MEMS THERMAL MASS FLOW METERS FOR HUMIDIFIED GASES

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Abstract

Measurement of gas with high humidity or gas converted from liquid phase is frequently encountered. Accurate metering is always a challenging process as the remaining liquid vapors may significantly affect the performance of the measuring unit. In this paper, we presented a novel design of a mass flow meter which is utilizing a single MEMS calorimetric mass flow sensor chip integrated with a substrate micro-heating circuitry. The results indicated that the design can effectively work for the gas flow measurement under the presence of high humidity or liquid vapors with no requirement of additional external heating assistance to avoid condensation that alternates the measurement results. The present meter calibration, tests and applications will be also discussed.

Introduction

MEMS mass flow meters have been employed for gas measurement since 1990s. The metrology unit of a MEMS mass flow meter is the micromachined mass flow sensors or the silicon flow sensors that are generally made on silicon wafers. The MEMS mass flow meters have been widely applied in the past decades in medical, automotive, and many other industries where clean and dry gas flow measurements are demanded for high accuracy, low cost and enhanced performances with small form factor and low power advantages. Examples are medical anesthesia gas control, personal ventilators, air intake of automotive electronic control units, and gas chromatography mass spectrometry. One of the earlier silicon flow sensors is disclosed by Higashi et al.[1] of Honeywell for a small footprint silicon flow sensor that has its binding wires to the control electronic interface exposed to the flow medium which limited its applications to only for clean, non-conductive and dry gases. Ueda et al.[2] and Fujiwara et al.[3] of Omron designed a complicated by-pass segregation channel to avoid the damages from impact of particles in the flow fluid as well as clogging of the flow channels. These mechanical package designs however could not change the application limitations of the silicon flow sensor as the conductive or high humidified fluids could easily destroy the sensor chip by shorting the bonding wires. Additional clogging by liquid condensation would also take place in cases that the fluid has the liquid vapor or is highly humidified. Mayer et al.[4] teach an integrated MEMS mass flow sensor chip using thermopile as sensing elements and CMOS integrated signal processing circuitry that could seal the bonding wires from direct contact to the flow fluids but will limit the flow channel size to within 2 mm in diameters by the geometry of the sensing chip. In another disclosures by Hecht et al.[5], and Wang et al.[6], the silicon mass flow sensors were designed without on-chip electronics and the sensor size is elongated such that the wire connections to the electronics interface could be completed sealed at one end of the flow sensor chip. And the sensor could be packaged into a formality of a probe that could be inserted into a flow channel of arbitrary sizes and to be calibrated together for the performance. However, because of the nature of the direct contact of the silicon flow sensor chip with the flow fluids during the operation, the fluid with vapors or highly humidified gas flow medium will still significantly affect the flow readout since the flow medium characters would be significantly deviated from those at the calibration. Application examples for these type of flow media are commonly seen in human respiratory, vaporized carbon dioxide for beverage and food, to name a few. Bonne and Satren[7] and Mayer et al.[8] revealed a similar structure that places the silicon flow sensor chip outside the flow channel to avoid the direct contact of the silicon flow sensor chip with the flow fluids. This structure can also be used in liquid fluid flow measurement therefore it is an effective approach for maintaining the sensor performance in a fluid with vapors or highly humidified flow medium. Nonetheless, the design limits the flow channel dimensions to be within a few mini-meters because of the small foot print of silicon flow sensors, which in return restricts the applications only for very small flow measurement applications. In addition, because of the small power of the silicon flow sensors, the package or flow channel material directly in contact with the sensor must have superior thermal conductive properties that also limits the package options and results in a high cost for the products. Alternative operation of the silicon sensor at an elevated current or high power of the micro-heater to avoid the sensor deviation in performance for flow fluids with vapors or high humidity as proposed for the thin film or hot wires flow sensors [9] is often difficult since the high current or high power could expose the silicon flow sensors to volatility during performance. Further, the continued operation of the silicon flow sensor in a fluid with vapors or high humidity would eventually leads to silicon flow sensor surface condensation as the desired low micro-heater power would not be sufficient to expel the vapor accumulation that would result in sensor malfunction or significant deviations in flow readout.

Therefore it is desired to have a completed new design of a silicon flow meter that shall perform in a fluid with vapors or high humidity. This meter shall be able to continue working in such environments and maintaining good accuracy and reliability. The desired silicon flow meter shall also keep its small foot prints while could be operated at a low power configuration. Further there should not be any limitations for the desired silicon flow sensors that shall be able to be packaged for arbitrary flow channel sizes and performed in any fluid properties for ~~the~~ variety of the applications.

Meter design

MEMS flow sensor with a heat circuitry

For a MEMS mass flow meter, the key component is the metrology measurement unit, or the MEMS mass flow sensor. For the proposed meter, the critical part is to design a MEMS mass flow sensor that shall be able to perform under high humidity or even with vapors. As it is discussed in the previous paper, [10] the metrology unit of the meter shall be assembled into a probe that shall be placed at the center of the meter flow channel.

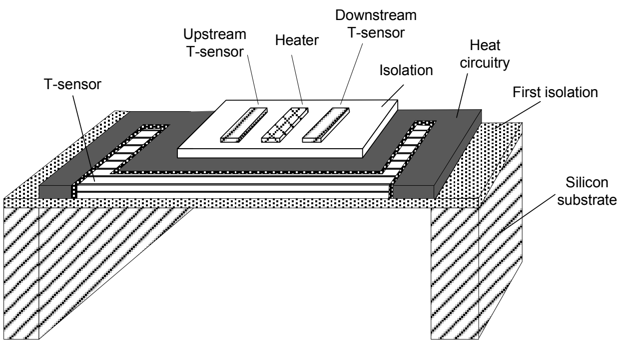

Figure 1.Schematics of the flow sensor with heat circuitry

Figure 1 shows the proposed structure of the MEMS mass flow sensor integrated with a heat circuitry. The first isolation layer was also the supporting membrane and was made with a low stress silicon nitride film using low pressure chemical vapor deposition (LPCVD) on a silicon substrate with a thickness of 1.5 micro meters. The critical element that designed for the prevention of the liquid vapor condensation on the flow sensor chip is the addition of an embedded heat circuitry in the sensor membrane structure beneath the flow sensing elements. The heat circuitry is made together with a temperature sensor on the silicon nitride supporting membrane by electronic beam evaporation of tungsten where the measured temperature shall provide feedback to the heat circuitry control electronics such that the heat circuitry can heat the silicon sensing chip at a constant and controllable temperature. The shape of the heater is designed to be wires in parallel with a wire width of 6 micrometers. The alternative shape of the heater can be spirals with the non-uniform width in order to ensure a homogeneous heat distribution. The micro heater can have the capability to elevate the structure on the membrane to a temperature above the common liquid vaporization temperature from 100 to up to 220°C. The size of the heat circuitry is designed to be the same as the membrane above the cavity.

Another layer of silicon nitride film with a thickness of 500 nm prepared by plasma enhanced chemical vapor deposition (PECVD) followed by the electronic beam deposition of the sensing elements as well as the micro-heater that formulate the calorimetric flow sensing structure. Both the micro-heater and the sensing elements are made of platinum. Us of the PECVD process instead of LPCVD process is due to the LPCVD process restriction of a high temperature that would cost damages to the pre-deposited heat circuitry structure. The completed sensing chip has a cavity as shown in Fig. 1 that is made via deep reactive ion etching. This cavity provides the thermal isolation that facilitates the sensitivity of the mass flow sensor as well as helping to maintain a constant temperature when the membrane sensing structure is heated with the heat circuitry. It also helps to operate the sensor with lower power consumption as the thermal isolation structure also limits the heat transfer via the substrate. On top of the sensing elements, another layer (not shown in the figure) of silicon nitride with a thickness of 300nm is made for surface passivation to prevent the sensing and micro-heating circuitry from damage. This surface passivation layer is also made by the PECVD process with a low stress receipt. In order to prevent the pin holes formation and to ensure the edge coverage, the plasma frequencies can be altered such that the film density would be higher.

The completed sensor chip has a foot print of 1.8×3.6mm with a standard silicon wafer thickness about 0.5 mm. The sensing zone is about 0.8×0.8 mm while the heat circuitry covered about 1.0×1.0mm.

MEMS flow meter control scheme

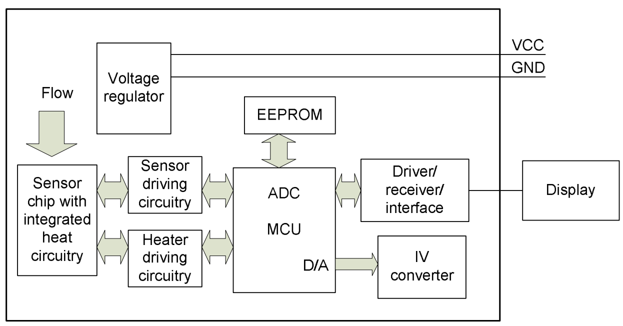

Figure 2.Schematics for the design of the proposed meter electronics

The functional block diagram of the proposed meter using the MEMS mass flow sensor chip as revealed in the previous section is shown in Figure 2.

The sensor driving circuitry powers the sensor while receiving the measurement information from the sensor and communicating with the ADC (analog to digital converter) and MCU (micro-controller unit) where the calibration data and other meter functional programming codes are processed. While the heater driving circuitry provides the constant temperature control such that the senor chip can be elevated to a desired temperature, and therefore the liquid vapor shall not attack the sensor from continuous operation. The MCU will also manage the drivers for display as well as data communications with external user interface. The D/A (digital to analog) converter provides the voltage output interface while the other standard output interface can be included for industrial standards such as Modbus protocol.

For an intelligent control scheme or when the extremely low power operation is required, the sensor can also provide warning notification of vapor attack to the sensor as the thermal conductivity of the liquid vapor is significantly different from that for the gas. Therefore the heater circuitry can be turned on interlocked when the sensor senses only the vapor phase in the fluid and it can be used to trigger the heat circuitry when the MCU shall also process to the corresponding calibration such that the accuracy can be maintained. The detailed discussions can be found in the following sections.

The power can be supplied externally or internally by a lithium ion battery. The total average power without the heat circuitry could be 0.8 micro amperes while the heat circuitry consumes about 20mA when the membrane structure temperature is maintained at 100°C.

MEMS flow meter mechanical design

The mechanical design for the meters contains a venturi flow channel where the sensor assembly is placed at the sidewall of the throat of the venturi structure when the flow pipe diameter is below one inch. And as for a larger pipe diameter the sensors shall be placed at a probe tip and inserted at the central position of the throat venturi channel. A pair of flow conditioning plates, which contains a flow straightener and a flow profiler, is placed at the entrance of the flow passage.

Meter performance

Meter uncertainties

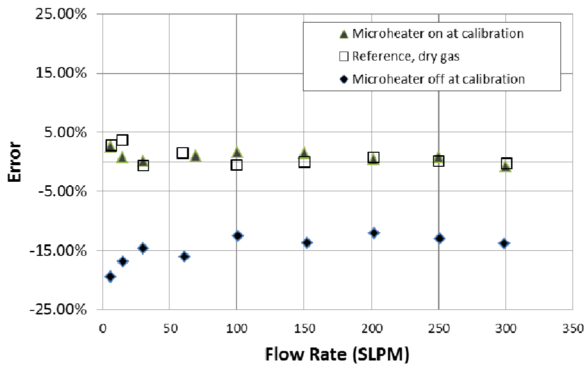

Figure 3. MEMS meter uncertainty measurement with and without the integrated heat circuitry.

The meters were all 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%. The verified uncertainties for the meters were obtained by another independent sonic nozzle system that has the same uncertainty of the one used for the meter calibration. At the time for calibration, the ambient conditions are 25°C and 101.325kPa.

For the meter discussed below, the flow channel has a venturi structure with the flow channel diameter of 22mm. The channel length is 120mm with a flow straightener and flow profiler installed at the entrance of the flow. The sensor chip was installed at the wall of the throat of the venturi structure.

Figure 3 shows the data that compares the uncertainties for the meter operated with the heat circuitry on in two calibration conditions: the heat circuitry is on or off while the meter is calibrated. In both cases, when the heat circuitry was power on and the temperature was set to be at 100±2°C. Additional study indicated that such a temperature set-point is optimal for the meter performance in the flow with water vapors since a higher temperature above 120°C could induce noise in signal output which will result instability for the meter readings. On the other hand, a temperature set-point lower than 80°C may not be sufficient for preventing the sensing unit from water vapor attack or may not be effective enough to vaporize the water droplets inside the flow media for the sensing unit. The data obtained from the meter operated with the heat circuitry off at both the process of calibration and operation, are also shown in the figure as the reference in the same figure for comparison.

It can be observed from the data in Figure 3 that the heat circuitry has significant impact to the meter performance. While the meter can perform well under the same conditions for both calibration and operation processes, the heat circuitry alone indeed heated the air that flows across the sensor chip surfaces as the observable negative shift of the uncertainties confirms this scenario. Since the sensor chip heat circuitry only has an area about 1 mm^2, it shall not have any impact to the air in the flow channel as an entity but limited to its actions in the heat circuitry surface area. Therefore we could reasonably assume that the pressure of the air flow inside the flow channel shall not be altered due to the heat circuitry operation. Hence the heat circuitry shall only change the air temperature across the surface of the heat circuitry. Using the *PV/T*=constant hypothesis for the flow at the surface of the heat circuitry that elevated the surface at a constant temperature of 100°C, the predicated negative deviations for the uncertainties due to the presence of the heat circuitry shall be about -20%. The actual observed negative deviations for the uncertainties were about -15%. It is interesting to notice that the measurement data indicated that while towards to lower flow range, the uncertainties were shifted larger and were close to the predicated value of -20%. The differences could be due to the less loss during heat transfer or the flow cooling effects as the low flow shall have less cooling effects. However, the data indeed indicate that the heat circuitry is effective to heat the air (gas) across its surface.

Meter performance with vapors

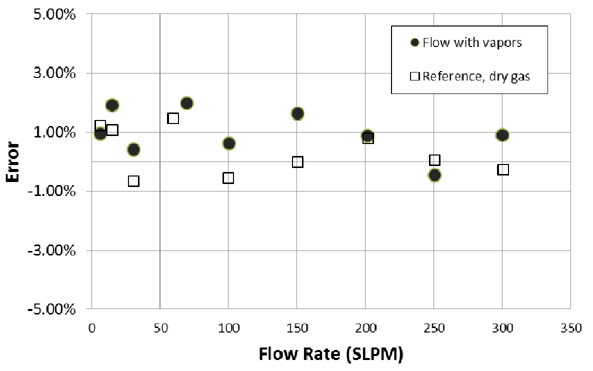

Figure 4.The measured uncertainties for air flow with vapor with the heat circuitry.

Figure 4 shows the data measured from the meter with the heat circuitry on while the air flow was added with water vapors using a humidifier. The results show that the flow measurement was stable with the addition of the water vapors into the air stream. On the contrary, without the heat circuitry the measurement was found merely possible as the water vapor shall attack the sensor and cause the data reading very difficult to establish. Hence it was not possible to collect a stable data into the same chart for comparison.

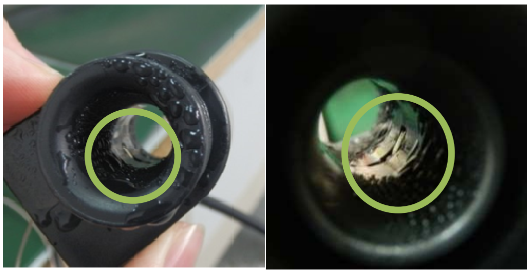

Figure 5. Photographs of the flow channel after air flow with water vapors. The circles indicated that there was no water condensation on the heated sensor surface.

Figure 6.Photographs of the flow channel showing the sensor surface was placed a droplet of the water and the water was vaporized within 15 seconds confirming the effectiveness of the heat circuitry.

Figure 5 shows the photographs of the flow channel that had been passed with air flow with water vapors. It can be seen that water did condense on the flow channel walls while no condensation found in the area of the sensor surface with heat circuitry. The photographs further confirms that the heat circuitry is effective to prevent the water condensation on the metrology sensing surface that ensured the continuous and normal operation of the flow meter under the presence of the flow with water vapors.

Further experiment to test the effectiveness of the heat circuitry was done by placing a water droplet on the surface of the sensing elements when the meter was with power off. And 15 seconds after the meter powered on the water droplet on the surface of sensing element was completed vaporized as shown in Figure 6. The sensor was again applied to the flow measurement with dry or vaporized air flow and it was found that the water droplet on the surface of the sensing unit shall not damage the sensing unit.

Concluding Remarks

The present study indicates that the MEMS mass flow sensor integrated with a heat circuitry is effective for preventing the water condensation on the sensing unit and can be used for measurement of such flow media. Additional work will be pursued to quantify the water vapor concentration and establish the correlations between the working powers for the heat circuitry and the concentration of the water vapors.

Although we only discussed the measurement for the air flow with water vapors, the same procedure can be applied to other gas flow with vapors such as gases with oils. Since the total power of the heat circuitry is small and the current is limited, there shall be no hazardous risks even for combustible gases with vapors.

The discussed sensor assembly can be mounted on the wall of the flow channel if the channel size is smaller than an inch or be placed at the center of the flow channel in the formality of an insertion probe. Therefore this metrology could be applied for various gas flow measurement applications where vapor is present.

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