Novel Design and Signal Transduction Concepts of Micromachined Flow Sensors

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In this work we investigate a novel design approach and signal transduction concepts for micromachined calorimetric flow sensors. Maintaining a constant average excess temperature of the membrane by means of a simple two-state electronic controller, a pulse modulated actuation signal is obtained. The sensitivity of the output signal can be influenced by altering the amplitude of the heating pulse. The proposed novel sensor design offers three different operating modes. Beside the conventional calorimetric transduction, such sensors are also operable in a mixed calorimetric-anemometric mode featuring low power consumption, high flow sensitivity, and an unambiguous transduction characteristic over a wide flow range.

Introduction

Commonly used micromachined calorimetric flow sensors feature heat source(s) and spatially separated temperature sensors, both embedded in a thin membrane [1]. These sensors exploit the flow dependent heat transfer altering the temperature distribution near the heater. Operating the flow sensor at a constant heating voltage, tantamount to a constant heating power, a high sensitivity is feasible only within a limited flow range. Due to efficient convective cooling at higher flow rates the output characteristic becomes ambiguous. For a wider measurement range, a constant temperature difference between the membrane and the fluid is necessary. This operational mode can be achieved using an electronic controller. Applying a standard PI-controller results in an unambiguous characteristic with moderate sensitivity at higher flow rates. In order to achieve better sensitivity, we investigated a novel signal transduction concept for the existing sensor layout as well as an improved sensor design.

Common Sensor Design

Figure 1 illustrates the membrane arrangement of the utilized flow sensor. Two thermistors (MT1, MT2) measure the local temperature at a position upstream and downstream of the heat source (thin-film heating resistor H). Without the flow, the generated temperature profile inside the membrane is symmetrical and both thermistors measure the same value. The convective heat transfer induced by the media flowing across the sensor surface disturbs the thermal symmetry. This change can be converted into an output voltage and evaluated for the determination of essential flow parameters such as flow velocity or mass flow.

The fluid temperature, which is typically close to the substrate temperature, can be measured with two additional thermistors arranged at the rim of the silicon chip (not shown in Fig. 1). The membrane consists of a SiO_2-Si_3N_4-SiN_x-sandwich with an overall thickness of 1.6 µm. The chip dimensions are 2 x 4 mm² (membrane area:

0.5 x 1 mm²). Further details of the technology and key specifications of such sensors can be found in [2], [3].

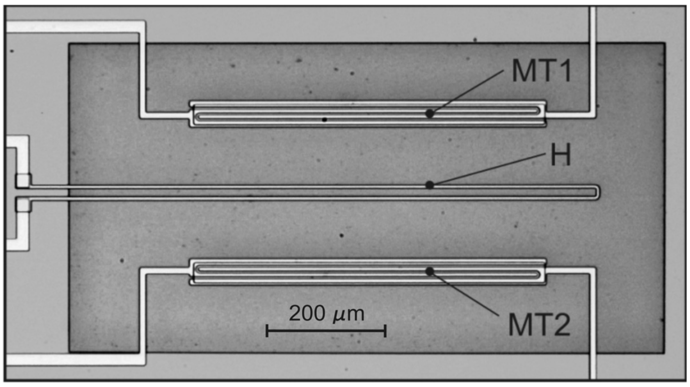

Fig. 1: Sensor layout with two temperature sensors (MT1, MT2) and a heater (H).

In the constant temperature excess mode, a constant difference between the temperature mean of the two membrane thermistors and the temperature mean of both substrate thermistors is maintained using an electronic controller. Instead of the commonly applied analogue controller we investigated the application of a two-state controller. For the design and optimization of the control loop a comprehensive SPICE model of the sensor's thermal system capable to fully cover its static and dynamic behavior was developed. This approach has proved to be a convenient method to investigate the interaction of the sensor and its evaluation/controlling circuit.

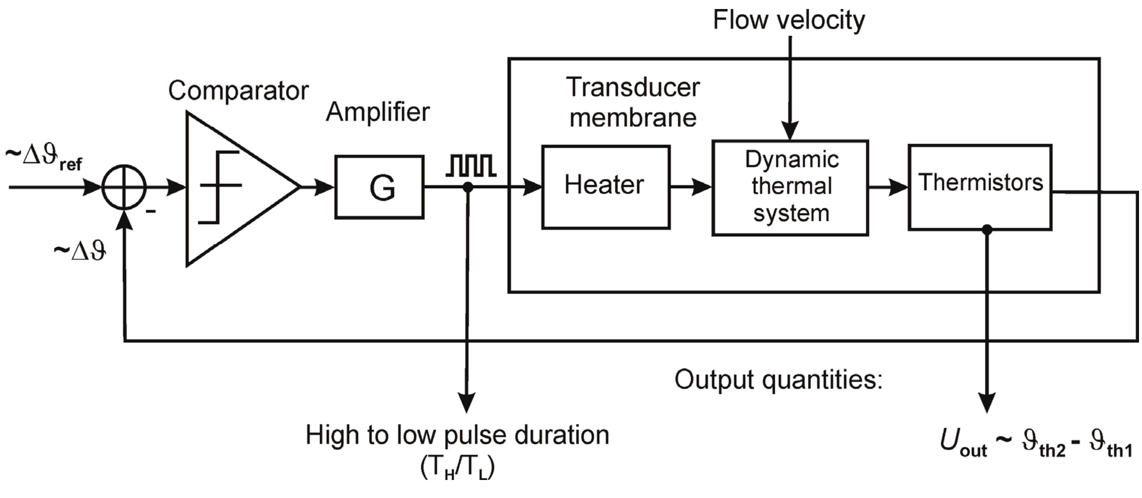

Fig. 2: Scheme of the novel operational mode using two-state closed loop controller which keeps the average excess temperature ($\Delta\vartheta$) of the membrane constant.

Implementation of a Two-State Controller

Figure 2 shows the scheme of the novel sensor operational mode based on a comparator operating in a negative-feedback closed-loop configuration. A constant bias of 0.5 V is applied to all germanium thermistors and each thermistor current is converted into a temperature-proportional signal by means of a current-to-voltage converter. The difference between the mean membrane temperature and the mean bulk temperature is compared with the equivalent of the excess temperature set point. The two-state controller establishes a train of voltage pulses at the heater. The pulse duration and repetition rate are determined by the selected amplitude and the dynamic characteristics of the thermal system, which in turn depend on flow velocity [4].

This approach offers the ratio of high to low pulse duration (T_H/T_L) as an output quantity in addition to the temperature difference signal (U_{out}). The basic properties of this flow dependent oscillator have been successfully modeled using PSpice. Related measurement results are depicted in Fig. 3 (left). The sensor is flush mounted into the wall of a rectangular flow channel (cross section 1.2 x 0.5 mm²). Due to convective cooling, the pulse duration increases and the pulse gap becomes smaller with increasing flow velocity. On the other hand, reducing the amplitude of the heating pulses at constant velocity evokes the same effect. In order to keep the average excess temperature ($\Delta\vartheta$) of the membrane constant, the controller must increase the average heating power and hence the ratio of high to low pulse duration (T_H/T_L) increases too. Thus, by altering the amplitude of the heating pulses one can influence the slope of the output characteristic in order to achieve better sensitivity.

In addition to the ratio of high to low pulse duration (T_H/T_L), the temperature difference signal (U_{out}) can also be used. For low flow velocities, this signal provides the highest sensitivity whereas the ratio T_H/T_L becomes the preferable output quantity at higher flow rates (Fig. 3, right).

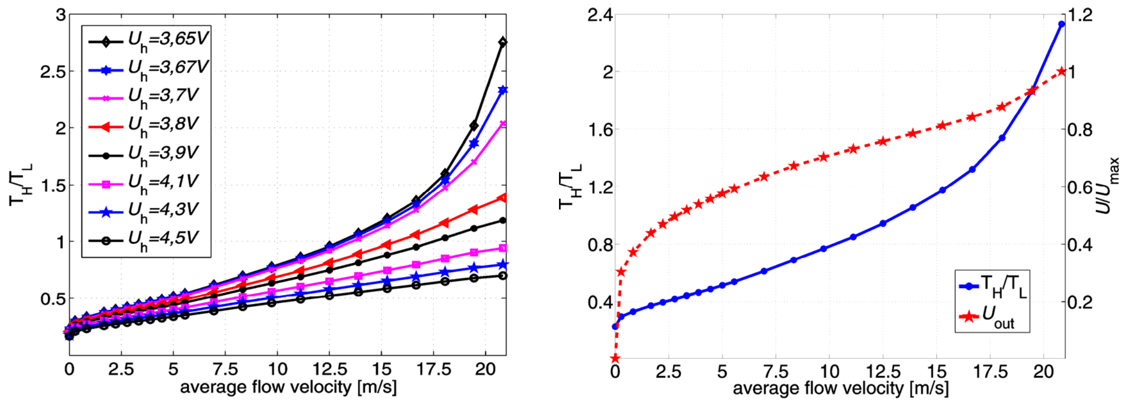

Fig. 3: Measured output characteristic for different amplitudes of the heating pulse (U_h). The ratio T_H/T_L serves as output signal. The average excess temperature amounts $\Delta\vartheta_{ref}$ ~ 5 °C (left). The comparison of two output quantities in case of an amplitude of heating voltage U_h = 3.67 V (right).

Novel Design Approach

A novel sensor design approach was first investigated by means of finite element simulations (COMSOL). This FE analysis is based on the schematic cross section indicated in Fig. 4 (left). A two dimensional model seems reasonable since all thin-film components on the membrane exhibit a large extension perpendicular to the flow direction. Two pairs of high-resolution thermistors are placed symmetrically to a thin-film heater on the sensor membrane. Additional substrate thermistors (ST) measure the fluid temperature. The air flow channel above the senor membrane is 1 mm high with a parabolic flow profile [5]. This novel design offers three different operating modes.

The first operating mode features the thin-film chromium resistor as a heat source and the pair of inner or, alternatively, outer thermistors as temperature sensors. The simulated output characteristic for constant heater voltage is depicted in Fig. 5 (left). For lower flow velocities, an excellent sensitivity is found. For higher velocities, however, the output characteristic saturates or it even becomes ambiguous. To solve this problem the heater voltage must be controlled to compensate for convective heat transfer, as described in the first paragraph. In this case the two substrate thermistors provide reference values of the fluid temperature.

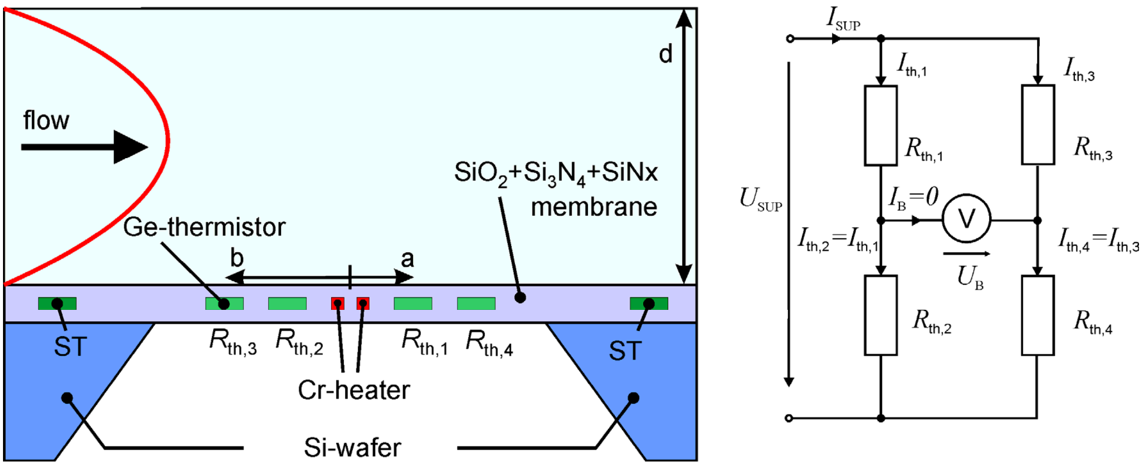

Fig. 4: Schematic cross section of the novel flow sensor design comprising four membrane thermistors, which can be connected to form a Wheatstone bridge.

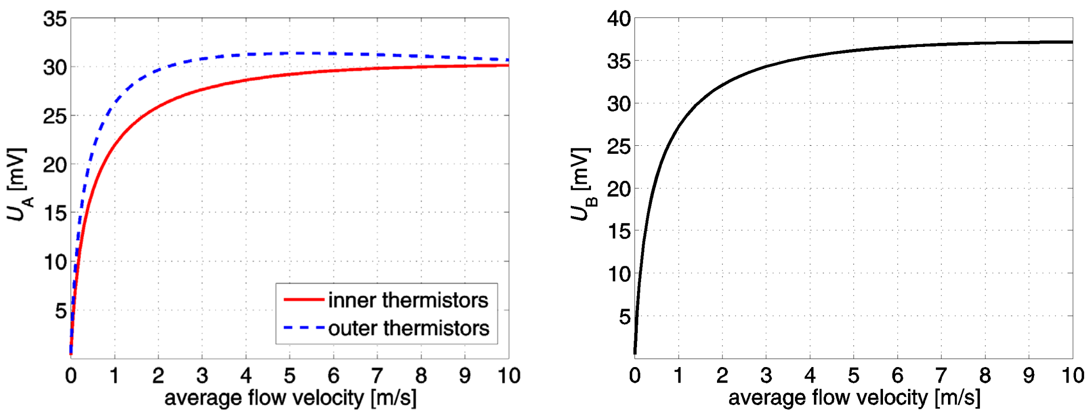

Fig. 5: Simulated output characteristics for the first (left) and second operating mode (right). In the first case, the output signal is proportional to the temperature difference of the membrane thermistor pair. In the second case, the voltage across the bridge U_B is used as an output quantity.

In the second operating mode the four membrane thermistors are connected to form a Wheatstone bridge (Fig. 4, right). The chromium resistor remains as the heat source. The simulated output characteristic is similar with the previous one (Fig. 5, right). The bridge is supplied with low voltage (1 V) in order to reduce the self-heating effect of the thermistors. The main advantage of this mode is that the Wheatstone bridge can be easily read-out, e.g., with a high-impedance galvanometer, without any need for complicated subsequent evaluation circuits. Moreover the calculations showed that this arrangement is insensitive to ambient temperature changes. Thus, the second mode does not need pre-calibration with respect to fluid and ambient temperatures.

Finally, the third operating mode (mixed calorimetric-anemometric mode) utilizes the self-heating effect of the membrane thermistors as a heat source. The chromium heater is switched off. In order to avoid the self-destruction of the thermistors due to their NTC characteristics the bridge is supplied with a constant current I_{SUP}= 50 µA, rather than with a constant voltage as it was the case in the second mode. The bridge voltage U_B as well as the voltage at the bridge supply terminals U_{SUP} depend on the thermistor resistance values and hence on the flow velocity

$$U_{\mathrm{B}} = I_{\mathrm{SUP}} \frac{R_{\mathrm{th2}}R_{\mathrm{th3}} - R_{\mathrm{th1}}R_{\mathrm{th4}}}{R_{\mathrm{th1}} + R_{\mathrm{th2}} + R_{\mathrm{th3}} + R_{\mathrm{th4}}}, \quad U_{\mathrm{SUP}} = I_{\mathrm{SUP}} \frac{(R_{\mathrm{th1}} + R_{\mathrm{th2}})(R_{\mathrm{th3}} + R_{\mathrm{th4}})}{R_{\mathrm{th1}} + R_{\mathrm{th2}} + R_{\mathrm{th3}} + R_{\mathrm{th4}}}. \tag{1}$$

The simulated output characteristics for both quantities are shown in Fig. 6. Evaluating the bridge voltage, an excellent sensitivity for flow velocities below 2 m/s is found. However, for higher velocities, the output characteristic becomes ambiguous as in the previous modes. Therefore the use of U_{SUP} as an output quantity is desired, resulting in a wider measurement range but moderate sensitivity for lower flow velocities.

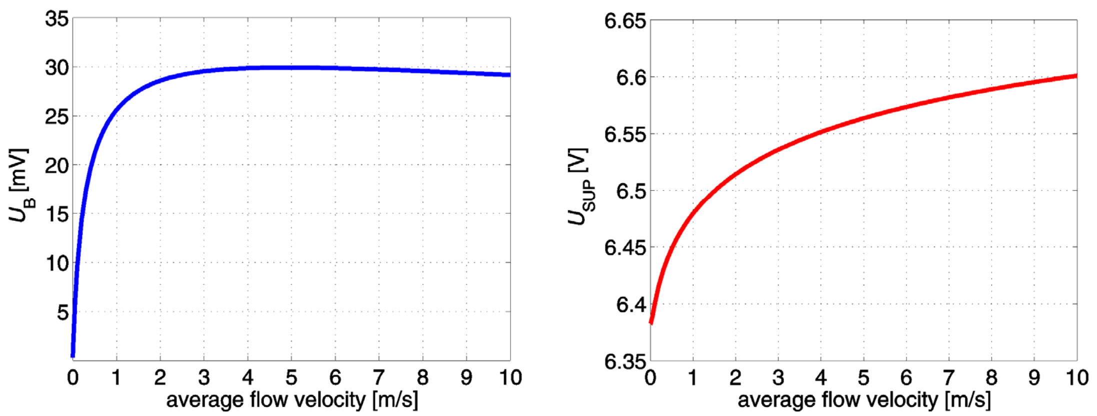

Fig. 6: Simulated output characteristics of the flow sensor using the bridge voltage U_B (left) and the voltage at the bridge supply terminals U_{SUP} (right) as an output quantity.

The power consumption in the first two modes amounts to approximately 3 mW, mainly dissipated in a chromium heater. In the third mode, however, the rated supply current limits the power consumption of all bridge thermistors to only ~ 0.3 mW. Thus, the third mode combines very low power consumption with high flow sensitivity or an unambiguous transduction characteristic.

Conclusion

We investigated novel design ideas and signal transduction concepts for micromachined calorimetric flow sensors. Maintaining a constant average excess membrane temperature by means of a simple two-state electronic controller, a pulse modulated actuation signal is obtained. This approach offers the ratio of high to low pulse duration as an output quantity in addition to the temperature difference signal. The sensitivity of the output signal can be optimized for specific applications by altering the amplitude of the heating pulse.

The proposed novel sensor design offers three different operating modes. Comprehensive finite element analyses revealed that beside the conventional calorimetric transduction such sensors are also operable in a mixed calorimetric-anemometric mode. Based on the self heating effect of the employed high resolution thermistors, this operational mode combines extremely low power consumption with high flow sensitivity or, alternatively, an unambiguous transduction characteristic over a wide flow range.

Acknowledgements

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