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To cite this article: Samir Cerimovic *et al* 2013 *Meas. Sci. Technol.* **24** 084002

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Bidirectional micromachined flow sensor featuring a hot film made of amorphous germanium

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Received 22 December 2012, in final form 25 April 2013

Published 10 July 2013

Online at stacks.iop.org/MST/24/084002

Abstract

We report on simulation-based sensor design and measurement results of a bidirectional micromachined hot-film anemometer. The device is based on a thin-film thermistor made of amorphous germanium embedded in a silicon nitride membrane. The germanium structure is divided by metal-strip electrodes into four thermistor segments which are connected to a Wheatstone bridge. The sensor combines hot-film and calorimetric transduction principles. The flow dependent cooling of the hot film results in a unipolar, strictly monotonic transduction characteristic which is utilized for flow velocity measurements. Moreover, convective heat transfer between the hot-film segments causes thermal asymmetry yielding a bridge detuning voltage with a bipolar characteristic where its sign corresponds to the flow direction. Consequently, the sensor features a strictly monotonic transduction characteristic over a wide flow velocity range combined with simultaneous detection of the flow direction. The device was characterized in constant-current and constant-temperature operating modes for stationary flows as well as step-like changes of the flow velocity. The sensor behaviour as a result of ambient temperature variations was studied in detail.

Keywords: hot-film anemometer, amorphous germanium, thermistor, MEMS

(Some figures may appear in colour only in the online journal)

1. Introduction

Nowadays, flow sensors measuring fluid velocity or mass flow rates are used for many applications such as industrial controlling systems, environmental monitoring, medical instrumentation and automotive engines. In order to achieve cost-efficient mass production and low power consumption combined with high sensitivity and quick response, micromachining technologies are becoming increasingly important. The thermal measurement principle seems to be

most promising for micromachined flow sensors. Such devices typically comprise heat sources and temperature sensors thermally decoupled from their carrier. According to the underlying physical principle, there are three different types of thermal flow sensors [1, 2].

- Hot-wire or hot-film flow sensors which exploit directly the cooling effect of the passing fluid on a heater. Here, the heater acts simultaneously as a heat source and temperature sensor.
- Calorimetric flow sensors utilize the flow dependent asymmetry of the temperature profile around a heater. In this case, temperature sensors arranged around the heat source are needed for the detection.



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- Time-of-flight (TOF) flow sensors which measure the passage of a heat pulse over a known distance between heater and temperature sensor.

Hot-wire anemometers are the oldest and most simple thermal-based flow sensors. The very first contributions date back to the beginning of the last century [3]. These devices are commonly used for studying turbulent and unsteady laminar flows [4, 5]. The sensor embodiments consist of one or more thin wire-resistors heated by an electric current. In operation, the convective cooling of a passing fluid changes the wire temperature and consequentially its electrical resistance. The resistance change can be exploited to acquire information about fluid velocity. In order to achieve a fast signal response, the wire diameter is usually in the range of several micrometres and therefore such wire probes are very fragile. Consequently, for measurement in liquid flows, more robust embodiments like hot-film heaters are utilized [4].

Hot-wire and hot-film anemometers can be operated in two different modes [3, 6]. In the first mode, the heater is supplied either with a constant current (CCA—constant current anemometer) or a constant voltage (CVA—constant voltage anemometer). The flow dependent resistance change of the heater is detected by measuring the heater voltage or the probe current, respectively. In the second operating mode, a constant temperature difference between the probe and the ambient is established by means of an electronic controller (CTA—constant temperature anemometer). The voltage or current required to maintain the overtemperature can be used as output quantity.

Typically, the probe axis points perpendicular to the flow. As convective cooling depends only on the magnitude of the flow velocity, hot-wire anemometers cannot detect the flow direction. However, this information is mandatory in a vast number of applications. For example, bidirectional flow sensors are required for the medical investigation of pulmonary function. Without additional elements to detect the direction, hot-wire or hot-film sensors are not appropriate for these purposes [7, 8].

Typical materials used for hot wires are metals like platinum or tungsten. They feature a linear temperature characteristic, but a relative low temperature coefficient of resistivity (TCR) in the range between 0.38 and 0.68%/K [9]. In order to improve the sensitivity, materials with a higher TCR like semiconductors must be used. For example, TCR of polysilicon depends on doping concentration and can reach values up to $-3\%/K$ [10, 11]. However, semiconductor thermistors feature nonlinear characteristic, making sensor design and read-out circuit more challenging.

Besides thermoresistive temperature sensors, some miniaturized flow sensors proposed in the literature rely on thermoelectric materials. Here, thermopiles consisting of in series connected thermocouples are used as a temperature sensor to determine the flow dependent temperature field around a heater [12]. The Seebeck effect of thermocouples enables good sensitivity combined with low offset and drift [9]. Moreover, they are compatible with complementary metal oxide semiconductor processing facilitating system-on-chip design, where both the sensor and the read-out circuit are

integrated on the same chip [13]. However, the layout of such thermocouple-based sensors is more complicated. Since thermopiles cannot operate as heat source, TOF or calorimetric transduction principles with separated heat sources must be implemented.

A calorimetric flow sensor realised with spatially separated heater and temperature sensors made of amorphous germanium (aGe) was introduced in [14]. TCR of aGe amounts to approximately $-2\%/K$, being five times higher than that of platinum. Moreover, aGe thin film exhibits resistivity of about $5\ \Omega m$ at room temperature and thermal conductivity of approximately $0.5\ W\ K^{-1}\ m^{-1}$ [15], which is much lower than the thermal conductivity of polysilicon or thermocouple materials [16]. This facilitates the design of flow sensors, since the current density through connecting leads and consequently their cross-section can be reduced. As a consequence, the parasitic thermal flow to the substrate is reduced too.

In [14], a chromium thin film serves as a heat source. To evaluate the temperature difference, a constant bias voltage is applied to germanium thermistors and each thermistor current is converted into a temperature-proportional signal by means of a current-to-voltage converter. Applying 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 even for gaseous fluids. In order to avoid this ambiguity and hence to obtain a wider measuring range, a constant temperature difference between membrane and fluid is necessary. This can be achieved by controlling the heater voltage with an electronic controller. Hence, besides the more complex design, such calorimetric flow sensors also require more sophisticated read-out circuits.

In this work, we present a simulation-based sensor design and corresponding measurement results of a bidirectional micromachined hot-film anemometer. The device relies on a thin-film thermistor made of aGe. In operation with a constant current supply (CCA), the read-out simplifies to voltage measurement and offset correction only. Typically, aGe thin films are connected with only two metal electrodes. The meander-like gap between the electrodes ensures almost uniform current density and temperature distribution in the thermistor [14, 17, 18]. However, hot-film sensors with such simple interdigital electrodes cannot distinguish the flow direction. Therefore, we propose contacting by metal-strip electrodes in order to divide the aGe structure into four thermistor segments. The power dissipation in the hot film remains the same, however, the new design enables detection of the flow direction without additional components.

In contrast to the calorimetric transduction scheme [14], a hot-film anemometer based on aGe thermistor always features a monotonic characteristic. Also, the transduction effort is significantly reduced as the separate heat source is omitted. The disadvantages of the nonlinear characteristic of aGe thermistors, resulting in high dependence on the ambient temperature variations, can be taken into account by operating the sensor in CTA mode. Here, the temperature dependence of the output characteristic is reduced to a minimum, although at the expense of a more complex sensor circuit.

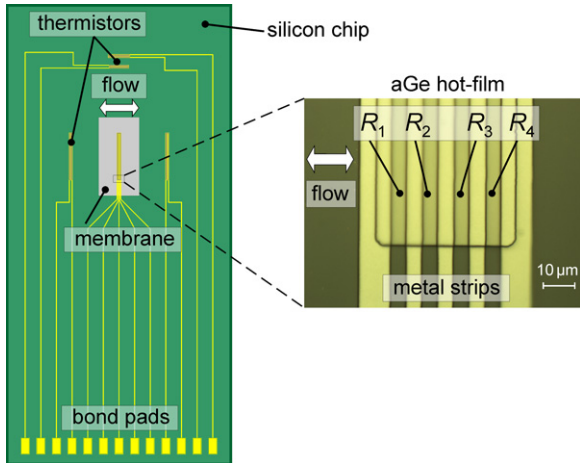


Figure 1. Sketch of the sensor layout (based on the mask data). The aGe hot-film thermistor embedded in a thin membrane is divided by metal strips in four segments (enlarged photomicrograph) which are connected to form a Wheatstone bridge.

2. Sensor design and fabrication

Figure 1 illustrates the top-view of the sensor chip. A 260 nm thick aGe hot film with dimensions of $45 \times 600 \mu\text{m}^2$ is embedded in a micromachined membrane. The dimensions of the membrane amount to $500 \times 1000 \mu\text{m}^2$. It consists of SiO_2 , Si_3N_4 and SiN_x layers with a typical overall thickness of about $1.3 \mu\text{m}$. The chip temperature, or equivalently the ambient temperature, which is in our measurement setup equal to the fluid temperature, can be monitored with additional aGe-thermistors placed on the silicon rim parallel to the hot film. Moreover, two additional substrate thermistors are located above the membrane (figure 1). They are needed to establish a CTA-mode as described in section 3.2. The overall chip size is $3 \times 6 \times 0.35 \text{ mm}^3$. The fluid flows tangentially to the sensor membrane as indicated by the double arrow in figure 1.

The micromachined sensor chip was fabricated using the following process flow (figure 2).

- A double-sided polished, (100) oriented, 4 inch silicon wafer with a thickness of $350 \mu\text{m}$ serves as substrate. The wafer has been coated by the vendor with thermally grown silicon dioxide (SiO_2) and low pressure chemical vapour deposited silicon nitride (Si_3N_4) featuring thicknesses of 180 nm and 150 nm, respectively.
- The sensor fabrication started with a photolithographic process and a high-vacuum vapour deposition of a 260 nm thick layer of germanium using an electron beam evaporator. This layer was patterned using lift-off technique to create the bulk of the hot film and thermistors.
- The second lithography followed by vapour deposition of a Ti–Au–Cr layer sequence (exhibiting thicknesses of 70–130–50 nm) and lift-off patterning was used to obtain metal strips for the segmentation of the hot film, interdigital electrodes for the substrate thermistors and connection leads to the bond pads.
- Next, a low stress silicon nitride (SiN_x) protective film of thickness about $1 \mu\text{m}$ was deposited utilizing a low temperature plasma enhanced chemical vapour

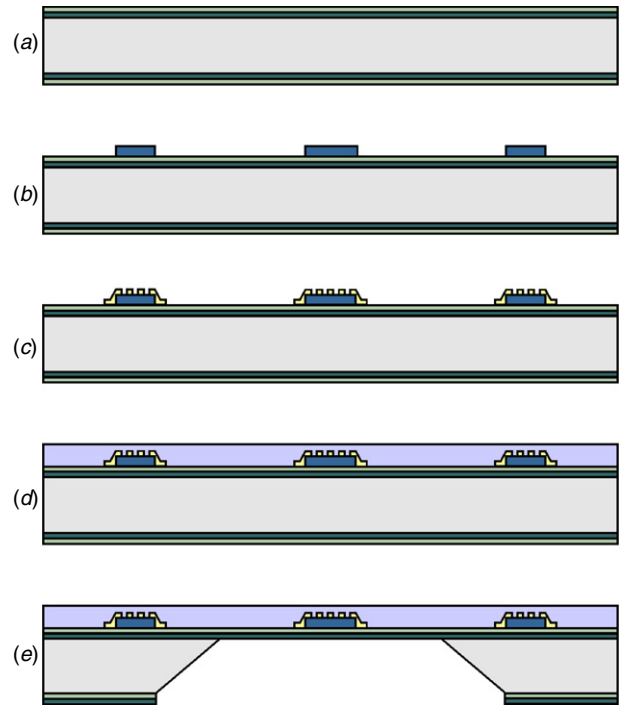


Figure 2. Fabrication steps of a micromachined thermal flow sensor.

deposition process. A low deposition temperature of about 100°C prevented the delicate germanium film from recrystallization. In order to obtain openings to the bond pads, the protective SiN_x film was patterned from the front-side using photolithography and a reactive ion etching (RIE) process. Afterwards, the chromium was removed from the bond pads by means of wet-etching (not shown in figure 2).

- Finally, square apertures were etched through the wafer backside coating by means of photolithography and RIE (not shown in figure 2). The membranes were then manufactured using a KOH based anisotropic wet etching process to remove the bulk silicon.

The hot-film thermistor segments are connected to a Wheatstone bridge, where the overall thermistor voltage U_{TH} as well as the bridge detuning voltage U_{B} can be used as output quantities. When supplied by a constant current (CCA), the whole resistive aGe film acts as heat source. Owing to the negative temperature coefficient (NTC) of aGe, convective cooling increases its overall resistance. In CCA mode, the voltage across the thermistor U_{TH} follows this change. This unipolar output characteristic is typical for hot-film transducers. On the other hand, convective heat transfer between the hot-film segments causes thermal asymmetry. The resulting bridge voltage U_{B} exhibits a bipolar characteristic, which is characteristic of calorimetric transducers. Consequently, the sensor combines hot film and calorimetric transduction principles, featuring a strictly monotonic transduction characteristic combined with simultaneous detection of the flow direction.

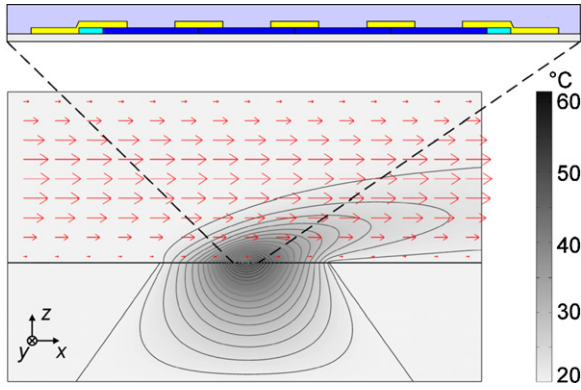


Figure 3. 2D FEM-model of the flow sensor. A 0.5 mm high flow channel enables tangential flow above the sensor membrane. The arrows indicate the parabolic velocity profile inside the channel. The inset illustrates location and schematic cross-section of the hot film.

3. Modelling and simulations results

Finite-element-method (FEM) simulations are a convenient tool to model the sensor behaviour and to estimate the transduction characteristic. We used the commercially available finite element analysis tool COMSOL Multiphysics. Since all thin-film components exhibit a large extension perpendicular to the flow direction, two dimensional modelling seems to be a reasonable choice in our case. Figure 3 shows the 2D model of the sensor with the enlarged cross-sectional view of the hot-film structure. Each hot-wire segment features an electric resistivity of about 250 kΩ at room temperature. Above the sensor membrane, a 0.5 mm high flow channel was added with nitrogen gas as test fluid. A parabolic flow velocity profile implying non-slip boundary conditions at the top and bottom of the flow channel was assumed. The trapezoidal cavity below the sensor membrane is filled with resting fluid. Its shape stems from KOH-etching during the membrane fabrication (figure 2, last step).

Due to the imposed flow velocity, solution of the general Navier–Stokes equation is not necessary and only the heat transfer equation incorporating conductive and convective heat transfer must be solved. The boundary condition at the in- and outlet of the flow compartment is implemented as convective flux, the remaining parts of the model circumference were kept at the ambient temperature ($T_{\text{LAB}} = 24\text{ °C}$). This is also the initial temperature condition for all domains.

3.1. CCA operating mode

Figure 4 illustrates the measurement setup in CCA mode. The temperature dependence of the hot-film segments can be excellently fitted by an exponential function [19]

$$R_i = R_0 \cdot e^{\alpha \cdot (T_{\text{LAB}} + \Delta T_i)}, \quad i = 1, \dots, 4, \quad (1)$$

where $\alpha = -0.02\text{ K}^{-1}$ and $R_0 = 391.5\text{ k}\Omega$ are the TCR and the segment resistance at reference temperature 0 °C , respectively. T_{LAB} is the ambient temperature and ΔT_i denotes the overtemperature of the i th segment depending on flow direction and velocity.

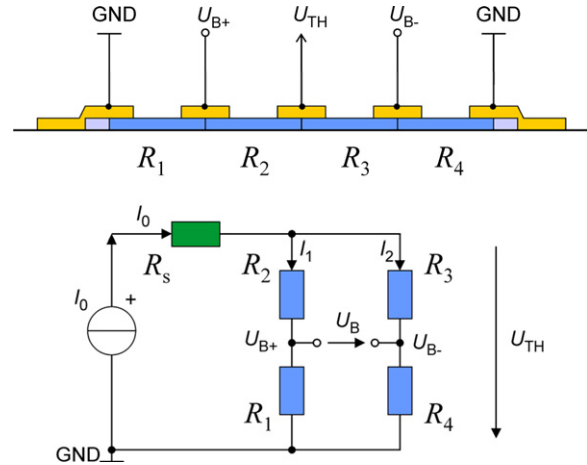


Figure 4. Measurement setup in CCA mode. The Wheatstone bridge composed of four hot-film segments R_{1-4} is heated by a constant current I_0 . Ambient temperature can be monitored by one of the substrate thermistors R_s connected in series with the hot film.

A fluid passing by the sensor surface cools the entire hot film. Consequently, the overall electrical resistance of the bridge R_{TH} increases with the flow velocity v . Due to the constant supply current, the voltage across the hot film U_{TH} behaves in the same manner

$$U_{\text{TH}} = I_0 \frac{(R_1 + R_2)(R_3 + R_4)}{R_1 + R_2 + R_3 + R_4} = I_0 R_{\text{TH}}. \quad (2)$$

FEM simulations determine the temperature distribution $T(x, y)$ in the sensor. The segment temperatures ($T_{\text{LAB}} + \Delta T_i$) are obtained through a subdomain integration of the variable T over each segment area. Applying (1) and (2) allows calculation of the sensor output characteristic U_{TH} . In order to investigate the dynamic behaviour of this output signal, we first simulate U_{TH} as a function of the supply current I_0 at zero flow velocity (first solid line, figure 5(a)).

Initially, the output voltage U_{TH} increases with increasing supply current. However, due to the increasing temperature of the hot film, the overall bridge resistance R_{TH} decreases influencing U_{TH} in the same manner. Therefore, for a rising supply current, the output voltage first reaches its maximum and begins afterwards to decrease as the second effect becomes predominant. Convective cooling of the fluid flow shifts the maximum to higher values of the supply current. The output signal for a constant supply current of $150\text{ }\mu\text{A}$ as a function of the flow velocity is depicted in figure 5(b). The same result can be obtained by intersecting the array of curves in figure 5(a) with a straight dotted line $I_0 = 150\text{ }\mu\text{A}$. Apparently, the dynamics of the transfer characteristic depends on the chosen supply current. For I_0 below $50\text{ }\mu\text{A}$, the dynamics (i.e. the difference between the lowest and the highest value of U_{TH}) is poor. Above $200\text{ }\mu\text{A}$, the dynamics does not improve significantly.

On the other side, the supply current determines also the average overtemperature of the hot film. The maximum overtemperature is reached at zero flow, i.e. without convective cooling (figure 6). During the manufacturing process, the wafer was heated gradually and finally temperature annealed at 150 °C for several hours. This ensures thermal stability of

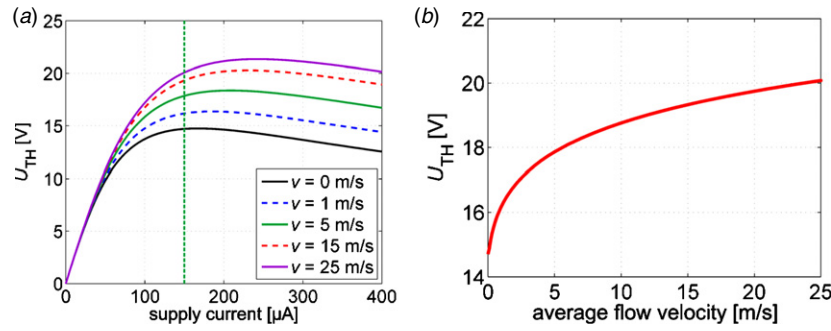


Figure 5. (a) Simulated voltage across the hot film U_{TH} as a function of the supply current I_0 for different flow velocities. (b) Simulated output signal U_{TH} for a constant supply current of 150 μ A.

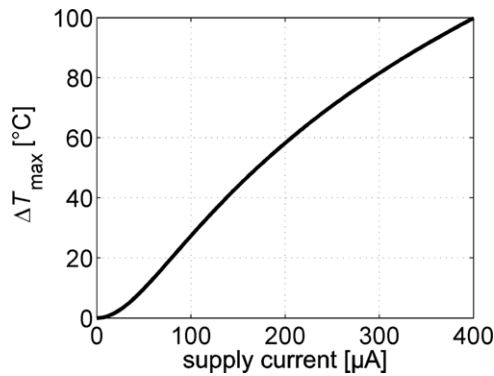


Figure 6. Simulated maximum overtemperature of the hot film as a function of the supply current I_0 .

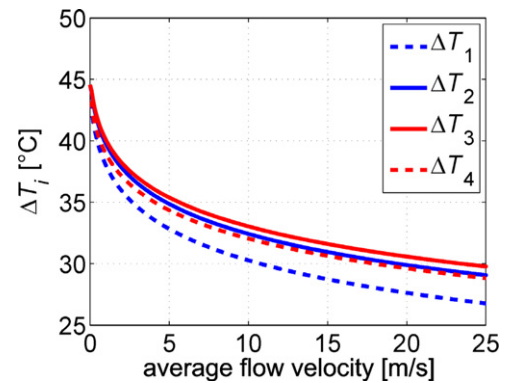


Figure 7. Simulated overtemperatures ΔT_i of each hot-wire segment as a function of the average flow velocity. The assumed ambient temperature is $T_{LAB} = 24$ $^{\circ}$ C.

the resistance value of the aGe thermistors at low temperatures. Should the overall temperature of the thermistor exceed 150 $^{\circ}$ C, the aGe structure would be changed. As a result of reduced number of dangling bonds, a permanent increase of the resistance value would be a consequence. The maximum overtemperature of the entire hot film at 150 μ A supply current amounts to approximately 45 $^{\circ}$ C (figure 6). Therefore, the maximum fluid and ambient temperature at this supply current should not exceed the value of 100 $^{\circ}$ C, which is fulfilled for most applications.

The dissipated electrical power in CCA mode depends on the hot-film resistance and hence on the flow velocity. Because of the constant supply current, this characteristic shows the same course as the output voltage U_{TH} (figure 5(b)). The dissipated power in the hot film for $I_0 = 150$ μ A supply current varies from 2.2 to 3 mW over the whole investigated flow range.

The overtemperatures ΔT_i of each hot-wire segment as a function of the average flow velocity in the channel are depicted in figure 7. For this simulation, the supply current of $I_0 = 150$ μ A and a nitrogen flow from left to the right were assumed. According to figure 7, the fluid flow cools down all hot-film segments, even though the cooling intensity is not exactly the same. Due to convective heat transfer, the segment next to the flow inlet (R_1) is cooled down more efficiently than the remaining three segments which exhibit similar temperature drops. The highest temperature features the segment R_3 , as it lies downstream between two other segments.

The voltage across the bridge U_B depends on the resistance values of all hot-film segments, i.e. on their overtemperatures and hence on the flow velocity

$$U_B = I_0 \frac{R_1 R_3 - R_2 R_4}{R_1 + R_2 + R_3 + R_4}. \quad (3)$$

For zero flow, the temperature profile inside the hot film is symmetrical regarding its midpoint. Therefore, the outer segments (R_1 and R_4 , dashed lines in figure 7) and the inner ones (R_2 and R_3) exhibit the same temperature, respectively. Hence, the bridge is in balance and U_B equals zero. With increasing flow, the temperature drop of the R_1 segment becomes dominant resulting in a rising positive U_B voltage. In the reverse flow direction, R_4 lies next to the flow inlet and U_B changes its sign.

Again, we first simulate U_B as a function of the supply current I_0 and a flow from left to right (figure 8(a)). For zero flow, U_B equals zero provided that respective hot-film segments exhibit exact symmetry regarding the hot-film midpoint. For low flow velocities, the bridge voltage increases with increasing supply current. However, for rising supply currents, the overtemperature of the entire hot film becomes high and the relative temperature difference between the segments decreases. As a result, the bridge voltage saturates, whereas the convective cooling counters the saturation. The output characteristic U_B can be obtained by intersecting the $U_B(I_0)$ curves with a straight line $I_0 = \text{const}$ (dotted line in figure 8(a)). Figure 8(b) shows the results for a supply current of 150 μ A.

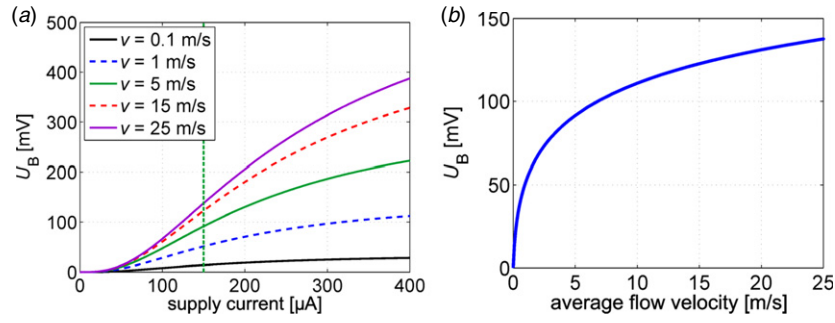


Figure 8. (a) Hot-film bridge voltage U_B as a function of the supply current I_0 for different flow velocities. (b) Simulated output signal U_B for a constant supply current of $150 \mu\text{A}$.

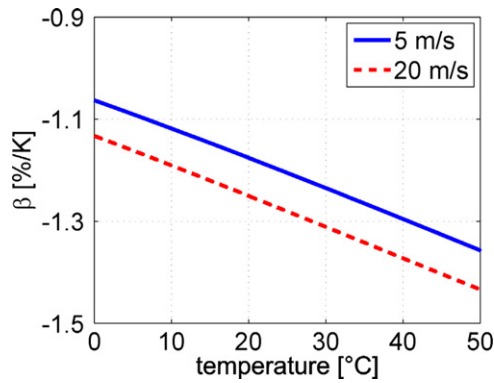


Figure 9. Relative change of the thermistor resistance β as a function of the ambient temperature for two different flow velocities.

Thermistors made of aGe feature a nonlinear temperature dependence (1). The TCR α is defined as relative change of the thermistor resistance R with the temperature

$$\alpha = \frac{1}{R} \frac{dR}{dT}. \quad (4)$$

The thermistor temperature $T = T_{\text{LAB}} + \Delta T$ is composed of the ambient temperature T_{LAB} and the thermistor overtemperature $\Delta T(I_0, v, T_{\text{LAB}})$, where the latter is a function of the quantities supply current, flow velocity and ambient temperature. Consequently, variations of the ambient temperature influence the output characteristic and must be therefore considered to ensure proper sensor operation. The relative change of the thermistor resistance R with the ambient temperature at a constant supply current is given by

$$\beta = \frac{dR}{R \cdot dT_{\text{LAB}}} = \frac{\alpha}{1 - \alpha \cdot \Delta T}. \quad (5)$$

As ΔT is a function of the flow velocity, the temperature coefficient β is also flow dependent. Figure 9 shows β as a function of the ambient temperature for two different flow velocities. With increasing flow velocity, the hot film is cooled down and the overtemperature ΔT decreases. Consequently, the temperature coefficient β tends towards the value of α (cf equation (5)).

Due to the flow dependence of ΔT , equation (5) cannot be directly used to correct the output signal if variations of the ambient temperature occur. Instead, a rather complicated correction by means of look-up tables must be applied. A more convenient way to make a system more robust to variations

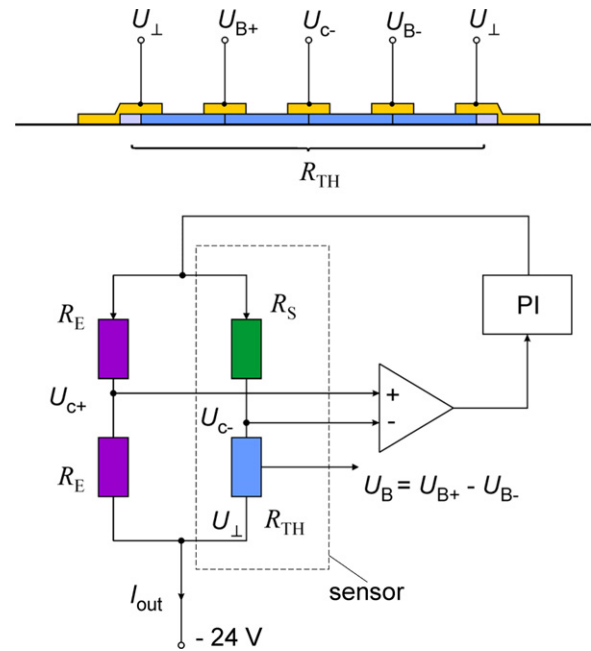


Figure 10. Measurement setup in the CTA mode. The hot-film thermistor R_{TH} is placed in a Wheatstone bridge and initially $R_{TH} > R_S$. An electrical current I_{out} heats the hot-film thermistor until $R_{TH} = R_S$. A common closed-loop PI controller adjusts the output current I_{out} to maintain the bridge balance and hence the hot-film overtemperature constant. The external resistors R_E feature the same fixed value.

of the ambient temperature is to keep the overtemperature ΔT constant, i.e. independent of the flow velocity. This is achieved in the CTA operating mode.

3.2. CTA operating mode

In order to keep ΔT constant, the whole hot-film thermistor R_{TH} is placed in one leg of an external Wheatstone bridge (figure 10). The other leg of this bridge consists of two equal, fixed value resistors R_E . The overtemperature is adjusted with a resistor R_S , which is preferably implemented by one of the substrate thermistors connected in series with R_{TH} . The substrate thermistor must be designed to feature a lower resistance value at operating temperature than the hot-film thermistor ($R_{TH} > R_S$). The closed-loop controller adjusts the output current I_{out} to set and maintain the bridge voltage

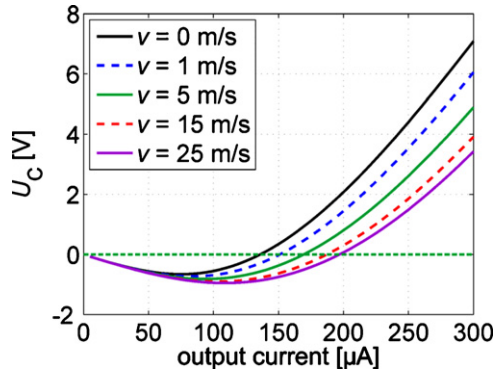


Figure 11. Simulated bridge voltage U_C as a function of the output current I_{out} for different flow velocities. The controller adjusts I_{out} to establish a bridge balance and consequently $U_C = 0$ (dotted line).

$U_C = U_{C+} - U_{C-}$ at zero. The electrical current heats the hot-film thermistor and its resistance decreases until $R_{TH} = R_S$. In the case of convective cooling by the passing fluid, the output current must increase to keep the bridge in balance. Therefore, independently of the flow velocity, the hot-film thermistor is heated to a constant value ΔT over the ambient (i.e. substrate) temperature.

The closed-loop circuit consists of the Wheatstone bridge, an instrumentation amplifier, and a conventional PI controller. The instrumentation amplifier is realised with three high-voltage operational amplifiers OPA551 using the common design [20]. The PI controller was chosen for its simplicity and sufficient control behaviour. The controller parameters were roughly estimated using Chien–Hrones–Reswick tuning method [21] and the step-response of the hot-film output obtained from the FEM simulations. The voltage across the bridge of the closed-loop circuit lies in the range of 20–35 V. In order to reduce the output voltage of the PI controller, the bottom node of the Wheatstone bridge is connected to $V_- = -24$ V.

Note that the entire sensor system in CTA mode comprises two Wheatstone bridges: the inner one embodied in the hot film and the outer one as a part of the closed-loop circuit. The outer bridge voltage is kept zero by the controller (i.e. $U_C = 0$), whereas the inner bridge voltage U_B is utilized to detect the flow direction. As an appropriate flow dependent output signal, the unipolar bridge current I_{out} can be used.

In order to obtain the output characteristics, we first simulate the outer bridge voltage U_C as a function of the

overall bridge current I_{out} at zero flow velocity (first solid line, figure 11). For low currents $I_{out} < 50 \mu A$, the hot film is relatively cold and due to the resistance difference $R_{TH} > R_S$ the controller input voltage U_C is negative. With increasing current, the temperature of the hot film increases and consequently, its resistance value R_{TH} decreases. As a result, the voltage U_C increases until a steady state $U_C = 0$ is reached. If the thermistor is cooled down by the flow, a higher current value is needed to reach this state.

The intersection points of the simulated characteristics with a straight line $U_C = 0$ (dotted line in figure 11) yield the output signal I_{out} as a function of the flow velocity (figure 12(a)). The simulations also provide the segment overtemperatures ΔT_i for each current value I_{out} . Using (1) and (3), the hot-film bridge voltage U_B can be calculated as a function of the flow velocity (figure 12(b)).

Because of the constant overtemperature, the resistance value of the hot film in CTA mode is flow independent. The dissipated electrical power in the hot film depends still on the flow velocity and its characteristic follows a similar course to the output current. The dissipated power in the hot film for $\Delta T = 15^\circ C$ varies from 0.7 to 1.6 mW over the whole investigated flow range, which is significantly lower than in CCA mode. This is not an intrinsic property of the CTA mode but rather a consequence of a much higher overtemperature reached in CCA mode. The lower the overtemperature, the less electrical power is dissipated in the hot film.

The maximum dissipated power in the CTA mode at $\Delta T = 40^\circ C$ obtained by FEM amounts to approximately 4 mW. Operation of the device in CCA mode with $I_0 = 150 \mu A$ yields comparable overtemperatures and power dissipation.

The closed-loop control system maintains a constant temperature difference between the hot film and the ambient. However, the output signals are not independent of the ambient temperature. On the one hand, the variation of the ambient temperature influences the hot-film resistance and hence the thermistor current needed to maintain the constant overtemperature ΔT . On the other hand, it modifies the overall resistance of the controller bridge and so directly the output current I_{out} . The relative change of the output current with the ambient temperature in CTA mode is given by

$$\beta_{I_{out}} = \frac{dI_{out}}{I_{out} \cdot dT_{LAB}} = \frac{\alpha}{2} \cdot \frac{R_S - R_E}{R_S + R_E}, \quad (6)$$

where R_E is the resistance value of the two external resistors placed in the other leg of the outer Wheatstone bridge

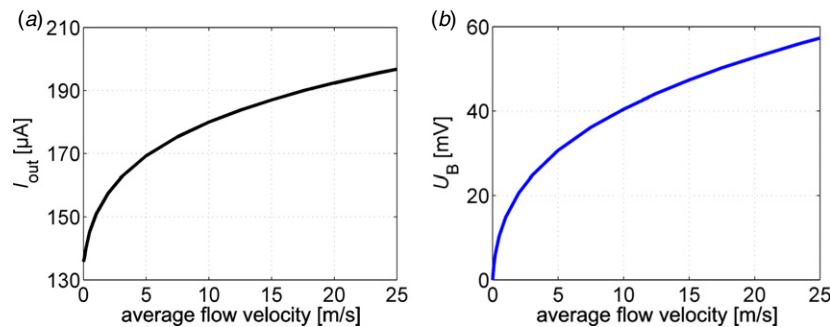


Figure 12. (a) Simulated output current I_{out} and (b) hot-film bridge voltage U_B in CTA mode with $\Delta T = 15^\circ C$.

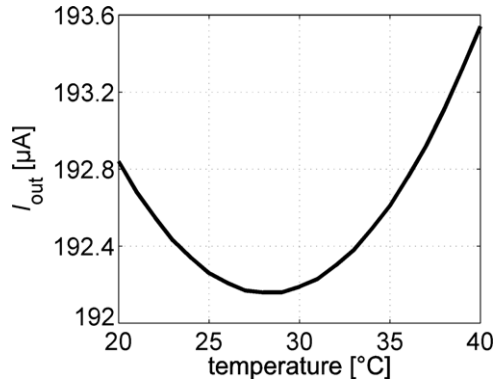


Figure 13. Output current I_{out} in CTA mode as a function of the ambient temperature T_{LAB} . For simulations, a constant overtemperature of $\Delta T = 15^\circ C$ and a constant average flow velocity of $v = 22.5 \text{ m s}^{-1}$ were assumed. The specific ambient temperature, where the relative change of I_{out} is reduced to a minimum, lies around $T_S = 28^\circ C$.

(figure 10) and $\alpha = -0.02 \text{ K}^{-1}$ is the TCR of the aGe thermistors.

As R_S is embodied by the substrate thermistor and therefore barely self-heated, its overtemperature ΔT is zero and its resistance value depends directly on the ambient temperature (1). For one specific value of the ambient temperature T_S , the condition $R_S = R_E$ holds and consequently $\beta = 0$ (cf equation (6)). Around this temperature, the relative change of I_{out} is very low and the output signal is practically independent of ambient temperature variations. Figure 13 shows the output current for $\Delta T = 15^\circ C$ and a specific ambient temperature value of about $T_S = 28^\circ C$. The relative deviation of I_{out} at $\pm 10^\circ C$ from the reference temperature T_S is less than 1%.

The relative change of the hot-film bridge voltage U_B with the ambient temperature in CTA mode is given by

$$\beta_{U_B} = \frac{dU_B}{U_B \cdot dT_{LAB}} = \frac{\alpha}{2} \quad (7)$$

and depends therefore on variations of the ambient temperature. However, for determination of the flow direction only the sign of U_B is needed, which is not affected by T_{LAB} , provided that a possible, temperature dependent offset is removed.

4. Stationary flow characterization

The same sensor packaging and measurement setup for experimental characterization was used in both operating modes CCA and CTA (figure 14). In order to achieve a tangential flow over the membrane, the sensor was incorporated in a printed circuit board (PCB) of about 1 mm thickness. A milled recess accommodates the sensor chip flush with the surface of the PCB. The gap between the sensor chip and the recessed walls was sealed using epoxy resin. Membrane destruction owing to possible large pressure variation can be avoided by implementing a pressure-compensation hole at the bottom of the PCB. Electrical connections between sensor chip and PCB were realized by gold wire-bonds protected by epoxy resin (figure 14(a)).

Standard 100 and 2000 sccm mass flow controllers were used to establish nitrogen gas flow. For stationary flow measurements, a PCB accommodating the flow sensor forms the bottom of a rectangular flow channel. A slit in a thin copper layer laid over the sensor surface forms a rectangular flow channel of 0.5 mm height and 1.2 mm width (figure 14(b)). Finally, the channel is covered with a plastic plate comprising flow in- and outlet connections. The flow direction in the channel is altered by simply switching the connections. With the known mass flow rate and cross-sectional dimensions of the channel, the average flow velocity as quantity of interest can be easily calculated.

4.1. CCA operating mode

The constant supply current of $150 \mu A$ was generated by a high-precision, temperature-stabilized current source. Figure 15 shows the measured and simulated thermistor voltage U_{TH} as well as the bridge voltage U_B . The thermistor voltage at zero flow depends mainly on the segment resistance at reference temperature (denoted by R_0 in (1)). Due to manufacturing tolerances, its value differs slightly for each sensor and also segment-wise inside one single specimen. Consequently, for different specimens, U_{TH} at zero flow also differs. Hence, to enable comparison between measurement and simulation results, the offset-corrected thermistor voltage $U_{TH} - U_{TH,offset}$ was used as output signal, where $U_{TH,offset} = U_{TH}(0)$ is the thermistor voltage at zero flow (figure 15(a)).

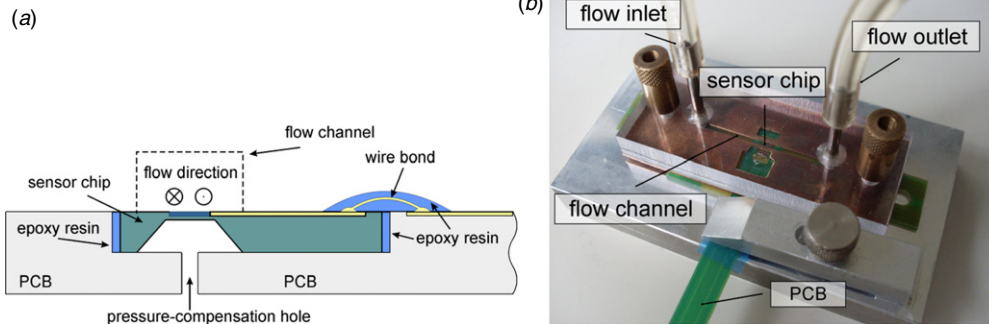


Figure 14. (a) Schematic cross-sectional view of the sensor mounted on the printed circuit board (PCB). A rectangular flow channel was placed above the sensor membrane. (b) PCB with the sensor chip incorporated in the wall of a miniaturized rectangular flow channel with cross-sectional dimensions $1.2 \times 0.5 \text{ mm}^2$.

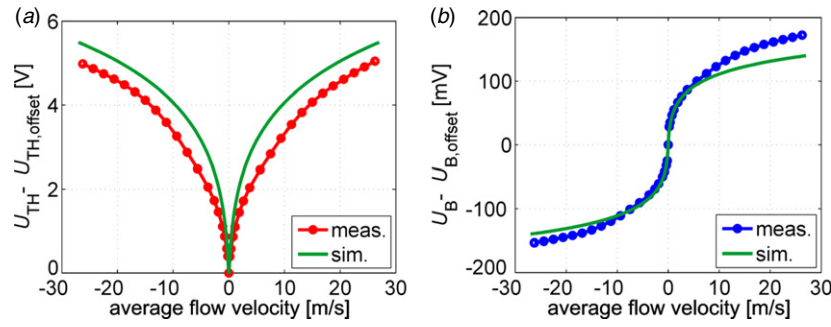


Figure 15. Comparison between simulation and measurement results for (a) an offset-corrected thermistor voltage U_{TH} and (b) an offset-corrected bridge voltage U_B in CCA mode with $I_0 = 150 \mu\text{A}$ and ambient temperature of 24°C . For the measured sensor specimen, $U_{TH,offset}$ amounts to approx. 14.8 V and $U_{B,offset}$ to approx. 16 mV .

The restrictions of the 2D FEM model are one of several reasons for the deviation between measurement and simulation of the thermistor voltage. In the 2D model, the hot film and the flow channel are assumed to be infinitely long in the y -direction (figure 3). However, the cooling of the hot film is influenced by the actual flow profile along the hot film as well as the parasitic conductive heat transfer perpendicular to the model plane. The latter can be investigated by means of thermography.

Infrared (IR) thermography is a convenient tool to investigate the temperature field of heated elements [22]. Based on measurements of the heat radiation, it facilitates contactless characterization and visualization of the temperature inhomogeneity [23]. To reduce the influence of the PCB on emitted heat radiation, the sensor chip was glued and bonded in such a way that the membrane projects beyond the edge of the PCB. The emissivity correction was established by a direct two-point calibration measurement to allow for proper temperature readout. For this purpose, the sensor specimen was placed at the bottom of a small temperature chamber attached to a Peltier temperature controller to realize isothermal conditions inside. Finally, the sensor membrane was aligned perpendicularly to the optical axis of the IR-camera. We used a high-resolution IR thermography system featuring an InSb sensor array with a spectral sensitivity from 2 to $5.5 \mu\text{m}$ wavelength (InfraTec, Image IR 8300 [24]). The applied germanium microscope lens enables a spatial resolution of $6 \mu\text{m}$ per pixel.

Figure 16(a) shows a thermogram of the sensor bottom with focus on the membrane and the hot film. The underside view was chosen since the embedded hot film lies closer to the bottom membrane surface. Moreover, the microfabricated cavity with the shape of a truncated pyramid below the membrane reduces the effect of natural convection. Thus, the obtained pictures appear somewhat clearer. The sensor was operated in CCA mode with $150 \mu\text{A}$ supply current without any flow.

The hot-film overtemperature obtained by means of resistance measurement comes to about 44°C . However, it represents a mean value of the entire hot-film area. The simulated mean overtemperature also amounts to approximately 44°C (figure 6). Figure 16(b) depicts temperature profiles in the x - and y -directions across the hot film. The highest overtemperature as well as the mean temperature of the hot film deduced from the thermogram

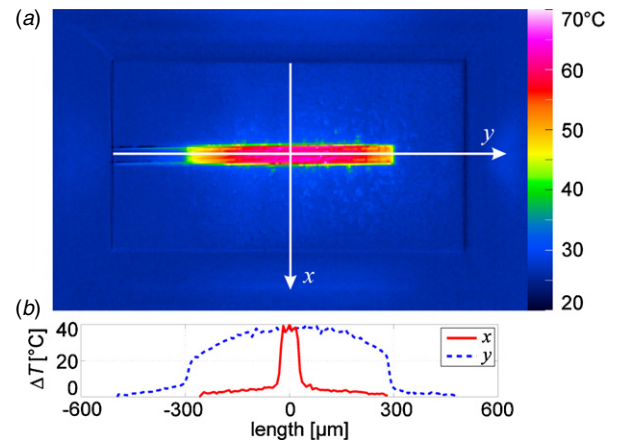


Figure 16. (a) Thermogram of the bottom membrane area in CCA mode with $150 \mu\text{A}$ supply current at zero flow and an ambient temperature of $T_{LAB} = 25^\circ\text{C}$. (b) Temperature profiles in x - and y -directions across the membrane with the hot-film midpoint as origin (membrane dimensions: $500 \times 1000 \mu\text{m}^2$, hot-film dimensions: $45 \times 600 \mu\text{m}^2$).

amount to approximately 40 and 30°C , respectively. Insufficient calibration of the emissivity due to semi-transparent sensor chip and associated diffuse radiation are reasons for a reduced output thermography signal.

The highest overtemperature value is reached in the middle of the hot film. Towards the hot-film edge along the metal strips in the y -direction the overtemperature is gradually decreasing. At the outmost right edge (around $300 \mu\text{m}$ in figure 16(b)) it lies almost 15°C below the highest value and decreases subsequently abrupt towards ambient temperature of 25°C . This indicates significant conductive heat transfer into the silicon substrate perpendicular to the intended flow direction. At the left edge of the hot film, the temperature is even a few degrees lower. Here, heat conduction along the metal strips additionally cools down the hot-film area. Therefore, the temperature decreases towards the silicon rim only gradually.

Owing to the limited spatial resolution of the camera ($6 \mu\text{m}/\text{pixel}$), the effect of the metal strips on the temperature distribution in x -direction cannot be well resolved. However, the visible ripple indicates the enhanced heat transfer due to the strips.

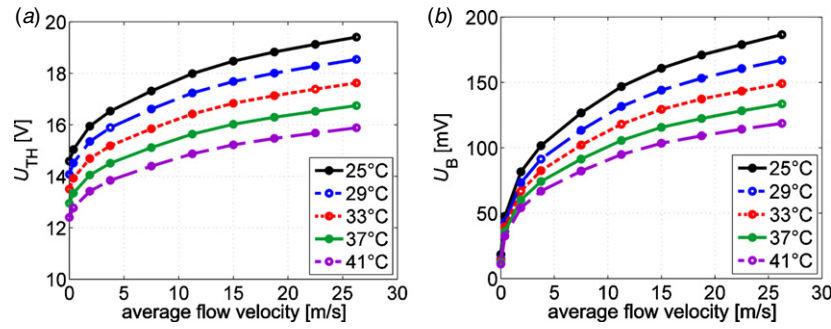


Figure 17. (a) Measured thermistor voltage U_{TH} and (b) bridge voltage U_B as a function of the average flow velocity for different ambient temperatures T_{LAB} (CCA mode with $I_0 = 150 \mu A$). The characteristics can be used to build look-up tables, in order to compensate for the variation of T_{LAB} .

The applied 2D FEM model (figure 3) arises from a cross-section in the middle of the hot film $y = 0$. Therefore, this model does not account for temperature gradients in the y -direction. This is the main reason for the slight mismatch between simulation and measurement results in figure 15(a). Moreover, uncertainties in the thermal parameters used for the silicon nitride membrane and the embedded elements as well as the deviations of the layer thickness owing to manufacturing tolerances may additionally influence the output characteristic.

If the hot-film segments are not exactly the same or at least symmetrically arranged regarding the hot-film midpoint (i.e. if $R_1 \neq R_4$ and $R_2 \neq R_3$, figures 1 and 4), the bridge voltage (3) exhibits an offset at zero flow, which must be subsequently removed. An offset-corrected bridge voltage U_B in comparison with the simulation results is depicted in figure 15(b). As expected, the measured characteristic is bipolar but not exactly an odd function of the average flow velocity. Owing to the deviation of the resistance values R_i of the hot-film segments, the heat dissipation is not perfectly symmetrical regarding the flow direction.

Since the bridge voltage is only used as an indicator for the flow direction, the asymmetry of the U_B characteristic has no impact on the sensor functionality, provided that the offset is ascertained and accounted for. Nevertheless, manufacturing tolerances also affect the even symmetry of the U_{TH} characteristics (figure 15(a)), even though much less than is the case for the bridge voltage U_B . Thus, for precise flow velocity measurements, the sensor must be calibrated in both flow directions.

Temperature dependence of the sensor was investigated on the assumption that fluid and sensor chip exhibit the same temperature. To establish this condition, a 10 m long copper tube with 4.4 mm inner diameter is inserted up-stream to the flow inlet. The coiled-up tube and the sensor chip are subsequently placed into a thermal chamber. Temperature is measured at the flow inlet, near the sensor chip, and at the chamber wall. After the flow through the long metal tube, the fluid temperature at the sensor inlet is independent of the initial fluid temperature and approximately the same as the chip (i.e. chamber) temperature. Using this setup it is possible to adjust the ambient temperature of the measurement setup with $\pm 0.1^\circ C$ accuracy.

For the characterization, the temperature of the chamber was changed in $2^\circ C$ steps in a range between 25 and

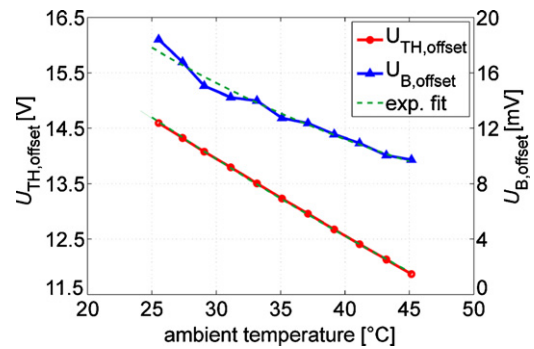


Figure 18. Dependence of U_{TH} and U_B on the ambient temperature for zero flow (CCA mode with $I_0 = 150 \mu A$). Dashed lines indicate the fit with an exponential function.

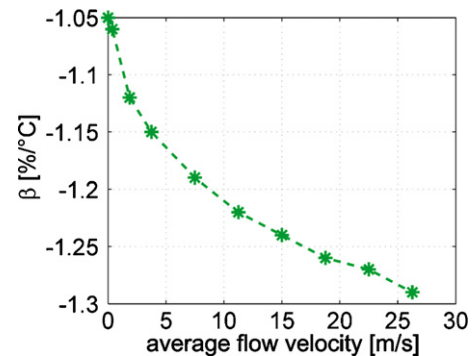


Figure 19. Mean temperature coefficient of U_{TH} as a function of the flow velocity (CCA mode with $I_0 = 150 \mu A$).

$45^\circ C$ while the thermistor and bridge voltages were recorded. Figure 17 depicts representative characteristics. Both U_{TH} and U_B feature NTCs, i.e. their value decreases with increasing ambient temperature. This can be best illustrated if the velocity is kept constant and only the temperature dependence of the voltage is shown. Results obtained for zero flow, i.e. for $U_{TH,offset}$ and $U_{B,offset}$, are depicted in figure 18.

Both characteristics were subsequently fitted with an exponential function (dashed lines). This procedure is convenient, as the temperature coefficient (TC) can be deduced directly from the exponent of the fitting expression. However, it gives a mean TC over the whole measurement range of the ambient temperature. In contrast, the simulation results in figure 9 show the actual TC as a relative change of the voltage for each single value of ambient temperature. Figure 19

depicts the mean TC of U_{TH} for all measured velocity values. As predicted by FEM simulations and equation (5) (in CCA mode, U_{TH} is directly proportional to the resistance of the hot-film bridge), the mean TC decreases with increasing flow velocity.

In applications where large variations of the ambient temperature are expected, the temperature dependence of the output signal must be taken into account. For this purpose, the ambient temperature is monitored by one of the substrate thermistors that is connected in series with the hot film (figure 4). Since the substrate thermistor is cooled by the silicon bulk, its overtemperature is approximately zero. Due to constant supply current and equation (1), the voltage across this thermistor is solely an exponential function of the ambient temperature. Thus, a logarithmic amplifier can be used to derive T_{LAB} . With a known ambient temperature, look-up tables based on the characteristics presented in figure 17 enable precise corrections of the output signal.

However, this method requires extensive sensor characterization (to gain the look-up tables) and high computational power (to achieve real time value corrections). Another, less complex method is to utilize the average TC β_{av} . The measured thermistor voltage U_{TH} is a function of flow velocity and ambient temperature

$$U_{TH}(v, T_{LAB}) = U_{TH,ref}(v) \cdot e^{\beta_{av}(T_{LAB} - T_{ref})}, \quad (8)$$

where $U_{TH,ref}$ is the thermistor voltage measured at reference temperature T_{ref} (e.g. results in figure 15 at $T_{ref} = 24^\circ\text{C}$). If the output signal is measured at a different ambient temperature, it can be corrected by multiplication with an appropriate function f_{corr} :

$$U_{TH,ref}(v) = U_{TH}(v, T_{LAB}) \cdot f_{corr}, \quad (9)$$

$$f_{corr} = e^{-\beta_{av}(T_{LAB} - T_{ref})}.$$

Here, β_{av} is the average TC for a certain flow range (e.g. $\beta_{av} = -1.2\%/^\circ\text{C}$ in a range up to 25 m s^{-1} , figure 19). Applying the inverse function of $U_{TH,ref}(v)$ yields a precise value of the flow velocity v . The second correction method is particularly suitable for flow monitoring in a narrow flow range at variable ambient temperature.

In order to investigate the minimal resolvable flow as well as the sensor resolution, the mass flow controller with 100 sccm flow range was used. It enables average flow velocities down to 1.5 mm s^{-1} . Figure 20 depicts results for the flow range up to 1 m s^{-1} . For very slow flow, the offset-corrected thermistor voltage U_{TH} becomes negative (figure 20, inset). In this range, the overtemperature of the last downstream segment increases due to convective heat transfer from other segments. Above approximately 13 mm s^{-1} , the convective cooling becomes the predominant effect and the output signal changes its sign.

The sensor resolution can be estimated from the sensitivity S (i.e. the slope of the characteristic) and the noise of the output signal. We define the noise equivalent resolution as

$$\delta v = \frac{3 \cdot \delta X}{S}, \quad (10)$$

where δX is the standard deviation of a respective sensor output (U_{TH} or I_{out}). The standard deviation of the thermistor voltage δU_{TH} was estimated by measuring 100 samples of U_{TH} at

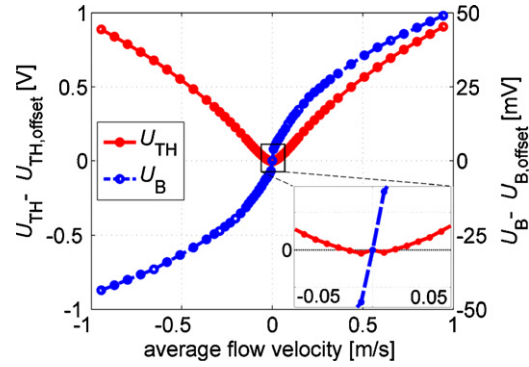


Figure 20. Offset-corrected thermistor voltage U_{TH} and bridge voltage U_B for a velocity range up to 1 m s^{-1} in CCA mode with $I_0 = 150\text{ }\mu\text{A}$. The inset shows the results for very low velocity range below 5 cm s^{-1} .

a multimeter gate time of one power-line cycle (20 ms) in order to suppress the crosstalk from ac power supply. The equivalent resolution was determined for three different supply current values 100, 125, and $150\text{ }\mu\text{A}$. More current, and hence more power, means increasing transduction efficiency but also increasing sensor noise. Both the sensitivity and the standard deviation are approximately linearly dependent on the supply current. This indicates that the dominant noise source is $1/f$ noise and not Johnson noise, which is proportional to the square root of the temperature [19, 25]. The best sensor sensitivity is achieved in a very low flow range and amounts to approximately 1.5 V (m/s)^{-1} at $150\text{ }\mu\text{A}$ supply current. As the sensitivity S and the noise level depend on the flow velocity, the sensor resolution (10) is also flow dependent. The resolution is better than 15 mm s^{-1} over the whole measurement range, whereas the best value for a low flow amounts to approximately $\delta v = 0.5\text{ mm s}^{-1}$. If a higher resolution is needed, averaging must be applied at the expense of response time.

4.2. CTA operating mode

The value of the overtemperature in CTA mode can be easily determined by the design of the substrate thermistor R_S . Its resistance depends only on the ambient temperature T_{LAB}

$$R_S = R_{S0} \cdot e^{\alpha \cdot T_{LAB}}, \quad (11)$$

where R_{S0} is the resistance at $T_{LAB} = 0^\circ\text{C}$. The value of R_{S0} in conjunction with R_0 determines the mean hot-film overtemperature ΔT . The controller adjusts I_{out} to establish the condition $R_{TH} = R_S$. The resistance of R_{TH} can be described by (1) with ΔT instead of ΔT_i . Therefore, ΔT is given by

$$\Delta T = \frac{\ln\left(\frac{R_{S0}}{R_0}\right)}{\alpha}. \quad (12)$$

Each sensor chip bears two different R_S thermistors located on the silicon bulk at the upper part of the chip (figure 1). We fabricated two sensor embodiments with substrate thermistors enabling 10, 15, 20 and 25°C overtemperatures. Figure 21 depicts a comparison of measured and simulated data for approximately $\Delta T = 15^\circ\text{C}$ corresponding to $R_{S0} = 291\text{ k}\Omega$.

Again, we use offset-corrected outputs in order to compare measurement and simulation. The deviations are more

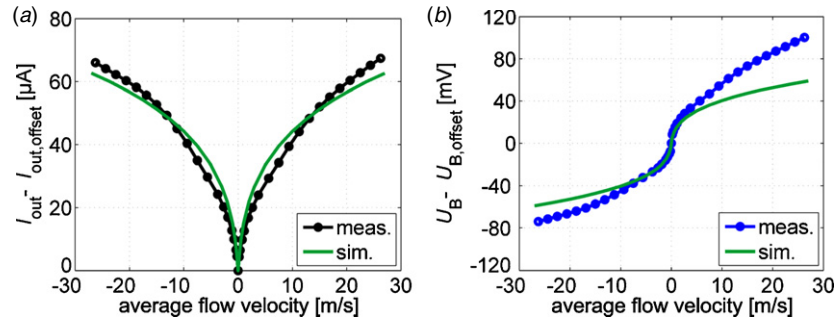


Figure 21. Comparison between simulation and measurement for (a) an offset-corrected output current I_{out} and (b) an offset-corrected bridge voltage U_B in CTA mode with $\Delta T = 15^\circ C$.

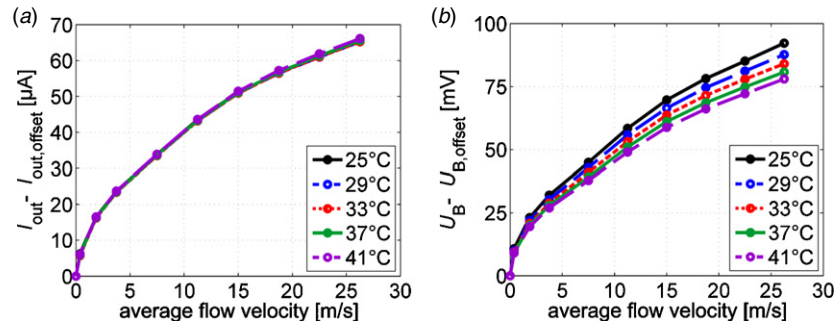


Figure 22. (a) Measured offset-corrected output current I_{out} and (b) offset-corrected bridge voltage U_B as a function of the average flow velocity for different ambient temperatures T_{LAB} (CTA mode with $\Delta T = 15^\circ C$).

emphasized in the bridge voltage characteristic (figure 21(b)). As the mean overtemperature ΔT in CTA mode is kept constant, the differences in the resistance value of the hot-film segments due to manufacturing tolerances yield a stronger effect than in CCA mode.

One of the major advantages of the CTA mode is the low dependence of the output characteristic regarding the variation of the ambient temperature. The relative change of the output current with the ambient temperature (6) depends on the substrate thermistor R_S and the external resistor R_E placed in the other leg of the outer Wheatstone bridge (figure 10). The value of R_E should be chosen in a way that for a desired specific ambient temperature T_S , R_E is equal to R_S (see (11) with T_S instead of T_{LAB}). Around T_S , the TC of the I_{out} (6) is very low and the output characteristic is almost independent of the ambient temperature variations.

Figure 22 depicts offset-corrected output characteristics for different ambient temperatures. In case of output current I_{out} , all curves are close to each other indicating the temperature independence. Results for one constant velocity $v = 22.5 \text{ m s}^{-1}$ are illustrated in figure 23. The value of R_E was chosen to achieve the minimal temperature dependence around $T_S = 30^\circ C$ ambient temperature. 10° higher, the relative change of the output signal amounts to only 1.5%, which is for many applications accurate enough. Hence, in CTA mode complex correction methods of the output signal are not necessary. However, a proper offset correction is mandatory as both $I_{out,offset}$ and $U_{B,offset}$ are temperature dependent. Their temperature characteristics vary from specimen to specimen and must be recorded before the flow measurements. During sensor operation, the ambient temperature is monitored by one

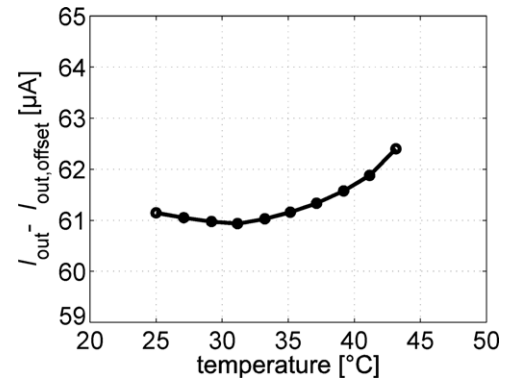


Figure 23. Dependence of the offset-corrected output current on ambient temperature in CTA mode with $\Delta T = 15^\circ C$ and $R_E = 163 \text{ k}\Omega$.

of the substrate thermistors and the offset is removed using the corrected value of $I_{out,offset}$ and $U_{B,offset}$.

Figure 24 shows output characteristics for low flow range up to 1 m s^{-1} . In contrast to U_{TH} in CCA mode (figure 20, inset), the offset-corrected I_{out} does not change its sign (figure 24, inset). As the controller maintains the average overtemperature of the hot-film constant, the calorimetric heating of the last downstream segment for very low flow is not dominant. Hence, the offset-corrected output current is positive for all velocity values and the minimal resolvable flow depends only on the sensor resolution and the total noise.

The standard deviation was measured under the same conditions as in CCA mode. The maximum sensor sensitivity S in CTA mode achieved in a very low flow range amounts to approximately $16 \mu A (\text{m/s})^{-1}$. The sensor resolution (10)

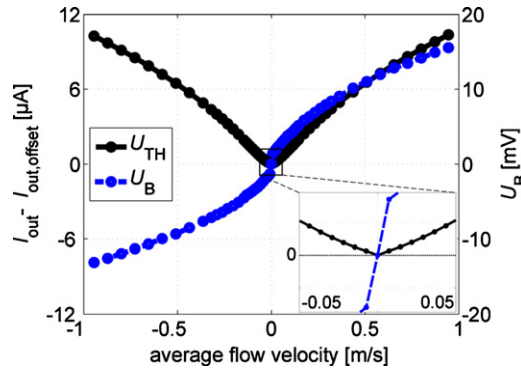


Figure 24. Offset-corrected output current I_{out} and bridge voltage U_B for a velocity range up to 1 m s^{-1} (CTA mode with $\Delta T = 15^\circ \text{C}$). The inset shows the results in the very low velocity range (below 5 cm s^{-1}).

depends again on the flow velocity. In the low flow range the best resolution amounts to approximately $\delta v = 1 \text{ mm s}^{-1}$. Over the whole measurement range it does not exceed the value of 30 mm s^{-1} . In comparison to the first mode, the CTA mode features a lower minimal resolvable flow since the characteristic is always positive, but the sensor resolution is worse. The latter is mainly due to worse sensitivity (as a consequence of lower overtemperature) and an additional noise arising from the control circuit, which comprises two thermistors (R_{TH} and R_S in figure 10).

5. Dynamic characterization

Dynamic characterizations are important in order to ascertain the sensor response to turbulent and fast-changing flows. Due to miniaturization, the thermal mass of the sensor chip is low facilitating fast response. The dynamic characterization was performed only for CCA mode because the properties of the applied electronic controller additionally influenced the response time of CTA operation.

We chose a large signal FEM analysis of the dynamic sensor response to study the sensing behaviour in highly dynamic gas flows. In a first step, the simulated stationary output characteristics $U_{TH}(v)$ and $U_B(v)$ (figure 15) have been fitted and the resulting polynomial functions were used to deduce the inverse characteristics $v_{TH} = f_{TH}(U_{TH})$ and $v_B = f_B(U_B)$. In the next step, the sinusoidal flow variations were assumed with a mean value of $v_{in,0} = 10 \text{ m s}^{-1}$ and amplitude of 5 m s^{-1} . The resulting voltage waveforms $U_{TH}(t)$ and $U_B(t)$ were then transformed into velocity signals $v_{TH,out}(t)$ and $v_{B,out}(t)$ using the inverse functions f_{TH} and f_B and subsequently compared to the input flow signal v_{in} . Figure 25 depicts a comparison of peak-to-peak magnitudes ($20 \log(v_{out,pp}/v_{in,pp}) \text{ dB}$) and phase angles ($\Delta\phi$) between input and output signals in a logarithmic frequency scale. The phase difference $\Delta\phi$ was defined as the delay of subsequent crossings of the signal with the respective mean line multiplied by $360^\circ/T$, where T is the signal period. Moreover, the mean value of the output signals is also shown. Owing to the nonlinear transduction and the utilization of the stationary characteristics (figure 15) to gain v_{out} , the output mean flow velocity is frequency dependent.

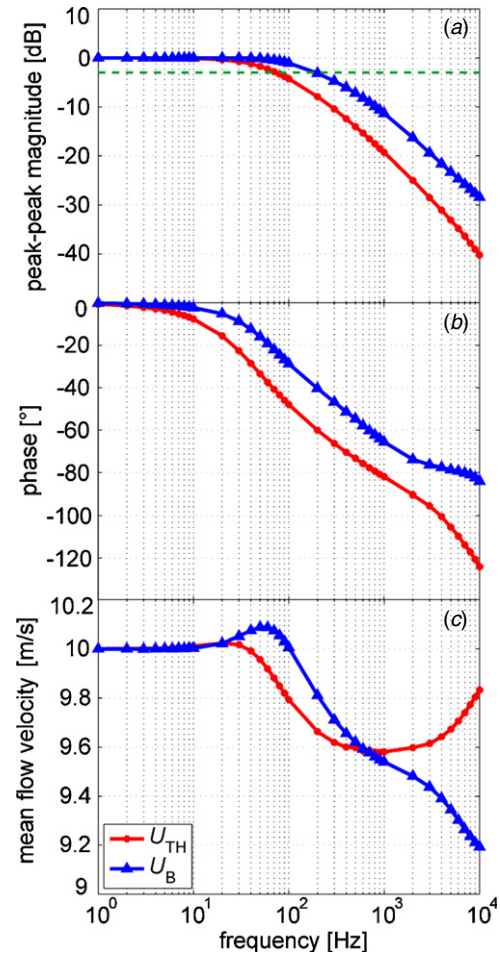


Figure 25. Comparison of simulated results: (a) peak-to-peak magnitudes and (b) phase angles between v_{in} and v_{out} as well as the output mean flow velocity (c) as a function of frequency of the input flow signal. Dashed line represents -3 dB threshold.

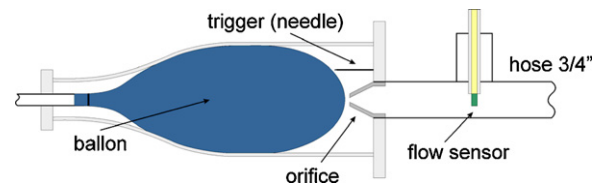


Figure 26. Cross-sectional view of the arrangement used for the generation of flow steps. The sensor is placed centrally in the symmetry plane of the cylindrical flow channel (15 mm in diameter).

These theoretical results were supported by experiments utilizing a simple shock wave generator schematically depicted in figure 26. Inside a bottle-like containment, a balloon is blown up with nitrogen gas. The burst is triggered by a simple injection needle positioned at the opposite end of the containment. An orifice of approximately 2 mm in diameter limits the outflow to the adjoining cylindrical flow channel with a diameter of 15 mm. The resulting shock wave induces a step-like change of the flow in the channel. A subsequent 15 m long 3/4"-hose provides sufficient delay of shock wave reflections at the open end. In order to suppress turbulence, the sensor chip was glued and bonded at the top edge of a PCB instead of being incorporated flush with the PCB surface. The PCB

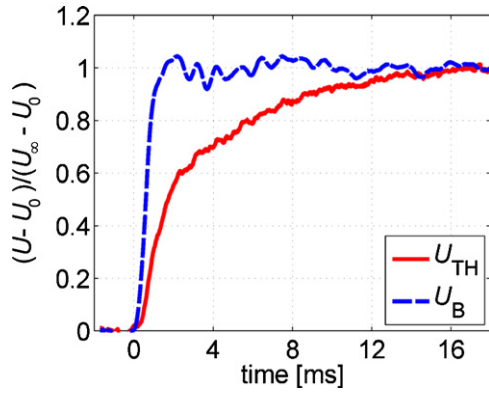


Figure 27. Relative response of the sensor outputs U_{TH} and U_B to step-like changes of the flow velocity (U_0 and U_∞ denote the initial and the final values, respectively).

carrying a sensor was then placed centrally in the symmetry plane, about 20 cm from the orifice. A minor disadvantage of this simple arrangement is lower reproducibility of the flow step amplitude, which depends on the actual burst pressure of each balloon.

A typical sensor response to a large flow step is depicted in figure 27. Significant noise reduction of the measured signal was achieved by applying a moving average procedure with a window size of $n = 7$ to the data sampled with $20 \mu\text{s}$ period. The signal course corresponds to a flow step from nearly zero to approximately 0.75 m s^{-1} . After the signal maximum of the bridge voltage U_B was reached, a ripple with a frequency around 1050 Hz is visible. With a sound speed for nitrogen of $c = 334 \text{ m s}^{-1}$ (at 25°C), the ripple frequency corresponds to a wavelength of about 32 cm and can be therefore attributed to an acoustic resonance inside the balloon containment.

The -3 dB cutoff frequency f_c of the peak-to-peak bridge voltage U_B in figure 25 amounts to approximately 200 Hz. The peak-to-peak thermistor voltage U_{TH} features a much lower dynamic range with a cutoff frequency around 75 Hz. With a rough assumption of a first order system, the 10–90% rise time can be calculated by

$$\tau_r = \frac{0.35}{f_c}. \quad (13)$$

Consequently, according to FEM prediction the response time to step-like changes of the flow velocity is in the range of 2 and 5 ms for U_B and U_{TH} , respectively. In contrast, the measured rise time is in the order of only one millisecond for U_B and about 8 ms for U_{TH} (figure 27). The experimental values differ slightly from the simulated predictions using large signal model. However, structure and geometry of the flow channel are completely different, which has a significant impact on the dynamics of the entire system.

6. Response to liquid flow

The described measurement setup used for the stationary flow characterization (figure 14) is best suitable only for gas flow measurements. A complex sealing procedure as well as a mandatory channel cleaning after each measurement series hamper the usage for liquid flows. Hence, to estimate the sensor characteristic for different liquids, FEM simulations were

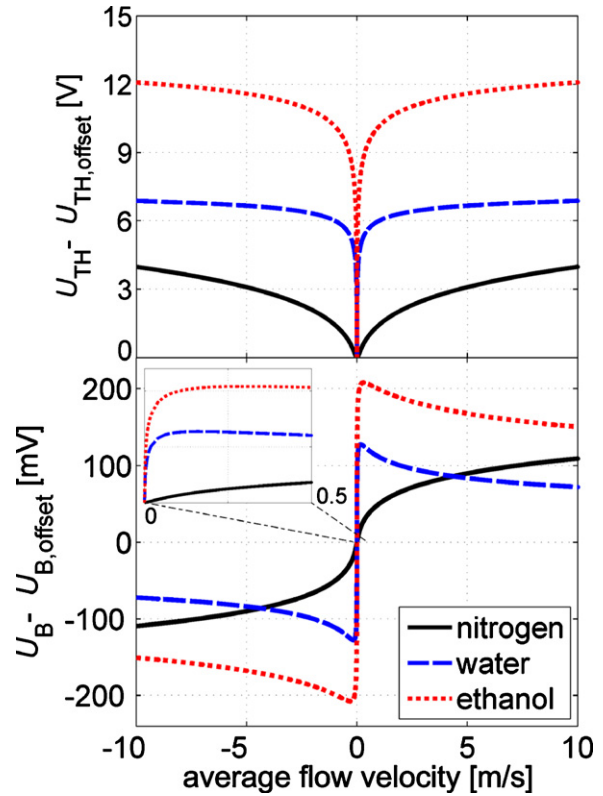


Figure 28. Simulated transduction characteristics for water and ethanol in CCA mode with $I_0 = 150 \mu\text{A}$. For comparison, the simulated characteristic for nitrogen flow is depicted too.

Table 1. Thermal properties of fluids used for the simulation. k , ρ , c_p and α are thermal conductivity, mass density, specific heat capacity and thermal diffusivity, respectively.

	$k \text{ (W K}^{-1} \text{ m}^{-1})$	$\rho \text{ (kg m}^{-3})$	$c_p \text{ (J kg}^{-1} \text{ K}^{-1})$	$\alpha \text{ (m}^2 \text{ s}^{-1})$
Nitrogen	0.026	1.204	1038	2.08×10^{-5}
Water	0.598	998.2	4182	1.43×10^{-5}
Ethanol	0.165	789	2430	8.61×10^{-5}

performed with water and ethanol as representative sample liquids.

Figure 28 summarizes the corresponding simulation results and depicts, for sake of comparison, also the characteristic for nitrogen flow. The output characteristics depend mainly on the thermal parameters of the fluids. Table 1 provides an overview of the fluid parameters used for the simulations. Liquids feature a much higher product of density and specific heat capacity ρc_p than gases. Therefore, the flow dependence of the output signal is generally stronger for liquids than for nitrogen gas.

Due to extensive heat convection in the liquids, the related characteristics show a very high initial sensitivity. Moreover, the thermistor voltage U_{TH} saturates and the bridge voltage characteristic U_B becomes non-monotonic. The latter is typical for calorimetric transduction principle where the spatial temperature difference determines the output signal. The difference between the temperature of the first segment and adjoined downstream segments increases initially with rising flow velocity (cf figure 7, for nitrogen). Beyond the maximum of U_B , it decreases gradually with increasing

velocity as a consequence of convective cooling which is more efficient for liquids. The maximum of the U_B characteristic shifts to lower values of the flow velocity for increasing thermal capacity of the fluid (inset of figure 28). Because of the minimized lateral extension of the hot-film segments, the characteristic for nitrogen gas is monotonic up to the highest investigated flow rates. The dynamics of both output characteristics, i.e. their initial slope and their maximum value, is a complex function of all thermal parameters as well as the geometry of the flow channel and the hot film.

The saturation of the output characteristic in the case of liquids limits the useful flow range to only a few metres per second. However, the extremely high sensitivity (the slope of the characteristic) in the low flow range can be favourably utilized to monitor the variation of liquid properties like viscosity. According to Hagen–Poiseuille’s law, the higher dynamic viscosity at the constant pressure drop, the lower average velocity in the flow channel. The low velocity variations induced by a viscosity change can be therefore easily detected by the flow sensor.

7. Summary and conclusions

We reported on the simulation-based sensor design and measurement results of a bidirectional micromachined hot-film anemometer. The sensor is based on a thin-film thermistor made of aGe embedded in a silicon nitride membrane. The germanium hot film is divided by metal-strip electrodes into four thermistor segments which are connected to form a Wheatstone bridge.

The sensor was experimentally characterized in CCA and CTA operating modes. In the CCA mode, the hot-film bridge is supplied with a constant current. The voltage across the bridge supply terminals is used as a unipolar output signal. Due to the nonlinear temperature characteristic of aGe, the sensor output in CCA mode is not independent of the ambient temperature T_{LAB} . The variations of the ambient temperature must be taken into account by means of look-up tables or complex correction algorithms.

In the CTA mode, a control loop adjusts the thermistor current to maintain a constant hot-film overtemperature ΔT . The overall controller current is a function of the flow velocity featuring a unipolar characteristic. In this mode, the relative error of the output signal caused by variations of the ambient temperature in the range of ± 10 °C around one specific T_{LAB} value amounts to only about 1%.

In both modes, the convective heat transfer between the hot-film segments results in thermal asymmetry giving rise to a bridge detuning voltage U_B with a bipolar characteristic after offset correction. Utilizing its sign, the flow direction can be detected. Thus, the presented sensor layout features a strictly monotonic transduction characteristic over a wide flow velocity range combined with simultaneous detection of the flow direction.

The sensor design was supported by FEM modelling. Comparison between measured and simulation results reveals in part relative high deviations. Besides the utilization of a simple 2D model which neglects, e.g., interconnecting leads,

this is mainly due to manufacturing tolerances of the resistance values of hot-film segments. Nevertheless, the simulation results are accurate enough to get a trend of the output characteristics and to estimate the dynamics of the output signal.

Besides the stationary flow characterization, the sensor response to a fast-changing flow was also investigated by means of FEM simulations and experimentally. The rise time for step-like changes of the flow velocity is in the range of 8 ms for thermistor voltage and around 1 ms for the bridge voltage.

Sensor characteristics for different liquids have been estimated with FEM simulations. For water and ethanol both characteristics show very high initial sensitivity. Due to extensive cooling, the thermistor voltage saturates, whereas the bridge voltage characteristic even becomes non-monotonic limiting the useful flow range to a few $m s^{-1}$ only. However, this behaviour can be utilized for online condition monitoring of liquid properties such as viscosity or thermal conductivity.

Acknowledgments

We kindly acknowledge the financial support by Austrian Science Fund (FWF), project number L657-N16. Furthermore, the authors would like to thank Artur Jachimowicz, Johannes Schalko, Sophia Ewert as well as Peter and Edeltraud Svasek for their support in the fabrication of the sensor device.

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