Thermally-Based MEMS Sensors (Part 2)

GAS-FLOW: A Critical Technology Comparison of Various Approaches

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Introduction

We have addressed in Part 1 of this article, which appeared in the March/April issue (Volume 6, Number 2) of this publication, the ability of thermally-based MEMS sensors to measure acceleration. This article, which is the conclusion of this two-part series, will address the very same mechanism of thermal sensing to measure gas-flow.

The need for gas-flow measurement is widespread. In the medical market, gas-flow measurements are critical in anesthesia delivery, chromatography, sleep apnea, spirometers, and ventilators. In the industrial sector, gas-flow measurement is needed for heating, ventilating and cooling (HVAC) systems and fume hoods. Analytical instruments, motor vehicle engines, fuel cells and turbines also rely on accurate and rapid gas-flow measurements. Such capabilities have been commercially available for many years, but until now have been relatively costly, bulky and available from a limited number of suppliers. MEMS-based gas-flow sensors offer a unique combination of capability and cost benefit to a wide variety of applications.

The high level of interest in advancing MEMS-based gas-sensing research has driven the Swedish Governmental Agency VINNOVA to award nearly a $1.5 grant to a consortium of 10 Swedish companies to develop sustainable production systems for high-technology manufacturing of MEMS based gas-sensing systems. Silex Microsystems AB, a MEMS foundry, is a major player in this effort.

As in every design trade-off situation, no one technology is best for all applications. The judicious critical assessment of the expected performance of the various sensors types available as compared to their ability to satisfy the application requirements of performance, size and cost must be addressed. We have attempted here to provide an objective analysis of various gas sensors and their pros/cons using a trade-off matrix (Figure 1) in an effort to assist the design engineer to facilitate their trade-off analysis in the selection of the optimum approach for their specific application.

Thermal Flow Sensors Overview

More recently, a number of companies have entered the market with MEMS-based mass gas-flow thermal sensors that are less costly and feature good performance levels. However, the theory of operation and the manufacturing processes employed to manufacture these sensors differ widely and affect one or more important performance parameters such as size, cost, dynamic range, minimum flow rates, and susceptibility to vibration. MEMS-based sensors provide many customer benefits inherent in their batch-mode manufacturing process as well as in their design. High volume, low-cost, high repeatability, robustness (as a result of no moving parts) and their ability to be manufactured using a monolithic process (no external signal conditioning) are amongst the major benefits.

There are several different thermal flow sensor technologies that are currently available to the system design engineer.

Thermal dispersion flow sensors measure the speed of the gas-flow as heat that is added to the flow stream. Others measure the temperature difference between a heated sensor and the ambient flow stream. Thermal flow sensors require one or more temperature sensors to measure the gas temperature at specific points.

Not all thermal flow sensors are alike. Some thermal flow sensors may achieve accuracy levels of 1%. However, others have accuracies in the 3 to 5% range. A comparison of MEMS thermal gas-flow sensor technologies with other technologies illustrates that it is superior when it comes to the important parameters of accuracy, dynamic measurement range, size, cost, power dissipation and ruggedness.

Thermal mass flow sensors have several major advantages. One is a relatively low price. Second, thermal flow sensors can measure the flow of some low-pressure gases that are not dense enough for Coriolis meters to measure. Both of these advantages give thermal flow sensors their own unique niche in the gas-flow measurement arena.

Another advantage is that they allow the monitoring of one or more of the thermal characteristics (temperature, thermal conductivity, and/or specific heat) of a gaseous media to define the mass flow rate. But they also have limitations, namely most of the gases they can measure accurately must be fairly clean and

<< Figure 1: Trade-off matrix of various gas-flow sensor technologies. No one sensor technology is best for all applications and a thorough trade-off analysis must be performed to provide the optimum results for the specific application. Source: MEMSIC Inc. >>

Item	MEMSIC Flow	Thermal MEMS	Capacitive MEMS(Coriolis)	Hotwire (Thermister)	Piezo(ultrsonic flow meter)	Vortex	Rotometer	Differential Pressure
Power	Excellent	Good	Good	Good	Good	Poor	Excellent	Excellent
Sensitivity	Good	Good	Good	Excellent	Good	Good	Poor	Good
Response Time	Good	Good	Excellent	Poor	Good	Poor	Poor	Excellent
Accuracy	Good	Good	Excellent	Good	Good	Good	Good	Good
% Error	Good	Good	Excellent	Good	Good	Good	Good	Good
Ruggedness	Excellent	Excellent	Excellent	Poor	Excellent	Excellent	Poor	Poor
Reliability	Excellent	Excellent	Excellent	Poor	Good	Good	Excellent	Good
Low flow applicability	Excellent	Good	Excellent	Good	Excellent	Poor	Poor	Excellent
Dynamic Range	Good	Good	Poor	Good	Good	Poor	Poor	Poor
Resistance to Contamination	Good	Poor	Excellent	Poor	Poor	Good	Good	Poor
Ease of Integration	Excellent	Excellent	Excellent	Good	Good	Poor	Poor	Excellent
Size	Excellent	Excellent	Poor	Good	Excellent	Poor	Good	Excellent
Cost	Excellent	Excellent	Poor	Excellent	Poor	Poor	Excellent	Good

non-corrosive. Otherwise, the metering medium must be made out of special alloys and pre-drying of the gas must be done to minimise corrosion.

Thermal Flow Sensors — Theory of Operation

An excellent example of a MEMS-based thermal gas sensor is the MEMSIC MFA 1100R, which operates on the principle of cooling a heated object placed in the gas-flow (Figure 2). The monolithic Silicon chip has a central micro heater and two symmetric temperature sensor thermopiles, one upstream at the gas-flow input and one downstream at the gas-flow output.

With no gas flowing, the two thermopiles have the same rise in temperature for a zero voltage difference. When a gas flows, the velocity of the fully developed laminar airflow unbalances the temperature profile between the two thermopiles, causing a voltage difference between them.

This measured output voltage is processed by an on-chip ASIC. This unique type of thermal flow measurement is characterised by delivering the mass gas and does not require any correction for gas temperature, pressure, viscosity and density changes (Figure 3).

Alternative Gas-Flow Sensing Principles

Let's examine some of the more popular types of gas-flow sensor technologies currently employed. Although our approach is not meant to be exhaustive, we believe that it addresses the most popular devices available on the gas-flow market today. Figure 1 presents a trade-off analysis of some of the key performance parameters of several different popular gas-flow sensors.

DIAPHRAGM/BELLOWS

This popular type of sensor, having been introduced over 100 years ago, is highly popular in residential gas meter applications. The diaphragm/bellows measures the volume of the gas used. However, it is highly affected by temperature, pressure and humidity levels. As such, heating-value compensation is required to measure the actual amount and value of the gas moving through the meter.

CORIOLIS EFFECT

A Coriolis gas-flow sensor consists of one or more pipes with longitudinally or axially displaced section(s) that are excited to vibrate at resonant frequency. When the gas within the displaced section is at rest, both the upstream and downstream portion of the displaced section will vibrate in phase with each other. The frequency of this vibration is determined by the overall density of the pipe (including its contents). This allows the meter to measure the flowing density of the gas in real time. Once the gas begins to flow, however, the Coriolis Effect comes into play. This effect implies a relationship between the phase difference in the vibration of the upstream and downstream sections and the mass flow rate of the fluid contained by the pipe. Coriolis gas sensors have a high initial cost and they become expensive and unwieldy in line sizes above 4 inches although more recently line sizes have increased up to 12 to 14 inches.

THERMISTOR-BASED

Also known as a hot-wire anemometer, it is basically a resistor thermometer or a temperature-sensitive resistor. It features a large negative-resistance/temperature coefficient (NTC) of typically 1 to 5%/°C. A thermistor's resistance changes exponentially with temperature. There are also positive-temperature coefficient (PTC) thermistors.

Thermistors tend to be fragile and are susceptible to breakage and dirt which makes them typically unsuitable for gas-flow temperature measurements. There are however, thermal flow sensors that use this principle, but they employ more rugged types of thermistors that are adapted to a harsh industrial environment, making them more costly than alternative gas-flow measurement methods.

ULTRASONIC

First introduced in 1963. They sense gas-flow by operating on two basic principles: transit time or time-of-flight and Doppler shift. The former type is the most common.

In the time-of-flight configuration, a pair of transmitters/detectors is placed at a distance apart inside the gas-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.

Multipath ultrasonic sensing is often used for natural gas-flow measurement where multiple pairs of ultrasonic transducers are used in the same gas pipeline. Data obtained from these transducers is averaged data to enhance measurement accuracy.

Ultrasonic gas-flow sensing is comparatively costly. It also requires the use of temperature and pressure sensors to compensate for environmental temperature and pressure changes.

VORTEX SHEDDING

This sensor makes use of a physical principle involving the formation of vortex swirls (vortices) downstream of an obstruction, called a 'shedder' or 'bluff' bar, placed in a flow stream.

<< Figure 2: MEMSIC's MFA1100R MEMS-based thermal gas-flow sensor module integrates the sensing element with on-chip signal-processing and software on a monolithic CMOS process. The gas-flow sensor's thermal principle of operation is the same as the one used on MEMSIC's accelerometer. Source: MEMSIC Inc. >>

This principle is similar to a flagpole in the wind, which produces a series a vortices alternating from each side of the obstruction. The alternating frequency of these vortices is proportional to the flow rate being obstructed.

The shedder bar sends ultrasonic signals crossing the path of these vortices. These signals are used to measure the frequency of vortices for changing sides and are sent to software to be converted to fluid velocity and flow rate readings.

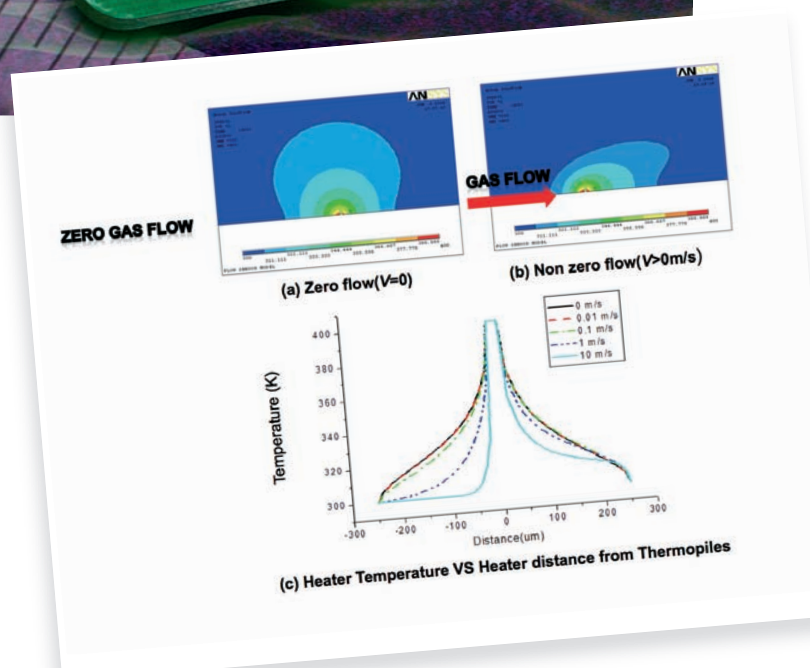
Use of only a small 'shedder bar' or 'bluff bar' in the path of the flow means very low-pressure drop across the flow meter. It also allows high sensitivity of the readings at low flow rates, meaning large turn-down ratios.

Vortex flow sensors are extremely versatile for measuring gases, liquids and steam. They're also reliable since they have no moving parts and feature relatively high accuracy. However, the presence of a bluff body in the stream of the gas or liquid flow may cause some drop in pressure of the medium being measured.

TURBINE

Gas-flow measurements can also be made using the turbine flow sensor, also known as an axial turbine sensor. It translates the mechanical action of the turbine rotating in the gas-flow around an axis into a user-readable rate of flow. The turbine tends to have all the flow travelling around it.

The turbine wheel is set in the path of the gas whose flow impinges on the turbine blades, imparting a force to the blades'



<< Figure 3: Principle of operation of a thermally-based gas-flow sensor. The elimination of moving parts greatly improves the reliability of these devices. Source: MEMSIC Inc. >>

surfaces and setting the rotor in motion. When a steady rotation is reached, the speed is proportional to the gas velocity.

This type of sensor can also be used for measuring liquid flow. The one difference for this type of measurement is the use of journal bearings, whereas gas-flow measurement makes of use of ball bearings.

The advantage of this type of measurement is higher flow rates and less pressure loss than other approaches. In fact, they are the meter type of choice for natural gas, water distribution and fire-hydrant systems. Their disadvantage is that they are less accurate at low flow rates.

ROTAMETER

Another common gas-flow (and liquid-flow) measurement is via a rotameter. This device measures the flow rate of liquid or gas in a closed tube. It belongs to a class of sensors called variable area, which measure flow rate by allowing the cross-sectional area the fluid travels through to vary, causing some measurable effect. A rotameter consists of a tapered tube, typically made of glass with a 'float', actually a shaped weight, inside that is pushed up by the drag force of the flow and pulled down by gravity. Drag force for a given fluid and float cross section is a function of flow speed squared only.

A higher volumetric flow rate through a given area increases flow speed and drag force, so the float will be pushed upwards.

However, as the inside of the rotameter is cone shaped (widens), the area around the float through which the medium flows increases, the flow speed and drag force decrease until there is mechanical equilibrium with the float's weight.

A rotameter requires no external power or fuel. It uses only the inherent properties of the fluid, along with gravity, to measure flow rate. A rotameter is also a relatively simple device that can be mass manufactured out of cheap materials, allowing for its widespread use. Since the area of the flow passage increases as the float moves up the tube, the scale is approximately linear. But there are also disadvantages. For one, because it uses gravity, a rotameter must always be vertically oriented and right way up, with the fluid flowing upward. And the reliance on the ability of the fluid or gas to displace the float results in graduations on a given rotameter that are only accurate for a given substance at a given temperature.

Due to the direct flow indication, the resolution is relatively poor compared to other measurement principles. Readout uncertainty gets worse near the bottom of the scale. Oscillations of the float and parallax may further increase the uncertainty of the measurement. Rotameters normally require the use of glass (or other transparent material), otherwise the user cannot see the float. This limits their use in many industries to benign fluids, such as water.

VENTURI

A Venturi sensor constricts the flow in some fashion, and pressure sensors measure the differential pressure before and within the constriction. This method is widely used to measure flow rate in the transmission of gas through pipelines, and has been used since the era of the Roman Empire.

An orifice plate has a hole through it, placed in the flow with hole constricting the flow of gas or liquid. Measuring the pressure differential across the constriction gives the flow rate. It is basically a crude form of a Venturi sensor, but with higher energy losses. There are three types of orifices: concentric, eccentric and segmental.

PITOT

A Pitot tube is a pressure measuring instrument used to measure fluid flow velocity by determining the stagnation pressure. Bernoulli's equation is used to calculate the dynamic pressure and hence fluid velocity. Pitot tubes are frequently used in aerospace applications.

Multi-hole pressure probes (also called impact probes) extend the theory of the Pitot tube to more than one dimension. A typical impact probe consists of three or more holes (depending on the type of probe) on the measuring tip arranged in a specific pattern. More holes allow the instrument to measure the direction of the flow velocity in addition to its magnitude (after appropriate calibration).

Popular Applications

RESIDENTIAL /COMMERCIAL GAS METERS

A growing application is in accurately measuring natural gas in the residential market. This is known in the oil and gas industry as custody transfer. Such a transfer involves the transactions in transporting physical substances from one operator to another. This includes the transferring of raw and refined petroleum from between tanks, tankers and gas pipeline stations all the way to delivering gas at the end user's gas meter that sits in front of many of our homes. MEMS-based gas-flow sensors measure the mass flow of natural gas consumed by appliances. Mass flow measurement is fundamentally more accurate than volumetric flow measurement because mass is not affected by changes in pressure and temperature which are common scenarios in the distribution of natural gas to homes and businesses. Therefore, MEMS gas-flow sensor can claim itself a future-proof measurement solution and can easily be integrated into 'smart' systems because of its small size and monolithic technology, which permits signal conditioning electronics and possibly communication functions on the same chip. MEMS–based gas sensors achieve very high turndown ratio, typically above 300:1. Usually, a flow meter with high turndown ratio provides accurate and repeatable measurement over a wide range, both at low and high flow rates. This makes both meter deployment and maintenance easier.

MEDICAL

During surgery, MEMS-based gas-flow sensors can be employed to measure the amount of oxygen, nitrogen or dinitrogen monoxide consumed from a respiratory apparatus so as to constantly provide precise information about the patient.

HVAC

MEMS-based gas flow sensors can be employed to measure the flow rate of circulated air in the complex ventilation system inside buildings, detecting how well air is being recycled and adjust the circulation of air to not only conserve energy but also to optimally distribute conditioned air to required areas.

COMBUSTION CONTROL

MEMS–based gas-flow sensors can be employed to precisely measure the amount of flammable gas and air in order to reach an optimum combination ratio so as to achieve complete combustion and as such reduce pollution and reduce cost of operation.

Conclusions

We have presented a critical assessment of some of the most popular types of sensors currently available on the market for the measurement of gas-flow. As stated earlier, no one sensor type is best suited for all applications. The system design engineer must address all of the specifics and nuances of their application from a technical performance, size and cost perspective to judiciously choose the optimal approach. MEMS-based gas-flow sensors are becoming increasingly more popular as their many inherent benefits are being discovered by the marketplace. CAVEAT EMPTOR (Latin: Let the buyer beware).

For More Information

Roger Grace will present a paper titled "MEMS-Based Systems Solutions for the Built Environment" at the Trillion Sensors Summit (www.tsensorssummit.org), which will take place at Stanford University from October 23-25, 2013. He will address several large volume applications of MEMS, from 'smart roads' to 'smart buildings', including gas meters.

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