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Flexible Flow Sensors for Air Conditioning Systems Based on Printed Thermopiles

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Abstract

Air conditioning systems need permanent monitoring of the mass and energy flows in air ducts to assess their proper operation and detect and correct changes that may occur with time. This is a prerequisite for optimization in terms of energy efficiency. Such distributed monitoring systems require low-cost and robust flow sensors that must not be extremely precise, but give a good indication of the flow distribution within the air conditioning system. In this paper we present a novel flow sensor based on thick-film thermopiles deposited by silk-screen-printing on a plastic carrier. The flexible printed thermopile transducer was characterised in a flow channel to demonstrate the feasibility of the technology for air conditioning systems. The transducer exhibits a strictly increasing behaviour with increasing flow velocity, which is in good agreement to FEM simulations.

Keywords: Flow Transducer, Thermopile, Thick-Film, Screen-Printed Sensor, Air Condition

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1. Introduction

Ventilation and air conditioning systems contribute significantly to the overall energy consumption of a building. However, after installation and commissioning, they are hardly ever evaluated, let alone optimized with respect to their efficiency during normal operation. One reason for this – apart from a lack of awareness of installers and operators – is the lack of efficient possibilities for distributed monitoring of the system, especially for larger installations. Still, analyses show that up to 40% of energy could be saved by improved control strategies [1]. Flow sensors used in air conditioning systems should be easy to install, cost effective, and robust. Micromachined thermal flow sensors based on thin-film technology are known to be very sensitive [2, 3]. However, they are fragile, and the

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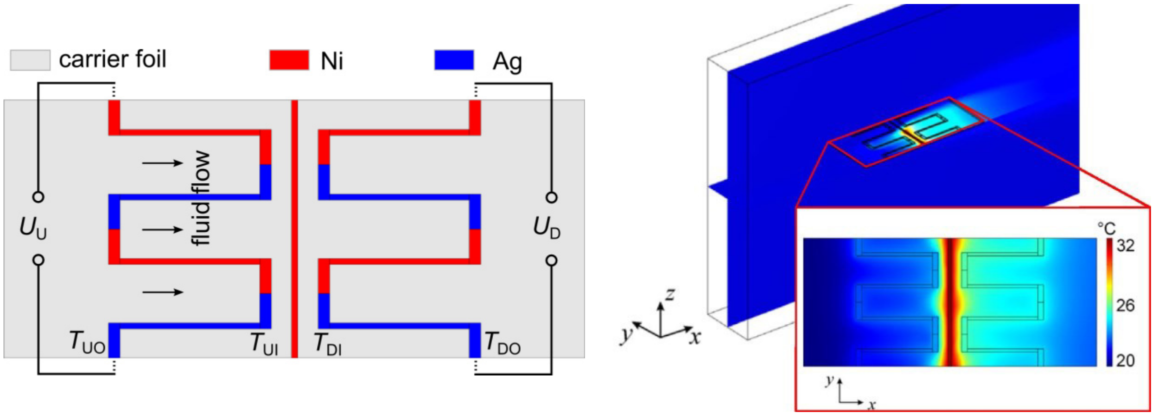
Nomenclature

U_U, U_D	Voltage of the thermopile-stack in up- and downstream direction of the heater
T_{DI}, T_{DO}, T_{UI}, T_{UO}	Temperature of the inner (I, next to the heater) and outer (O, next to the periphery) thermo-junction in up- and downstream direction
$\overline{T}_I, \overline{T}_O$	Mean temperature around the central heater (I) and the foil periphery (O)



(a) (b)

Figure 1: (a) Sketch of the sensor layout. Ag and Ni metal films are deposited on a carrier foil. The metal films form two thermopiles symmetrically arranged around a central Ni-Heater. The length of the foil can be adjusted to fit into various air duct geometries. (b) Color coded temperature distribution results from a 3D FEM simulation for a constant heater power of 100 mW and the maximum flow velocity in the positive x-direction of $v_{\max} = 0.5$ m/s.

technology is relatively costly. In an attempt to use the same basic operation principle, but more robust designs, thin flexible PCB (printed circuit board) carriers turned out to be a promising technological basis [4, 5]. With respect to the large dimensions of the air ducts and the always turbulent flows, the sensors should also have some integration or averaging capabilities across the diameter of the air ducts rather than providing spot measurements [6]. Thermal (calorimetric) flow sensors exhibit this property and can be shaped accordingly to fit into different flow channels. Moreover, they can be produced at low costs, e.g., using standard printed circuit board technology [7]. However, a drawback of such PCB-based sensors is the low resistance of the copper leads used as thermistors, making readout electronics challenging. Thermopiles can be used as an alternative to measure the temperature difference upstream and downstream of a heating element exposed to the flow.

2. Design

The sensor layout is depicted in Fig. 1a, where Ag-Ni thermopiles are arranged symmetrically around a central Ni-Heater. The convective heat transfer induced by the media flowing across the sensor surface influences the temperature field generated by the heater. On the one hand the thermo-junction temperature next to the heater is higher than that next to the periphery and on the other hand, the overall temperature downstream the flow is higher. The different temperatures lead to two thermo-voltages U_D, U_U in up- and downstream direction. Each voltage is proportional to the temperature difference of the inner and outer thermo-junction.

FEM simulations, as depicted in Fig. 1b, reveal that for a constant heating power the sum of the thermopile voltages as output signal is applicable only in a low flow range of about $v < 2$ m/s. To compensate for effective convective cooling at higher flow rates, the heating power must be appropriately adjusted by an electronic controller. The sum of the thermopiles voltages was chosen as process parameter to be controlled for that purpose, which is given by following equation:

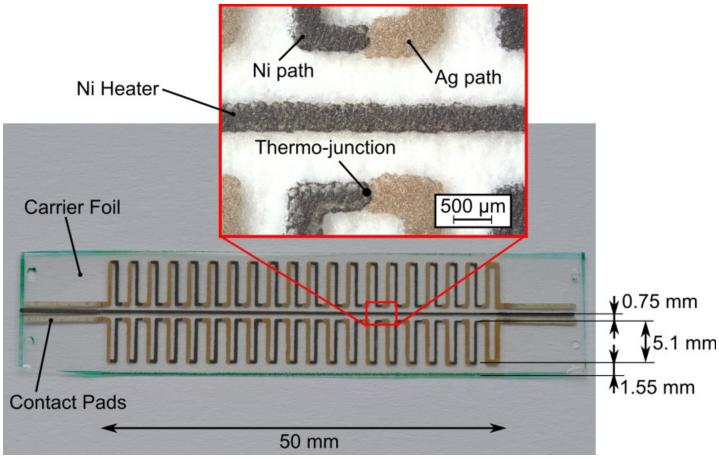


Figure 2: Photograph of the screen-printed transducer. The inlay depicts a micrograph of the region of the thermo-junctions around the central heater element. Large contact pads are located at each end of the transducer in order to establish a sufficient electrical connection during the characterization within the flow channel.

$$\begin{aligned} U_\mathrm{U} + U_\mathrm{D} &\propto (T_\mathrm{DI} - T_\mathrm{DO}) + (T_\mathrm{UI} - T_\mathrm{UO}) \\ U_\mathrm{U} + U_\mathrm{D} &\propto (T_\mathrm{DI} + T_\mathrm{UI}) - (T_\mathrm{DO} + T_\mathrm{UO}) \\ U_\mathrm{U} + U_\mathrm{D} &\propto \overline{T}_\mathrm{I} - \overline{T}_\mathrm{O} \end{aligned} \quad , \qquad (1)$$

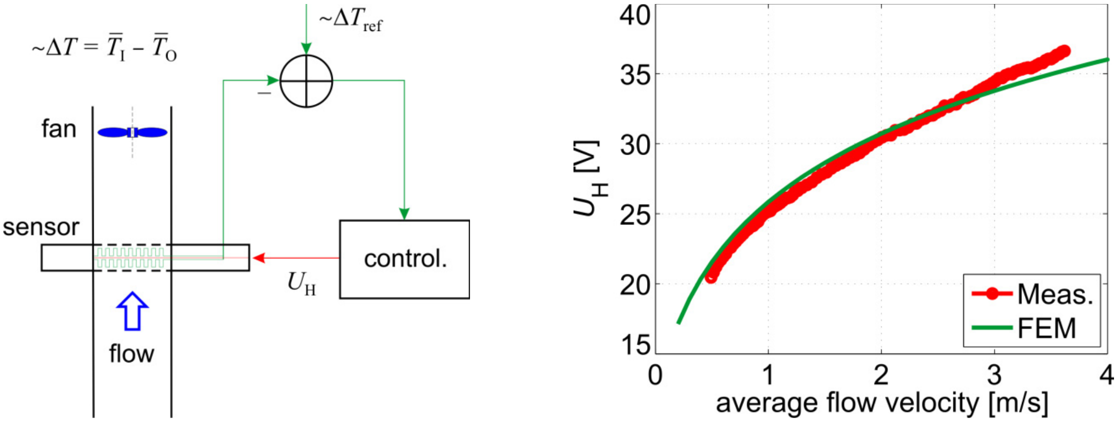
This voltage which is proportional to the difference between the mean temperature around the central heater and the mean temperature at the foil periphery $\Delta T = \overline{T}_\mathrm{I} - \overline{T}_\mathrm{O}$.

The thermopiles are screen-printed on a flexible 75 µm thick PET carrier foil (Fig. 2). A commercial thermosetting screen-printing paste was employed for the Ag parts while the Ni paste was prepared from a dielectric binder and Ni flakes with an average size ≤ 20 µm. The Ag/Ni thermocouples and thermopiles were prepared in a two-step process. Commonly, the Ag parts were printed first and dried briefly at 50°C. Then the Ni structures were added. The thermocouple Ag/Ni was selected for its advantageous thermoelectric properties and the corrosion stability of the two metals. The average line width was measured with 300 µm and 500 µm while the height was quantified with 10 µm and 2 µm for the Ni and Ag paths, respectively. The Seebeck coefficient was experimentally determined about S=11.5 µV/K for room temperature in a previous work [8].

3. Measurement and Result

Figure 3a depicts the schematic concept of the measurement and evaluation approach. An acrylic glass pipe with a total length of 82 cm and a diameter of 5 cm was used as a flow channel to characterize the screen-printed transducer. A fan was mounted at one end of the pipe in order to establish a constant and well defined air flow. A PC controlled power supply regulates the voltage of the fan and thereby sets the flow velocity in the channel. The chosen fan type makes it possible to achieve average flow velocities in the range of about 0.5 to 3.5 m/s. The transducer was located in the middle of the pipe, and the voltage across the heater U_H was measured with a digital multimeter controlled via a PC. A hundred measurement points were recorded for each flow velocity value and the resulting mean value was used to plot the transducer’s output characteristic.

A conventional PI controller was applied to establish the operating mode with a constant temperature difference ΔT. The sum of the thermopile voltages U_U+U_D, which is proportional to ΔT, was first low pass filtered, amplified and subsequently compared with a reference value $U_\mathrm{ref} \sim \Delta T_\mathrm{ref}$. The controller adjusts the heater voltage and thus the heating power until the desired temperature difference is reached. The voltage U_H is than proportional to the flow velocity and exhibits a strictly increasing behavior as depicted in Fig. 3b, which is in good agreement to FEM simulations.



(a) (b)

Figure 3: (a) Sketch of the sensor electronic circuit and measurement approach. The sensor is placed in the middle of a flow channel. A PI controller adjusts the heater voltage U_H in order to keep the difference between the mean temperature around the heater and the mean temperature at the foil periphery at a constant value ($\Delta T = \Delta T_{ref}$). (b) Measured output characteristic of the flow sensor in comparison with FEM simulation results when the over temperature is set to $\Delta T_{ref} = 290$ mK at an ambient temperature of 23°C.

4. Conclusion

The presented transducer for the measurement of flows in air ducts bases on screen printed thermopiles. An Ag/Ni thermocouple is printed on a PET carrier foil, where two thermocouples are arrange symmetrical around a central Ni heater. The length of the transducer can be adapted to span the whole diameter of an air-duct which has the benefit of an inherent averaging effect. This way, the influence of local flow turbulences on the transducer output can be reduced. To increase the operating range, the temperature between the mean temperature around the central heater and the mean temperature at the foil periphery is used as parameter to control. This temperature difference is kept constant by adjusting the voltage at the heater. The approach was experimentally verified with a flow channel and the resulting output exhibits a strictly increasing behavior over the whole measurement range of 0.5 up to 3.5 m/s. The thermopiles are screen-printed and while the materials used are rather stable, future works still have to address the effects of a protective layer. Although such a layer will decrease the transducer response due to the resulting thermal short circuit, it will be still needed to protect the thermopiles from contaminations.

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References

[1] L. Pérez-Lombard, J. Ortiz, and C. Pout, "A review on buildings energy consumption information," Energy and Buildings, vol. 40, no. 3, pp. 394–398, 2008.
[2] N.T. Nguyen, "Micromachined flow sensors–a review," Flow measurement and Instrumentation, vol. 8, no. 1, pp. 7–16, 1997.
[3] F. Kohl, R. Fasching, F. Keplinger, R. Chabicovsky, A. Jachimowicz, and G. Urban, "Development of miniaturized semiconductor flow sensors," Measurement, vol. 33, no. 2, pp. 109–119, 2003.
[4] N.T. Nguyen, X.Y. Huang, and K.C. Toh, "Thermal flow sensor for ultra-low velocities based on printed circuit board technology," Meas. Sci. Technol., vol. 12, no. 12, pp. 2131-2136, 2001.
[5] A. Petropoulos, D.N. Pagonis, and G. Kaltsas, "Flexible PCB-MEMS Flow Sensor," Procedia Engineering, vol. 47, pp. 236-239, 2012.
[6] T. Sauter, H. Steiner, T. Glatzl, W. Hortschitz, F. Wenig, C. Heschl (2015): "Towards Distributed Enthalpy Measurement in Large-Scale Air Conditioning Systems," IEEE Systems Conference 2015, Vancouver. 460-465.
[7] T. Glatzl, H. Steiner, F. Kohl, T. Sauter, and F. Keplinger, "Development of an air flow sensor for heating, ventilating, and air conditioning systems based on printed circuit board technology," Sensors and Actuators A, vol. 237, no. 1-8, 2016.
[8] H. Steiner, T. Glatzl, A. Talic, S. Cerimovic, F. Kohl, M. Schlauf, T. Schalkhammer, F. Keplinger, and T. Sauter (2015): "Towards Low-cost Printed Flow Sensors," IEEE Sensors 2015, Busan, Korea, pp. 1303-1306.