By Maarten Vraanes, Consultant, Steven Lee, Technical Director, Integrated Device Technology, Inc.

Abstract: This paper reviews the emergence of MEMS-type thermal mass flow sensors as replacements for various traditional types of flow sensors. The increasing demand for monitoring and controlling flow in expanding applications drives the need for lower cost, smaller form factor, and higher integrated solutions. One type of MEMS thermal mass flow technology, based on the calorimetric principle, has gained acceptance and offers the advantages of higher sensitivity, miniaturization, and scalability with lower cost. Furthermore, the use of porous silicon technology with a silicon carbide coating makes the MEMS thermal mass flow sensor highly robust and expands its uses to different gases and liquids.

Keywords: MEMS, thermal mass flow sensor, gas flow, liquid flow, porous silicon, thermocouple, thermopile, silicon carbide, thermoelectric sensing

Introduction

The global flow sensor market reached $5.62B in 2014 and is expected to increase at a compound annual growth rate (CAGR) of 7.1% through 2020[1]. The flow sensor market is highly fragmented with gas and liquid measurement applications in many industries, including oil and gas, food and beverages, chemical processing, pharmaceutics, automotive, and consumer. The proliferation of flow sensors is enabled by the many available measurement techniques using magnetic, mass, ultrasonic, vortex, thermal, and Coriolis forces. Among the main drivers for the growth of flow sensing applications is an increased demand for monitoring and controlling flow, often as a result of environmental regulations. For example, there is an increased focus on reducing greenhouse gases from power plants in the U.S. and European Union with a target of reducing carbon dioxide and others by 20% from 1990 to 2020. Another example is the emergence of disposable flow sensors for fast, accurate, and precise measurements of clinical infusion therapies, which is essentially medication administered to patients through a needle or catheter.

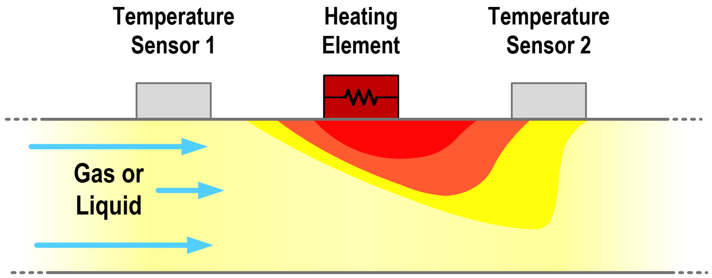
Flow meters represent the instrumentation of flow sensors and are used to measure the amount of flow that passes through them. There are in principal five different flow meter types: velocity flow, positive displacement flow, differential pressure flow, open channel flow, and mass flow. Mass flow meters are one of the dominant types in the market due to their faster response and better accuracy than other flow meters. They can also be effectively miniaturized and manufactured on silicon wafers. The emergence of MEMS has already revolutionized the consumer electronics market for motion, pressure, and other sensors, and similar micro-machining processes are now being adapted to fabricate flow sensors. Flow sensing applications are typically high-mix and low-to-medium volume compared, for example, to motion sensors that have become ubiquitous in hundreds of millions of smartphones. This paper will focus on the emergence of thermally-based MEMS mass flow sensors and how they match up with existing and more traditional flow sensor technologies.

Thermal Mass Flow Sensor Overview

Thermal mass flow sensors are volumetric in nature and measure the mass of a substance (i.e., gas or liquid) that passes per unit of time. A common measurement unit for mass flow of a medium is liters per minute or LPM. Thermally-based mass flow sensors are designed to measure the difference between a static state (i.e., no flow) and the heat transfer to a gas or liquid that occurs during flow. They typically combine a heater element with one or more temperature sensors. Figure 1 illustrates a simple thermal mass flow sensor. The “warm” colors represent the heat transfer that occurs when gas flows from left to right. Closer to the heater is hotter (darker red color) and farther away is cooler (yellow color).

[1] “Flow Sensors Market Set to Reach 8.49 USD Billion by 2020,” IndustryARC, 2016.

Figure 1. Thermal Mass Flow Sensor Principles



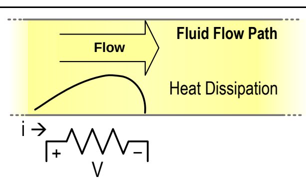
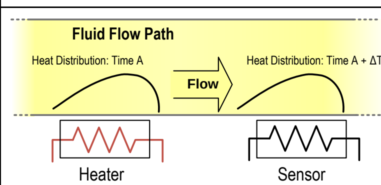
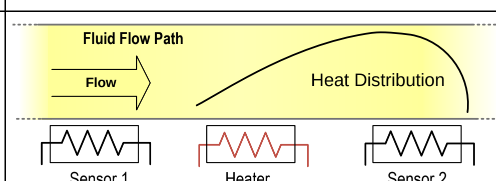
Source: IDT

Historically, thermal mass flow sensors have been large and clunky mechanical devices, including moving-vane meters and hot-wire sensors. MEMS technology offers an alternative to traditional flow sensors with the benefits associated with miniaturization. This includes low unit cost, scalable processing, small device footprint, improved sensitivity, and on-chip integration. These tiny flow sensors can measure up to hundreds of liters per minute and down to the ranges of microliters and nanoliters per minute. Thermal mass flow sensors, also known as thermal dispersion/displacement flow sensors, can be used for both liquid and gas applications. Many MEMS-based flow sensors are restricted to clean non-corrosive gases (e.g., air, nitrogen, helium, argon, oxygen, etc.) to prevent them from degradation and avoid irreversible damage. There are some exceptions with sensors employing protective layers, such as silicon carbide, to protect them from harsh environments. These sensors can be used for corrosive media, such as gasoline and diesel. Thermal mass flow sensors are used in a growing number of applications that are challenging to measure with other technologies. This is mainly due to the fact that they have excellent measurement sensitivity, a fast response rate, and the capability to measure multiple characteristics (flow and temperature) to accurately determine the mass flow rate.

Thermal Mass Flow Sensor Types

The measurement principle of thermal mass flow sensors relies on the heat transfer between the sensor's heater and the flowing medium. This thermal change is measured by temperature sensors, and the output sensor signal is proportional to the flow change. There are three forms of thermal flow sensors, including hot-wire and hot-film, time-of-flight (TOF), and calorimetric (see Table 1). Hot-wire and hot-film sensors measure the heat transfer from a heated element to a gas or liquid. As the term implies, hot-wire uses a resistive wire whereas hot-film uses a thin-film resistive element to measure flow. When gas or liquid passes over the sensor, it changes the resistance in the sensing element, which is measured to determine the flow. TOF sensors measure the transit time of a thermal pulse (created by the heater) to a downstream sensing element. This transit time will depend on the thermal conductivity and diffusivity of the gas or liquid, distance between heater and sensor, and the average flow velocity. Calorimetric sensors use a heater and at least one temperature sensor downstream to detect the thermal profile caused by the gas or liquid flowing by. The asymmetry in the thermal profile allows these sensors to determine velocity, and two sensing elements (upstream and downstream) can be used to determine flow direction. It is important to note that the type of gas or liquid must be known to accurately measure the flow rate since each medium has its own unique thermal conductivity properties.

Table 1. Mass Flow Sensor Types – Measurement Principle and Model

Parameter	Hot-Wire / Hot-Film	Time-of-Flight (TOF)	Calorimetric
Measurement Principle	Resistance	Time	Voltage
Design Model			

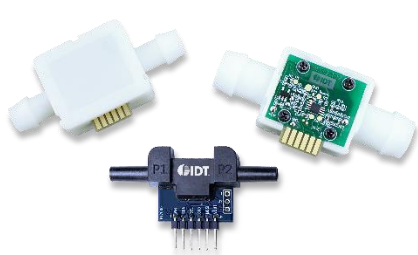
There are several methods for measuring the heat transfer in thermal mass flow sensors, including thermoresistivity and thermoelectrics. Thermoresistive sensors or thermo-anemometers are based on resistance changing as a function of temperature, typically associated with hot-wire sensors. These devices are currently the most popular mass flow sensors due to their simple construction. Thermoelectric flow sensors use thermopiles to measure temperature transfer as a medium flows by. Thermopiles are essentially a set of individual thermocouples that are connected together in series, to increase the sensor output voltage by summing the voltage from each thermocouple. There are, however, design tradeoffs. Thermal conduction between hot and cold junctions as well as Johnson noise increase with the number of thermocouples, which negatively impacts the sensor performance. That is why high thermal isolation is desired and used to maximize the difference between the hot and cold junctions. Thermocouples and, by extension, thermopiles use the Seebeck effect to generate an analog sensing signal. The Seebeck effect explains the phenomenon that a temperature difference between two dissimilar electrical conductors or semiconductors produces a voltage (without the flow of an electrical current). It enables higher sensitivity and unbiased output voltage with no offset or drift. This signal is very weak (i.e., low driving strength) and is typically connected directly to a high input-impedance amplifier, such as an operational amplifier.

Thermal Mass Flow Sensor Features

Microfabrication of flow sensors has greatly matured since the first MEMS flow sensors were developed in 1974. The fabrication of MEMS flow sensors has traditionally been complex with less conventional processes and materials, but CMOS (complementary metal-oxide semiconductor) compatible processing is increasingly being used. This means reduced processing costs, and it also provides a platform for scaling production. These are major reasons why MEMS flow sensors are gaining popularity in a range of applications, from monitoring airflow in combustion engines to complementing technologies, such as microfluidic channels, valves, pumps, and heaters for complete lab-on-a-chip (LOC) devices, also known as micro total analysis systems (µTAS). There are both thermal and non-thermal MEMS flow sensors, but this paper focuses exclusively on the thermal type. The construction of a MEMS flow sensor can be very simple, and micromachining allows creating and integrating elements, such as micro-heaters and thermal sensors on the same chip, without moving parts. Managing thermal pathways in the chip is important, and the “leakage” of heat through the substrate or electrical leads should be minimized in the device design to avoid thermal losses and degrading sensor performance. This greatly simplifies the design and makes these sensors mechanically robust and highly reliable.

Traditionally, MEMS mass flow sensors have been designed with a fragile membrane suspended over a vacuum-sealed cavity to provide thermal isolation. An alternative is to use porous silicon, which eliminates the need for a cavity (and diaphragm) while ensuring that there is a good thermal isolation between the heater and the sensing element (see example in Figure 2). Porous silicon (PS or pSi) is silicon with nanopores to increase the surface-to-volume ratio and has been proven effective as a thermal barrier. This solid construction allows the sensor die to be covered with various ceramic films (e.g., silicon carbide) to provide long-term stability and protect it from abrasive wear, as well as corrosive gases and liquids. Another common feature of MEMS flow sensors is the use of resistive elements to measure heat transfer and, by extension, mass flow. Resistors are simple to fabricate on silicon wafers, but are inherently noisy. A Wheatstone bridge or similar sensor interface can be used to minimize the impact of the sensor noise. An alternative is the use of thermopiles (i.e., thermocouples) with a very high signal-to-noise ratio. The output signal can be tuned by optimizing the number of thermocouples per thermopile, and the Seebeck coefficient can be optimized by tuning the dopant type and concentration. Thermopiles can be fabricated from polysilicon or metals (e.g., aluminum), and they are both commonly used in thermoelectric flow sensing.

Figure 2. IDT’s FS2012 Sensor Module with Solid Flow Sensor Construction



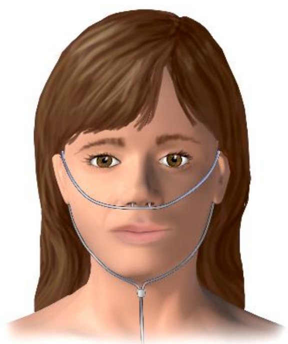
Source: IDT

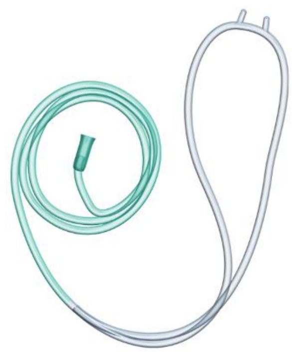
Case Studies

Case Study: Oxygen Cannula

The nasal cannula was invented by Wilfred Jones in 1949 and patented by the company he worked for, BOC (now Linde Group). Nasal cannulas are flexible tubes used to deliver supplemental oxygen to patients who need respiratory help. On one end, it connects to an oxygen supply (e.g., portable oxygen generator or wall connection at a hospital) and, on the other, it has a loop with two extended prongs with openings that fit into the patient's nostrils. The tubing is looped around the patient's ears or has an elastic head band to hold the cannula in place. Figure 3 shows a patient wearing a typical oxygen cannula and the cannula. For adults, a cannula delivers 1 to 5 liters of flow per minute with 28% to 44% oxygen content. Higher rates can dry out the patient's nose and cause bleeding over time. However, higher flow rates can be supported through a humidified nasal cannula. An inline flow meter can be used to monitor the flow through the cannula and can be used as a control feedback loop for the oxygen supply.

Figure 3. Patient Wearing Nasal Cannula and Nasal Cannula





Source: Bruce Blaus, *Blausen Medical Communications Inc.*

MEMS mass flow meters are well suited for oxygen cannulas. They can be made at low cost and potentially disposable in large enough volumes. The light weight, minimal power consumption, and fast, accurate response allow these sensors to be embedded into cannulas for a seamless integration. The ability to accurately control the airflow is important since, for example, children and adults have different breathing requirements. An inline flow sensor would be able to simultaneous capture the airflow and nasal pressure. The nasal pressure can be used to indicate snoring and to monitor sleep. Traditionally, temperature sensors (e.g., thermistors and thermocouples) have been used to detect sleep disordered breathing (SDB) during sleep studies (i.e., polysomnography). This method is a surrogate alternative to measuring the actual patient airflow. The sensors are slow due to their relatively large thermal mass, which makes it challenging to make nuanced measurements to detect more subtle disorders. Use of MEMS mass flow sensors is one method to help better detect and diagnose sleeping disorders by monitoring the nasal prong pressure (NPP).

Case Study: Soda Machine

Flow meters are used to measure the volume of water that is being used in commercial coffee and soda machines (see Figure 4). This volumetric measurement is used to ensure that the beverage is served with the same amount of water per serving. The main idea here is that the consumer can expect the same level of consistency and quality every time. The system can also be configured for accurate dosage of different beverage sizes, such as small, medium, and large cup sizes. Old-fashioned turbine-type flow sensors are commonly used in liquid dispensing machines. A MEMS-based mass flow sensor with integrated microcontroller offers a valid alternative. These smart sensor modules can be made relatively affordable and in a small form factor to fit inside a dispensing machine. MEMS sensors are very sensitive and can measure flow more accurately than other sensor types. They are very versatile and can be calibrated to many different flow ranges, with the main limitation being the diameter of the tube where the flow sensor is mounted. For example, a smaller diameter tube will restrict the flow whereas a larger diameter tube will allow higher flow rates.

Figure 4. Commercial Coffee Maker (left) and Soda Dispensing Machine (right)

Source: Pixabay (left) and IDT (right)

Summary

New applications and technological advancements are important drivers for a growing flow sensor market. Traditional flow sensors are being increasingly replaced by lower cost and more integrated solutions, such as MEMS mass flow sensors. These devices are fabricated on silicon wafers and can be rapidly scaled up to production volumes. They represent a paradigm shift in sensitivity, versatility, reliability, and miniaturization. In addition, MEMS sensors can be easily integrated with a microcontroller to make small, compact digital flow meters. MEMS fabrication has come a long way since the first flow sensors were developed in 1974. The ability to make solid state structures with protective layers (e.g., silicon carbide) is enabling these tiny sensors to be used for corrosive gases and liquids. In sufficient volumes, it might even be possible to make disposable sensor modules.

Corporate Headquarters

TOYOSU FORESIA, 3-2-24 Toyosu,
Koto-ku, Tokyo 135-0061, Japan
www.renesas.com

Contact Information

For further information on a product, technology, the most up-to-date version of a document, or your nearest sales office, please visit www.renesas.com/contact-us/.