1. Sensors

TRULY CALORIMETRIC FLOW SENSOR CHIP BASED ON SURFACE CHANNEL TECHNOLOGY

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ABSTRACT

In this paper we present a truly calorimetric flow sensor. The technology to fabricate the sensor is based on surface channel technology. The nominal measurable air flow is 0.8 ml/min. The material of the sensor element is silicon nitride which is resistant to most commonly applied chemicals.

The measurement tube is freely suspended and has a wall thickness of only 1 micron. This gives the tube an extremely low thermal mass which facilitates true calorimetric flow sensing. Calorimetric flow sensing allows for conversion between different gases based on their density and heat capacity product (ρ·Cp). This was checked experimentally for several common gases. Conversion between gases was found to be within 2%.

KEYWORDS

Thermal flow sensor, MEMS, Microfluidics

INTRODUCTION

Calorimetric flow sensors have the interesting property of ρ·Cp conversion between gases. This facilitates calibration on a single gas (e.g. nitrogen) and conversion to other gases simply by ρ·Cp for volumetric flow and Cp for mass flow. For decades these sensors have been manufactured mainly in steel. Since steel sensors typically have a relatively large thermal mass, these sensors have a response time typically higher than 1 s.

FLOW SENSOR DESCRIPTION

Novelty

Here we present a truly calorimetric MEMS gas flow sensor as opposed to semi calorimetric sensors introduced in literature before [1]. It has a nominal air flow of 0.8 ml/min. It has a fast response time in the order of milliseconds and is chemically inert to most common gases.
gold with 15 nm chromium for adhesion. They are sputtered on top of the nitride channels and are therefore galvanically separated from the medium.

Voltage difference is a function of flow. It is measured in the midsection ($U_A$ in figure 3) using a high impedance differential amplifier. The temperature dependent resistors have a DC value of approximately 100 Ω at $T = 25^\circ$C. The analog signals are digitized using a 24 bits analog to digital converter (ADC). This is then converted to an RS-232 signal in a microcontroller for communication with a computer.

![Figure 2: SEM picture of the chip with schematic representation of the gold resistors and the flow direction.](image)

![Figure 3: Heater / temperature sensor resistors in a Wheatstone bridge. The resistor numbers correspond to the definition in figure 2. A voltage is placed between $U_B$, the resulting voltage difference is measured at $U_A$.](image)

**Electrical and fluidic interface**

The chip has four temperature dependent resistors (figure 2) which are placed in a Wheatstone configuration (figure 3). A 100 mV potential is placed across the bridge ($U_B$ in figure 3) using a digitally controlled voltage supply. The thus occurring electrical power heats up the resistors. If a flow is applied in the direction given in figure 2 a voltage difference occurs between the midsection of the left side and the right side branch of the bridge. This voltage difference is due to the temperature effect.

![Figure 4: Left: Electrical chip interface. The chip looks distorted, because of an optical effect caused by the plastic cover. Right: Fluidic chip interface.](image)

![Figure 5: Schematic view of the setup. Gas pressure is delivered using a mechanical pressure controller at 10 bar. A pressure meter ($P$) is used to electronically control the pressure using an electromagnetic valve. Between the device under test (DUT) a restriction is placed and as a reference a 50 ml/min piston prover (FPP) is used.](image)

**EXPERIMENTAL**

The setup we used to characterize this system is given in figure 5. Gas flow is generated by an electronically controlled pressure at the inlet. We use a pressure controller for this (Bronkhorst, EL-PRESS) and a constant leak. The outlet is at atmospheric pressure which is also monitored during the experiment using a pressure sensor. As a volumetric flow reference we use a 50 ml/min piston prover (Bronkhorst, FPP-050). Before the DUT (device under test) we placed a restriction (10 cm long stainless steel tube with an inner diameter of 125 μm). In this way the range of the pressure controller is more efficiently used. This in turn gives a higher resolution for the pressure control. We tested the sensor chip with 4 different gases, Argon (Ar), Helium (He), Nitrogen ($N_2$) and Carbon dioxide (CO$_2$).
RESULTS

In this section we present and discuss the results obtained with the setup described above. We measured the resulting sensor signals as a function of the reference flow measured by the piston prover. An example of such a curve, measured with N₂ is given in figure 6.

![Image of sensor signal vs. reference flow](image)

Figure 6. Measured sensor signal for N₂ as a function of reference flow by a 50 ml/min piston prover. The fit is a 3rd order odd function polynomial fitted by the least square method. The fit is reasonable up to approximately 0.8 ml/min, which we define as its nominal flow rate.

We fitted the data with a third order odd function polynomial. This means we only used the first and third order term. This fit was found to describe the sensor signal most effectively. Later this polynomial function can also be applied to linearize the sensor response. The coefficient of the first order or linear part of the fit is used as the sensor sensitivity, Sₓ, for a specific gas, x. If we plot this sensitivity as a function of ρ-Cₚ for different gases we find a linear fit (figure 7). This is expected since we suppose Sₓ is indeed a linear function of ρ-Cₚ.

Moreover we find that Ar and He show similar sensitivities, which is expected since they have a similar ρ-Cₚ product. To prove that the sensor sensitivity is a function of ρ-Cₚ we define two types of conversion factors, a theoretical conversion factor TCFₓ and an empirical conversion factor ECFₓ. These are then used to directly compare the measured values with theory for each gas. In equation (1) TCFₓ is defined.

\[
TCFₓ = \frac{ρₓCₚₓ}{ρN₂CₚN₂} \quad (1)
\]

In TCFₓ, the ratio of ρ-Cₚ product of the gas of interest to the ρ-Cₚ product of N₂ is determined. ECFₓ is defined in equation 2.

\[
ECFₓ = \frac{Sₓ}{SN₂} \quad (2)
\]

Here the ratio of the empirical sensitivity of the gas of interest and the empirical sensitivity of N₂ is determined. The theoretical and empirical conversion factors can be compared to determine the accuracy of conversion solely based on the ρ-Cₚ product.

![Image of sensitivity vs. p-Cp](image)

Figure 7. Measured sensitivity (slope of the linear part of the fit in figure 6) as a function of the theoretical ρ-Cₚ product at 1.2 bar(a) and 30°C (average pressure and temperature inside the sensor).

In table 1 we show the conversion factors for different gases. Also the deviation between the theoretical and the empirical conversion factors is given. The deviation is well below 2% which is good enough for a proof of principle. Not only does this facilitate conversion between gases, it will also result in reproducible behavior between chips when applying gas mixtures that vary in composition during a measurement.

<table>
<thead>
<tr>
<th></th>
<th>ECFₓ [measured]</th>
<th>TCFₓ [theoretical]</th>
<th>deviation [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>He</td>
<td>0.707</td>
<td>0.711</td>
<td>-0.57</td>
</tr>
<tr>
<td>Ar</td>
<td>0.719</td>
<td>0.714</td>
<td>0.69</td>
</tr>
<tr>
<td>CO₂</td>
<td>1.317</td>
<td>1.298</td>
<td>1.43</td>
</tr>
</tbody>
</table>

Table 1: Measured and theoretical conversion factors with respect to N₂

CONCLUSION

To conclude we presented a truly calorimetric flow sensor chip. The sensor element is made of silicon nitride and the heaters are galvanically separated from the inner part of the sensor element. This makes the sensor chemically resistant to most gases. We tested this chip with several common gases and found predictable behavior. Moreover we found a
\( \rho C_p \) relation between different gases. This eliminates
the need for calibration with actual gases and opens
up the road to measuring various mixtures
reproducibly between sensor chips.

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