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Development of an air flow sensor for heating, ventilating, and air conditioning systems based on printed circuit board technology

Thomas Glatzl[a,b,*], Harald Steiner[a], Franz Kohl[a], Thilo Sauter[a], Franz Keplinger[b]

[a] Center for Integrated Sensor Systems (CISS), Danube University Krems, Viktor Kaplan Straße 2, 2700 Wiener Neustadt, Austria
[b] Institute of Sensor and Actuator Systems, Vienna University of Technology, Gußhausstraße 27-29, 1040 Vienna, Austria

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ABSTRACT

This work presents a novel air flow sensor for measuring flow velocities in heating, ventilating, and air conditioning systems. The transducer relies on printed circuit board technology allowing the fabrication of robust, design flexible, and cost-effective devices. Due to the interaction with the streaming fluid, the transducer generates an electrically measurable signal for determination of the total flow of the fluid. The measurement principle is based on a modified calorimetric principle where the heater is excited through a DC current and the sensing resistors are excited through a sine. Guided by extensive numerical simulations, a series of electrically transducer designs were investigated, optimized, and fabricated. Afterwards, these samples were characterized and compared to simulation results.

1. Introduction

The supply of today's urban agglomerations would not be possible without modern energy management technologies. Big residential and commercial buildings demand for considerable energy supplies. About 35% of the end energy is consumed here, by so-called heating, ventilating, and air conditioning (HVAC) systems. Two thirds of this amount are imputable to private living space and one third is attributed to service buildings [1]. In the private sector, significant improvements have been made to reduce the overall energy consumption. On the contrary, there are serious concerns about the absence of such an adequate progress in the service sector. Analyses have shown that up to 40% of the energy demand can be saved by optimizing the air ventilation and conditioning systems [1]. To improve this suboptimal status the installation of a sufficiently large number of sensors and actuators is required to obtain a detailed picture of the actual state of the HVAC system. Hence, sensing numerous parameters is a precondition for optimized building automation and enable environmental monitoring. The new system will also be valuable in other applications like environmental monitoring.

When it is not required to achieve the highest sensing accuracy, but to get robust, design flexible and in layout, and cost-effective sensors, manufacturing technologies are needed that are suited for mass production based on polymers. Moreover, the fabrication should only consist of few and inexpensive process steps to keep the total costs of the system affordable. Printed circuit board (PCB) is such a technology for high-volume production which is used in the consumer electronics market and has also applications in the medical, aerospace and industrial area. Therefore, it is not surprising that this technology has become interesting for the production of various types of sensors [2–7].

Each PCB is custom-designed for the circuit it carries and the design has a strong effect on the mechanical and electrical performance. The material properties are given by the chosen type of board, its way of laminating and the interconnections between the conductive layer. The board layers consist of a conductive laminate material and an insulating dielectric substrate. The conductive material is a commonly copper foil. It is adhesively bonded under heat and pressure to the substrate. The most common substrates are phenolic paper (synthetic resin bonded paper) and glass reinforced epoxy (FR4) [8]. The fabrication of a flow sensor with this PCB technology fits the requirements of a thermal micromachined flow sensor, such as: sufficiently large temperature coefficient of the active material, and thermally insulating substrate.

Micromachined flow sensors have a large number of applications. They are used to measure wind, wall shear stress, viscosity,

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[*] Corresponding author.
E-mail address: thomas.glatzl@donau-uni.ac.at (T. Glatzl).

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monitor gas in gas chromatography, and fluid flow in flow cytometry [9–20]. Flow sensors can be classified either as thermal or non-thermal. The thermal designs seem to be most promising for low-cost devices because of the lack of moving parts or complex transducers. Micromachined thermal flow sensors can be subclassified regarding the basic principal in: thermoresistive, termocapacitive, thermoelectric, thermoelectronic, pyroelectric, and frequency analog sensors [21]. The temperature dependence of the dielectric constant of a number of materials allows the realization of temperature sensors based on the thermocapacitive effect. The thermoelectric effect (Seebeck effect) can also be applied to measuring temperature differences. The thermoelectric effect is based on the temperature dependence of the pn-junction characteristics of diodes or bipolar transistors. The sensing concept of frequency analog sensors utilizes the temperature dependence of the oscillating behavior of mechanical elements such as cantilevers and membranes. Thermoresistive sensors [22] exploit the approximately linear relation between the electrical resistance of a material and the temperature.

There are two basic concepts of thermoresistive sensors based on hot-wire or hot-film conversion and calorimetric flow transduction. The first ones operate by heat transfer from a heated element to the surrounding fluid. This method needs one resistor which acts as heater and transducer at the same time, and, in some cases, a second resistor as sensor for the ambient temperature. These technology is known to be very sensitive regarding the flow velocity [23]. However, several drawbacks are the fragile design and the relatively expensive technology. To compensate this drawbacks, attempts with thin flexible PCB carriers [6,24] and thin-film technology on flexible PCB substrates [25,26] were made. On the contrary, the calorimetric principle requires additional temperature sensors up- and downstream of the heater. The work presented in this paper employs a modified version of the calorimetric operation. The sensor is based on standard flexible PCB technology only and is optimized for the use in HVAC systems [27]. Previous works established the concept of such PCB thermal sensors and discussed advantages and disadvantages [28,29].

2. Transducer layout

The calorimetric transducer is based on flexible PCB substrate (FR4 glass epoxy) with a thickness of 100 µm and the layout is designed to build up a calorimetric transducer. The laminate material is copper with a nominal thickness of 18 µm which was chemically etched to the final thickness of 9 µm. Cooper exhibits a temperature coefficient of resistivity of 3930 ppm/K. The effective transducer length (meander length of the copper leads) is variable and depends on the diameter of the duct. In a previous proof-of-concept (Fig. 1) there were one heating element in the middle, and four sensing (resistor) elements, two upstream and two downstream of the heater [29,28,27]. This setup allows to form a Wheatstone bridge for the readout in order to increase the sensitivity.

Fig. 2 depicts the first transducer prototype where several improvements are implemented. The heater bond pads were both on the side of the sensing elements terminals for better interconnectivity. The heater bond pads were separated from the resistor pads in the first place to minimize the heating effect outside the flow test channel. However, preliminary works have reveled that this influence is negligible and, hence, all connections were located on the same side. After measurements regarding the soldering influence (Section 3.3) the bond pads were replaced by contact areas for a female connector (Fig. 2). This plug simplifies the handling of the transducer for various tests and measurements. Additionally, the connection area holds holes for screws and alignment pins to fix the transducer exactly with the plug. Thereby, a reliable low resistance connection can be established and short circuits are avoided.

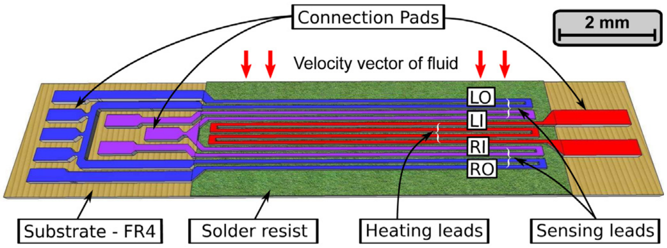

Fig. 1. Schematic for the transducer layout of the proof of concept: The length of the meander is 50 mm and the overall thickness is around 120 µm (100 µm substrate and 20 µm copper and solder resist). Heating leads are red, the sensing leads are blue and purple (RO: right outer, RI: right inner, LO: left outer, LI: left inner resistor), the solder resist is green and the substrate is yellow. At the left and right end of the transducer are connection pads for soldering/bonding. (For interpretation of reference to color in this figure legend, the reader is referred to the web version of this article.)

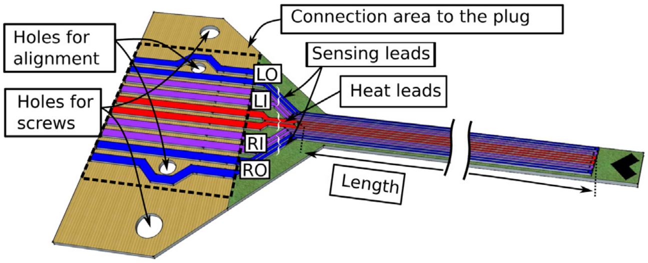

Fig. 2. Schematic of the second transducer layout: Heating leads are red, the sensing leads are blue and purple (RO: right outer, RI: right inner, LO: left outer, LI: left inner resistor), the solder resist is green and the substrate is yellow. The soldering/bonding pads are replaced by an area for the plug with holes for alignment pins and screws. (For interpretation of reference to color in this figure legend, the reader is referred to the web version of this article.)

There are different designs for the first transducer prototype. Design I is the normal design without any modification. The second one does have an increased gap (between all copper meander) of 300 µm which slightly increases the output voltage of the sensor because of a higher thermal resistance in the substrate. The reduced heat transfer through the membrane leads to a higher temperature difference between the sensing leads and, therefore, to a larger resistance change. The third design features an increased gap width of 100 µm and holes between the meander (100 µm diameter and 100 µm spacing). The holes reduce the heat transfer through the PCB and increase the output voltage. Design IV is nearly the same as design III except the spacing between the drill holes is 300 µm. The last one, design V, is identical with design III but does have an increased substrate width (8.86 mm) from the outer copper leads to the edge of the transducer. Table 1 summarizes all this varieties and gives an overview.

Table 1
Differences of the produced designs of the first prototype transducer to compare the varied parameter individually.

Design number	Gap between the leads (µm)	Holes diameter (µm)	Holes distance (µm)	Substrate width to the edge (mm)
I	100	None	None	0.2
II	300	None	None	0.2
III	300	100	100	0.2
IV	300	100	300	0.2
V	300	100	100	8.86