A Multi-Directional Thermal Flow Sensor Fabricated On Flexible Substrate

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***Abstract*—A multi-directional thermal flow sensor was developed and preliminary evaluation was made. The presented device utilizes simple manufacturing techniques and commercially available components. In addition, the sensing elements are completely isolated from the flow channel and therefore the device is ideally suited for a wide range of applications. Preliminary experimental results indicate adequate flow rate and direction sensitivity.**

Keywords-thermal flow sensor; directional; plastic substate

I. INTRODUCTION

Directional flow sensors are used in a variety of applications, including meteorology [1], avionics [2], wind turbine design and monitoring [3], building ventilation systems design [4], agricultural production optimization [5] and the automotive industry [6]. Thermal directional sensors, in particular, have been developed and studied more extensively since the introduction of relative silicon-based devices [7] and various implementations have been presented, introducing diverse designs in order to enhance sensor performance. Additional sensing elements in varying distances from the heater have been shown to widen the flow rate detection range, [8] [9], while the addition of sensing elements in tighter angles, as expected, provides a more accurate flow direction estimation [10] and the incorporation of more than one heater improves sensitivity [11] [12]. However, most of the existing implementations require complicated MEMS manufacturing technology and are relatively fragile due to bonding wire connections and exposed sensing elements.

In this work a simple, inexpensive implementation of a thermal multi-directional flow sensor based on previously published work [13] is presented, resulting in a robust, maintenance-free device suitable for harsh environments.

II. PRINCIPLE OF OPERATION

The present device incorporates a quadruplet of orthogonally placed sensing elements equidistant in respect to a centered heater (Figure 1a). This configuration allows for determination of the two main flow parameters (flow value and direction).

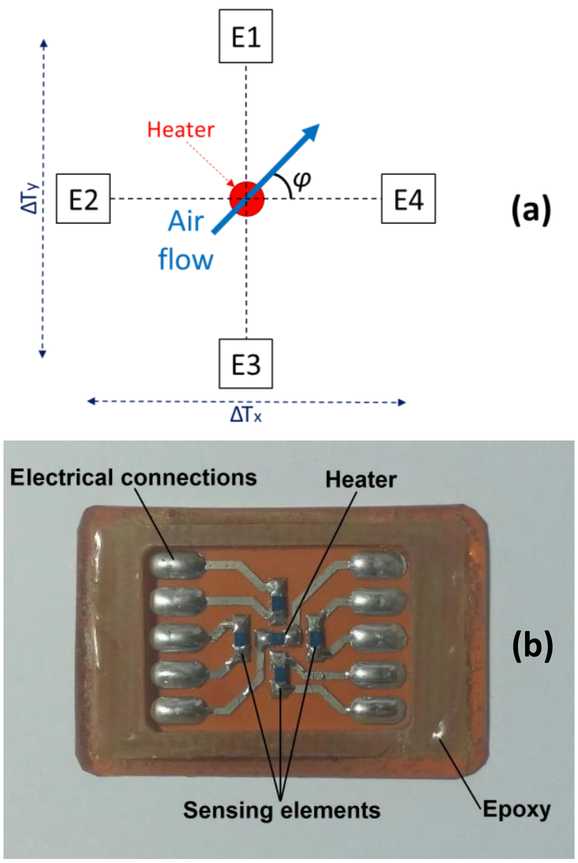

Figure 1. a) Sensor layout representation. ΔT_x and ΔT_y are the temperature differences measured between sensing element pairs E2-E4 and E1-E3 respectively.
b) Actual device layout, shown before encapsulation. The center heater and the surrounding sensing element pairs are visible.

The heater is operated in constant current mode in order to simplify the sensor interface. The flow rate value can be extracted from the temperature drop of the heater, while the flow angle φ is derived from the differential signals of the sensing elements, which are correlated to the flow direction according to the following functions [11]:

$$\Delta T_x = \Delta T_0 \cos\varphi \quad (1)$$

$$\Delta T_y = \Delta T_0 \sin\varphi \quad (2)$$

$$\varphi = \arctan (\Delta T_y / \Delta T_x) \quad (3)$$

ΔT_0 represents the temperature drop induced on the sensing element pairs by the applied flow (Figure 1b). The signs of ΔT_y and ΔT_x must be taken into account when calculating the inverse tangent in order to obtain four-quadrant results.

III. Sensor Fabrication

The sensor is based on standard Printed Circuit Board manufacturing technology and readily available components, thus producing a simple, cost-effective approach with highly repeatable results.

A 100μm thick polyimide film is used as substrate. After patterning of conductive traces and soldering the sensing elements at a distance of 2,5mm from the heating element, the device was sealed using epoxy materials and flipped vertically (Figure 2), thus the heater/sensing elements are completely chemically and mechanically isolated from the fluid while allowing thermal interaction via the thin polyimide membrane. Despite the sensing element isolation, sufficient thermal coupling is attained due to the small thickness of the membrane, hence adequate sensitivity and detection range are achieved. It should be underlined that flow is applied on the external surface of the substrate (Side 2 in Figure 2e).

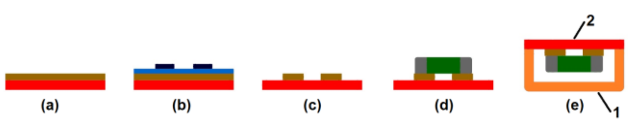

Figure 2. Fabrication steps: (a) pre-laminated substrated, (b) masking & definition, (c) patterning and copper etching, (d) PT100 element soldering, (e) sensor encapsulation in epoxy material < 1 >, allowing thermal coupling of the flipped sensor to the fluid only via the polyimide membrane < 2 >. note: dimensions are not to scale

IV. Results

Device characterization was made using a measurement setup consisting of a controllable flow rate source providing the reference flow, whereas the device was mounted to a turntable controlled by a stepper motor. A 30mA current was applied to the heater by a Keithley 2612 sourcemeter, corresponding to 110mW under zero flow conditions. The sensing elements' response was constantly monitored by a multi-channel Keithley 2000 multimeter. Figure 3 illustrates the device response as a function of the flow, for rates in the region 0-50 Standard Liters Per Minute.

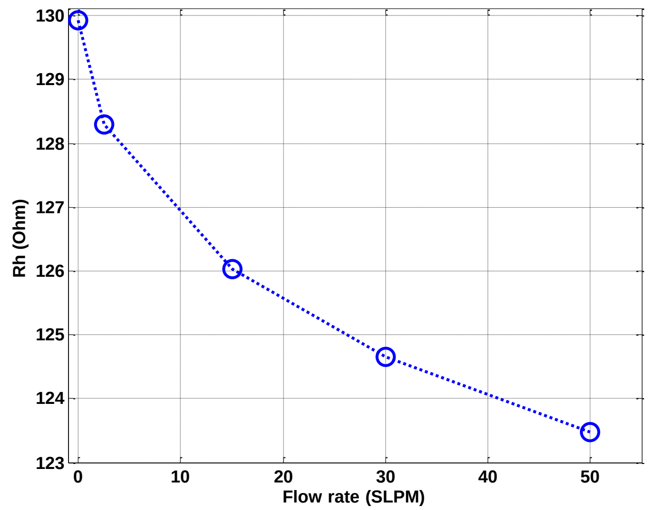

Figure 3. Heater resistance as a function of the applied flow

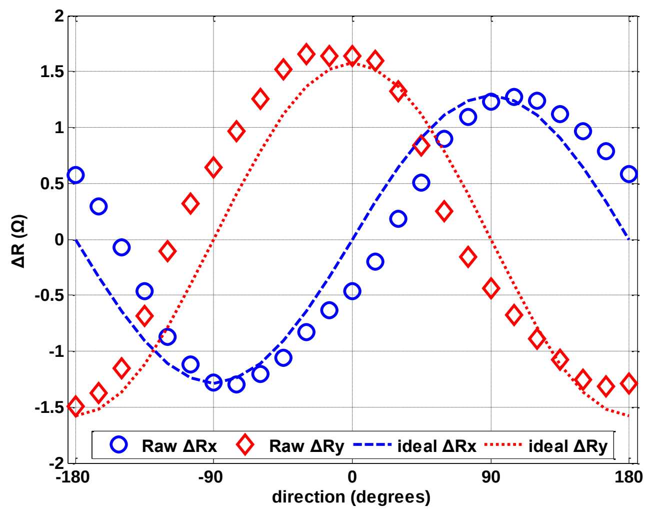

Figure 4. Heater resistance as a function of the applied flow

The aforementioned response corresponds to the heater's resistance change under hot-wire principle of operation. As mandated by the IEC60751 standard the PT100 sensing elements' resistance presents an effectively linear correlation to temperature for T > 0°C and a small temperature variation, therefore ΔT_x and ΔT_y in equations (1), (2) and (3) can be substituted by $k\Delta R_x$ and $k\Delta R_y$ respectively, where ΔR_x represents the difference in resistance of the element pair along the x and y axis accordingly and k a linear constant factor. The device response as a function of flow direction is presented in Figure 4, where the parameters ΔR_x and ΔR_y are plotted in relation to the turntable angle in the range -180 to 180 degrees in 15 degree steps. A constant flow rate of 40 SLPM was applied during the directional response evaluation. Experimental results indicate that the flow angle can be extracted with sufficient accuracy. Although a phase difference and a small vertical offset is observed in comparison to ideal response curves, the deviations can be attributed to slight asymmetries in the device layout. Partial compensation can be made by subtraction of the phase offset from the data waveform and amplitude normalization around zero as indicated in Figure 5. In this case, improved direction estimation can be obtained (Figure 6), resulting in a mean error in the order of ±3.5 degrees.

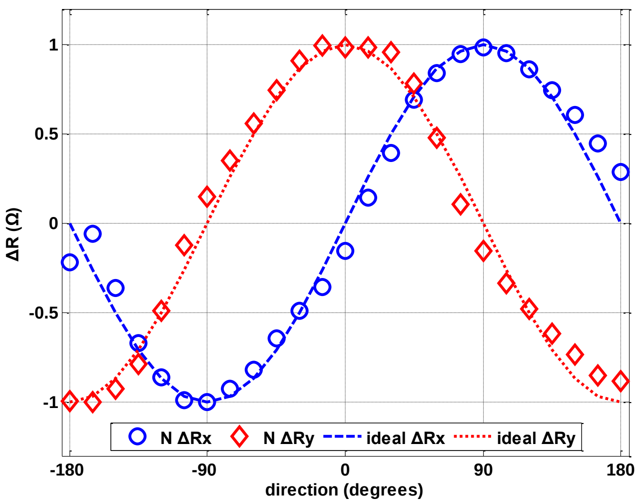

Figure 5. Compensated differential data as a function of the flow angle

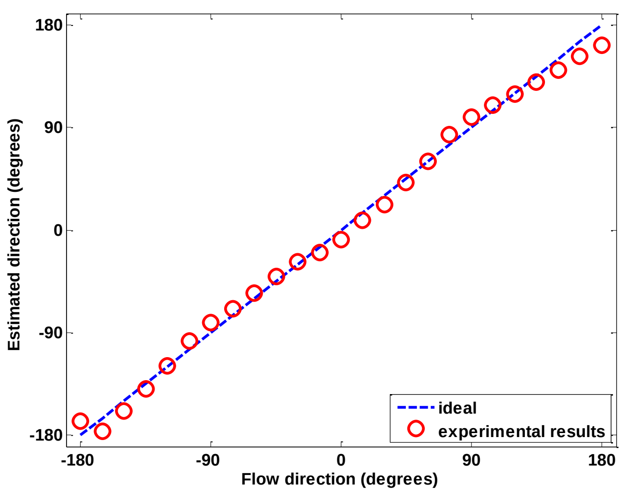

Figure 6. Estimated flow angle as a function of the actual values

V. CONCLUSION

In this research, a thermal gas flow sensor for measuring two-dimensional flow was developed and a preliminary evaluation in constant current mode was performed. In the proposed approach the flow is completely isolated from the active elements of the device. Obtained measurements show promising results considering the low cost and complexity of the implementation with a measurable flow rate range extending from about 2 up to more than 50 SLPM and a mean absolute angle error of ±3,5 degrees, after applying simple software phase compensation on the measurements. Further sensor development with improvement of the layout precision and additional processing of the measurements is expected to provide a solid low-cost alternative option, especially for harsh environment applications.

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