the measurement into micro-flow domain. On the other hand, the MEMS chip manufacturers often take the conventional thoughts to squeeze the chip footprint (below 2x2mm for the whole sensing chip size in most of the current products) for better cost structure. This however might impact on reliability resulting in restrictions to applications in clean and dry gas only as moisture and particles may damage the sensor and sensor wire bonding.

Some manufacturers integrate the signal conditioning circuitry with the sensing element leading to excellent accuracy, very compact final package and further cost reduction, but it also limits the package of the sensor for the final products which are forced into a bypass configuration. The small sensing channel could be blocked when particles or powders are present in the fluid otherwise the filtering settings can result in a high pressure loss.

Siargo designed additional sensing elements utilizing the energy dispersion measurement principle (anemometry) and integrated with the calorimetric sensing elements onto the same sensor chip which extends the maximum measurable flow speed up to 90 m/sec with the anemometry while the lowest flow speed detected with the calorimetric sensors would be down to 5 mm/sec. This design makes the theoretical turn-down over 18000:1 when the two sets of sensors working at the same time. In addition, the design has left enough footprint that enables the effective sealing of the wire connections to the signal processing electronics and prevents moisture and tiny particle impact from fatality during operation. Because of this sensor design, sensor can be packaged into a probe either directly inserting into the center of the flow channel that would provide additional sensitivity in a large pipelines or at the wall of the flow channel for small pipelines depending on the application requirements.

3.3 Coriolis Sensors

The MEMS micro Coriolis mass flow sensor is best for small volume liquid and usually cannot be used for gas flow measurement particularly when the gas is not under high pressure or the density is low. The sensor made by ISSYS[8] consists of a silicon microtube via silicon wafer fuse bonding and has integrated a temperature sensor, which could measure liquid mass flow, density, binary concentration and temperature at the same time. Another advantage for the MEMS Coriolis mass flow sensor is that it usually operates at a much higher resonant frequency that will have substantially less vibratory impacts from the environments as compared to those for the traditional Coriolis mass flow technology.

Similar to the MEMS thermal mass flow sensors, micro Coriolis mass flow sensor also requires clean fluid (liquid) as particles can damage the sensor. In addition, the sensor will not function well in liquid with high viscosities and liquid with chemical reactions. The high speed liquid flow may also alter the performance of the sensor unless bypass configuration is applied.

3.4 Time-of-Flight Sensors

MEMS thermal time-of-flight sensors has been discussed for many years.[9] In this technology, the flow speed is measured by determining the precise travel time of a thermal pulse generated from a micro heater and carried by the fluid to the downstream sensor that is located at a fixed precise distance. Since the traveling time of the pulse would not be altered by the fluid composition, the flow speed measured by this technology will be independent of the fluid composition thus making the measurement of the fluid with variable concentrations a very simple task. However, the pure time-of-flight sensors are not easy to manufacture as the heater/sensor response can be fluid composition dependent. One of the solutions to decompose this dependency is to have an ultra sharp pulse generator that on the other hand can be very vulnerable to the rough conditions in many practical applications. This could be one of the reasons that even many of the research data indicated the possibility but products is rarely seen for more than 70 years since the idea was proposed.

4. MEMS Mass Flow Meters and Controllers

4.1 MEMS Flow Meters for General Purpose Industrial Applications

Many of the current MEMS mass flow meters are applicable for clean and dry gas flow in a pipe diameter less than 1”. Yamatake offers capability for gas flow in a pipeline up to 6” while Siargo offers similar products but can measure a much higher flow rate and have a much lower pressure loss. Insertion meters are also offered by Siargo to measure gas flow in pipelines with diameters up to 60” for a maximum flow rate of 400000m^3/hr (standard conditions: 20ºC, 101.325kPa). The advantages, however, of using the MEMS flow meters compared to those by the traditional thermal mass flow technology in the high flow rate applications would not be many except for a better cost or sometimes the power advantages as the MEMS meters can be powered by batteries whereas it is impossible for a traditional thermal mass flow meter. The advantages in smaller pipelines are more obvious since the meters made of the capillary thermal mass flow technology would often struggle with the offset stability, response time and the high cost. On the other hand, the performance of the MEMS mass flow meters for industrial applications are inferior to the ones made by traditional technologies as the MEMS sensors are more fragile for the high pressure and high temperature applications as well as for corrosive fluids. The excessive protection of the MEMS probe by some manufacturers also leads to a much higher pressure loss which either requires higher energy consumption or limits its capability in the applications.

As the cost of a MEMS sensor scales with the volume, low power MEMS flow meters for applications in moderate conditions now can be made at a cost comparable to those for variable area flow meters or rotameters. This scenario paves the way for the massive deployment of the MEMS mass flow meters in those traditional applications as its clear advantages in accuracy, package, data safety, remote control and networking.

4.2 MEMS Mass Flow Controllers

MEMS mass flow controllers in recent years have been quite popular as many of the traditional mass flow controller manufacturers introduced products using MEMS flow sensors for a compact size, more stable at the offset shift and better cost. However, the current design of the MEMS sensors compared to those for the capillary flow sensor technology is far less robust for high pressure and high temperature applications as well as for those where the fluid is corrosive, conductive or moisturized. Again the MEMS mass flow controllers at present are applicable in most cases for dry and clean gases. Products of liquid flow controllers are yet to demonstrate in the mainstream.

4.3 MEMS Flow Meters for Utility Gas Applications

City gas measurements have been dominated by mechanical meters of diaphragm, positive displacement and turbine meters for more than a century. These technologies have been proved to be reliable. With the demands for remote data management, digitization of the data from the meters made by the mechanical technologies is often very costly and difficult to prevent the errors during mechanical to digital data conversion. In addition, the pure volumetric diaphragm meters could not compensate the differences between data from a mass flow measurement at the gas portal and those at the local. Turbine meters often do not have the necessary dynamic measurement range needed in the actual applications while the positive displacement (roots) meters run at the risk of cutting off the supply by debris or particle clogging.

The domestic gas meter made by ABB/MEMS[AG] demonstrated that the MEMS mass flow technology can be applied to city gas measurement that requires long term reliability and custody transfer. One of the key advantages is that the meters could be powered by battery with a life time over 8 years, which outperformed those by the current diaphragm meter technology in many aspects. And it makes the data transmission and remote management possible. However, the bypass design of the domestic meter raised the concerns of long term reliability as the cleanness of the gas flow cannot be ensured by all means. Furthermore, the nature of custody transfer in city gas applications limits the abrupt growth or massive replacement of the new technology in a short period of time. Adding to the barrier is the optimization of the cost structure of the new technology in the domestic applications. Nonetheless, the all-electronic MEMS gas meters offer a much compact size compared to those of bulk mechanical counterparts, in addition to its add-value features. And since the MEMS gas meters do not have moving parts, thus the cost reduction from the maintenance, installation, logistics and even the materials would be very significant. The other MEMS mass flow meters introduced by Azbil have excellent accuracy and dynamic measurement range that covers the requirements for commercial applications but the design is unfortunately limited by the very high pressure loss that makes the applications for city gas very difficult.

The gas meters for city gas applications by Siargo have been commercialized and applied to industrial and commercial installations that have covered the flow ranges by all type of current mechanical meters. The battery powered meters have the sensor assemblies inserted at the center of the flow channel in each model with the channel diameter ranging from 15 to 150mm, and the maximum flow rate from 2.5m^3/hr to 3600m^3/hr with the pressure loss similar to those by the mechanical meters. The large dynamic mass flow measurement range or turn-down over 100:1 make the management of the gas data becomes much easier for mending the differences between the data at the gas portal and those from distributions.

5. Concluding Remarks

Applications of the MEMS mass flow technologies have been significantly increased and beyond those by the automotive industry. On the one end, applications in the micro-flow domain where the traditional technologies are limited will certainly have fast growth pace. On the other ends, the continuously increasing demands for more accurate measurement in mass flow will push the scaling of the cost structure and make the way for wider applications, particularly in disposable applications for medical instrumentations and consumer products. The significant cost reductions in making of the MEMS flow meters will also eventually replace the mechanical technologies such as the variable area flow meters.

After the efforts of more than a decade by the industry, the applications for city gas measurements became commercialized and attracted more and more gas companies to deploy this technology that echoed today’s high demands for better energy management. The technology will continue to improve and the corresponding market share will gradually grow.

The market demands will surely drive the MEMS mass flow technologies to advance, particularly to where the technologies based on mechanical approaches cannot excel.

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