Advanced Thermal Flow Sensors

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Miniaturized flow sensors composed of a thin membrane supporting appropriately positioned heating resistors and temperature sensors were studied by computer-numeric analysis. Significant improvements of steady-flow transduction characteristics as well as responses to step-like changes of the dissipated power are feasible by design modifications and new transduction schemes.

Introduction

Calorimetric flow sensors are preferable devices for limited space applications in mass products like cars or domestic appliances. They are well-known for ruggedness, sensitivity, and fast response, each of which may be achieved using MEMS technologies. After a brief description of state of the art designs, we discuss new concepts enabling faster response, enhanced transduction efficiency, improved durability as well as means for in-service monitoring of the functionality.

Theory

Calorimetric flow sensors rely on flow dependent heat transfer altering the temperature distribution close to a small heat source. The temperature field is probed at a few preselected sites. Based on these recordings, a representative characteristic of the flow field is determined using suitable calibration information. The cross sectional view depicted in Fig. 1 is typical for the majority of micromachined versions of calorimetric flow sensors.

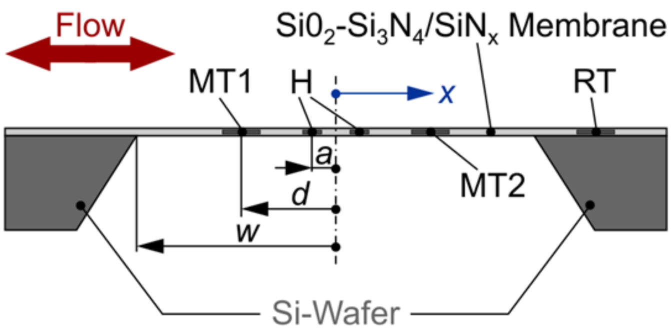

Fig. 1: Schematic cross section of a typical calorimetric flow sensor design

The heating resistor H generates a temperature profile in the membrane and the surrounding fluid. Due to convective heat transport, the profile is altered if the fluid flows along the membrane surface as indicated. Local changes of the temperature profile are probed using the thermistors MT1 and MT2. Flow related information can be derived from variations of their temperature difference $T_{MT1}-T_{MT2}$ wherein the subscripts indicate the measuring site. In contrast to hot-wire and hot-film anemometers, calorimetric sensors offer flow direction information in principle.

More refined structures employ larger one-dimensional arrays of temperature sensors to optimize the sensitivity over a wide measuring range [1], whereas two-dimensional arrangements of these components are used to gain directional resolution [2]. To achieve high sensitivity and fast response, all essential components are made by thin-film technology, and they are embedded in an extremely thin membrane.

Experimental

Sample Preparation

Figure 2 depicts the usual placement of thin-film components on the membrane which measures 1 mm in length and 0.5 mm in width. A KOH based anisotropic wet etch process and backside lithography is used to shape this membrane. A closer examination of the pattern reveals a 10 µm misalignment caused by the backside lithography step. Further details of the technology and key specifications of such sensors can be found elsewhere [3], [4].

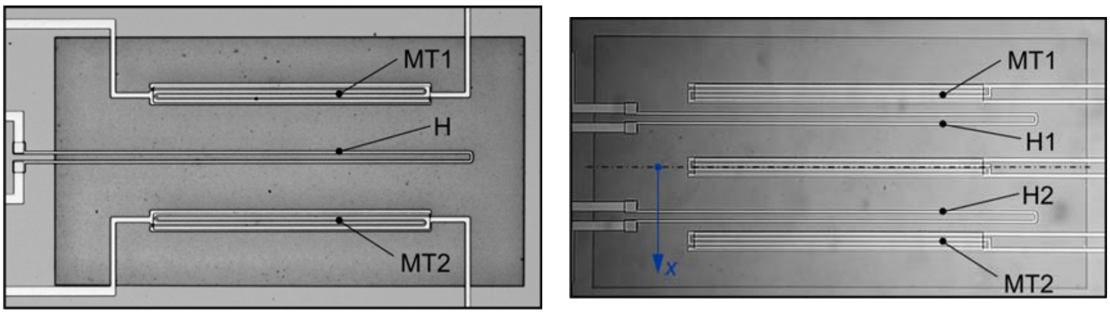

Fig. 2: Top view of the membrane area of a flow sensor featuring a common layout (left) and alternative design (right). The latter uses two equal-valued heating resistors together with the top and bottom thermistors. Highest sensitivity is achieved for flows in ± *x*-direction.

With an alternative arrangement of components on the membrane shown in Fig. 2, the specifications and monitoring capabilities can be significantly improved. For comparison, equally sized membranes, series connection of heating resistors, and only MT1 and MT2 are used. We investigated the progress achievable by these design improvements using finite element (FE) computations. The analysis is based on a two-dimensional (2D) FE model corresponding to the cross section shown in Fig. 1. The results presented below were obtained using COMSOL Multiphysics. Based on the Navier-Stokes equations for incompressible fluids, air-flow velocity fields were calculated approximately. The temperature dependencies of fluid viscosity, density, heat capacity, and thermal conductivity were not considered. Thus the effects of natural convection were neglected throughout the model. To reduce the computational effort, a uniform flow profile was assumed at the model inlet, which is situated 0.5 mm upstream of the heater. Due to the sticking of the fluid at the sensor surface, typical flow boundary layers emerge. However, this simplification ignores the fluid displacement due to the finite thickness of the sensor chip, which would inevitably occur if the bare flow sensor chip was inserted into a homogeneous flow field. All computed FEM results are in good agreement with experiments [3], [4]. Hence, the 2D FEM analysis is an appropriate tool to predict the behavior of new sensors designs.

Four main areas of significant improvement of the performance of common calorimetric flow sensors were identified, which can be achieved by design modifications and modified transduction schemes, i.e., without any change of technological processes.

These fields are (i) improved sensor dynamics, (ii) reduction of the thermal stress acting on the sensor membrane, (iii) improvement of existing tools and new possibilities for in-service operability checks, and (iv) removal of the saturation of the transduction characteristics at very high flow velocities.

Common Design versus Alternative Approach

Constant excess temperature operating modes are based on closed loop control of temperature(s) at specific site(s) on the membrane by means of the heating resistor. Actually, the mean excess temperature of the membrane thermistors $\Delta T = T_{MT1}+T_{MT2}$ is controlled (enhanced CT mode). Figure 3 shows computed temperature profiles of the enhanced CT mode for the indicated set of free-field air velocities. All curves of the diagram are normalized to $\Delta T = 1$. In case of high flow velocities and a standard design, the temperature response to variations of the heating power becomes very small at the site of MT1 and the thermal output at very high flow rates saturates at $|T_{MT1}-T_{MT2}| \rightarrow 2{\bullet}\Delta T$. Thus, an in-service check of the functionality of the upstream temperature sensor is hindered considerably. The improved design provides a much larger excess temperature at the upstream thermistor site. Thus the functionality of MT1 can easily be monitored during sensor operation. Moreover, this marked improvement is obtained in spite of the moderate maximum excess temperature of $2.3{\bullet}\Delta T$.

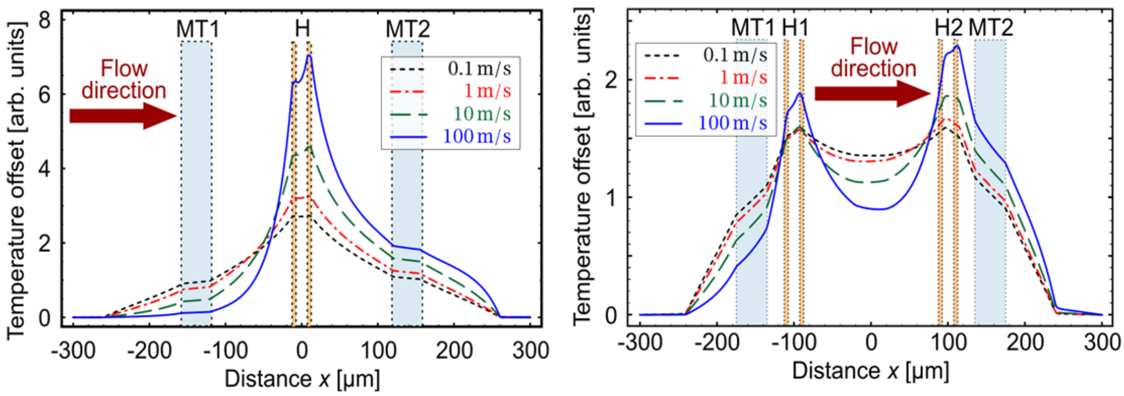

Fig. 3: Temperature profiles across the membrane region of flow sensors (left: standard design, right: alternative design) when operating in the enhanced CT mode.

It can be seen that the maximum of the temperature offset is located near the downstream heater trace. It grows with rising flow velocity by a factor of three up to the sevenfold of ΔT. Compared to the standard CT mode, the enhanced CT mode offers a higher thermal output $|T_{MT1}-T_{MT2}|$ by the same factor.

The thermal delay between heater and membrane temperature sensor limits the achievable performance of the control loop employed by the enhanced CT operational mode. The calculated responses to step-like changes of the heating power are shown in Fig. 4 for both designs.

Due to the smaller distance between heater and adjacent thermistor, the new sensor design exhibits significantly lower delays. For the enhanced CT operation mode, a much faster response to sudden flow changes can be achieved with the new design.

The sensor characteristics of the standard and the advanced design are also shown in Fig. 4 for both, the CP and the enhanced CT mode. The characteristics of the new design are shifted up by a factor of two approximately to coincide with those of the standard design at low flow velocities. The reduced useful transduction range of the CP mode due to the non-monotonous characteristics becomes obvious. As outlined above, the transduction characteristic of the standard sensor design saturates at high flow velocities even in the enhanced CT mode. Due to the closer spacing of heater and neighboring temperature sensor, the saturation of the transduction characteristic of the improved design occurs beyond the investigated flow range. In terms of resolution at high flow velocities the new design outperforms the conventional device significantly.

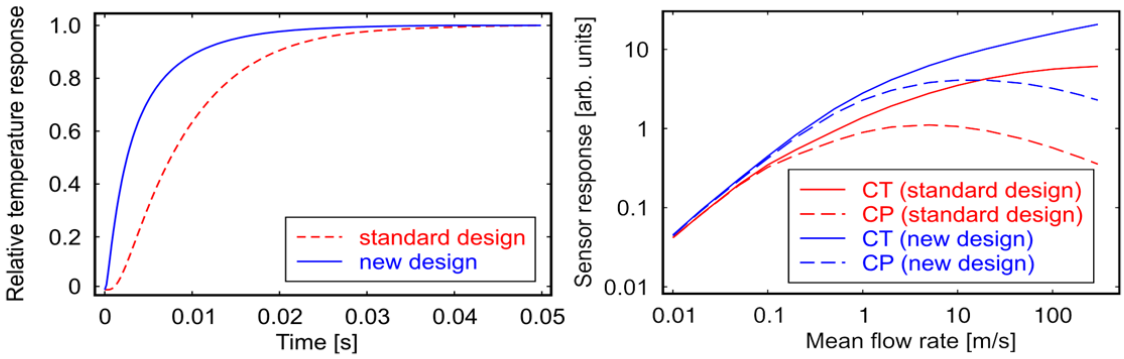

Fig. 4: Left: Zero-flow temperature sensor response to step like changes of the power dissipated by the neighboring heater. Right: Flow responses calculated for each sensor design and two operating modes

Conclusion

FEM analysis of calorimetric flow sensors proved that faster response, extended measuring range, reduced thermal load, and improved in-service functionality monitoring is obtainable at the same time through more sophisticated arrangements of heat sources and temperature sensors on the sensor membrane.

Acknowledgements

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