Research on an ultra-low power thermoelectric-type anemometer

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Abstract. Beyond the conventional hot-wire sensor, a new thermoelectric sensor with ultra-low power consumption without heating is proposed. Using the TSMC 0.35 um CMOS-MEMS process, the thermoelectric sensor is fabricated with 32 pair of central-symmetrical thermocouples positioned. When the fluid passes through the thermopile, the fluid will take away the heat, so that a temperature difference is generated between the cold end and hot end of the thermocouples. The temperature sensor is calibrated and senses the drop of temperature at the center of membrane during the measurement. For different flow velocities, it is interesting to find that the drop of temperature is verified by the output voltage of sensing circuit from thermopile and the same for temperature sensor which behaves as a function of flow velocity. The new approach for the anemometer of sensing flow velocity is realized by our proposed thermopile which is proved to be a practical technique with ultra-low power consumption.

1. Introduction

Thermal flow sensors plays an important role by means of heating and temperature measurement which are widely used to measure thermal mass-flow rate of fluids. Most of these sensors mainly include a heater, which is designed on a membrane and placed in the stream of flow to reduce the solid heat conduction and also the power of heating. The membrane for the heater is fabricated and floating while the substrate beneath is removed with thermally decoupling. As compared with sensors which the heater is directly placed on bulk silicon or ceramics, it leads a benefit to reduce the lower power consumption of heating and give a better performance with a faster response time and high sensitivity since both the solid thermal conductance and the heat capacity of the membrane is much lower [1-4].

However, these thermal flow sensors based on heat convection principle usually suffer the long-term drift of TCR and reading due to the continuous heating of hot-wire. Therefore, it is a great challenge to reduce the power consumption and temperature drifting issues and avoid of repeated time-consuming calibrations. It is necessary to develop a robust flow sensor design with high stability over the proper flow range and working temperature conditions. Several modulation of heating techniques for micro thermal flow sensors [5] have been presented and it is difficult to maintain a reliable reading during the dynamic operation and time-varying heating. The main reason for the instability of continuous heating is because the heater of thermistors is exposed to high temperatures over time, sometimes referred to as “aging,” their resistivity can change over time. Temperature
dramatically change may be thought of as a main factor of aging [5]. Besides, the cumulative exposure to high temperature that has the greatest influence on a thermistor component.

2. Convection-cooling and sensing principle
Based on the Newton’s law of cooling, the hot-wire sensors operate by heat transfer to measure the heat dissipation from a heated element to a surrounding cooler fluid. It means the mathematical model of increasing fluid flow and forced convective cooling of the element can be described and a baseline calibration for the model is necessary for sensing applications. King’s Law describes the coefficient of convection for the heat transfer from the sensing element to the flow in terms of the flow velocity and geometrical factors of sensor. These constants including complex combination of fluid thermal conductivity properties and flow geometry and usually it is derived from empirical experiments.

To build a model for the flow sensor with gain and lose energy by heating and dissipation of thermal conduction including the solid conductance and convection, it can be described in equation (1). We omit the thermal radiation because the working temperature is at the ambient temperature without the infrared radiation exchange between sensor and environment.

\[
(\rho A_s \Delta x) s \frac{\partial T}{\partial t} = \phi_{path} - \phi_{convection} + I^2R
\]  
(1)

Usually, there is a heating power of the heater in equation (1) which may come from the Joule’s effect and the heat loss to the surrounding by solid conduction depending on the geometrical factors of the details of structure and also the material along the conduction path in equation (2). These formulations of effect and law have been rebuilt and modelled by numerous researchers. The differential form of analytical description for the heat transfer by Morris and Foss (2003) as a useful reference for the convective-cooling effect. The thermal behaviour of the sensor due to the heat loss under the flow through the membrane can be described in equation (3). Especially, it is for the small piece of heating element between the supported ends can be subdivided into short length segments, \( \Delta x \), and each segment can be described by the thermal balance equation. For the \( \Delta x \), the heating power is \( FR \), our proposed ultra-low power thermoelectric flow sensor where \( \phi_{path} \) equal to axial heat transfer,

\[
\phi_{path} = -K_s(A_s \Delta x) \frac{\partial^2 T}{\partial x^2}
\]  
(2)

The convection heat transfer from the sensor to the flow is potential to the temperature difference and can be expressed as equation (3):

\[
\phi_{convection} = h_s \pi D_s \Delta x \left[ T_f - T_s \right]
\]  
(3)

where the subscript ‘s’ refers to the sensor. The convection coefficient, \( h_s \), is expressed in terms of the Nusselt number, Reynolds number and Prandtl number and the expression is as equation (4):

\[
Nu = \left[ 0.42 Pr_f^{0.26} + [0.57 Pr_f^{0.33}] Re_f^{0.45} \right]
\]  
(4)

While \( Nu = h D_s / k_f \) and \( Re = \rho V D_s / \mu \) where the value of the Reynolds number is used to determine whether the flow is laminar or turbulent and \( D_s \) is the diameter of sensor. It is expected the thermal sensor installed in the steam of flow, the reduction of temperature on the membrane of sensor is induced from equation (3). For our proposed thermopile, a thermoelectric output voltage for the serial connected thermocouples is generated from Seebeck effect and given as equation (5):

\[
V_{enf} = -S \Delta T
\]  
(5)

2.1. Thermoelectric type sensor
For the investigation of convective cooling, a thermopile is fabricated by using the standard CMOS TSMC 0.35 um process and after these processes the silicon substrate beneath the floating membrane
is removed subsequently by TMAH. The following figure, figure 1 shows the design of central-symmetrical layout of thermoelectric elements of flow sensor.

![Figure 1. Illustration of structure drawing of proposed convective thermopile.](image1)

![Figure 2. Photography of proposed thermopile after fabrication.](image2)

There are 32 pair of thermocouples placed around the center of membrane and each thermocouple is designed with two kinds of material, n+ Poly and metal in series which give a weak voltage according to the difference of temperature between the hot and cold junctions. We also consider a temperature sensor of thermistor situated at the centre of sensing area and the two terminals of resistor are connected with interconnection to the PAD. The material of thermistor is designed with p+ Poly and the resistance of sensor is 720 Ω at 25 ℃. After the CMOS process, a series of post-processes including an isotropic RIE and wet etching processes to remove the silicon under the membrane are proceeded. The photography of microscope of final chip is shown in figure 2.

2.2. Sensing circuit of thermoelectric sensor

The circuit diagram of sensor signal processing composed of amplifier, ADC and data acquisition is shown in figure 3. This data acquisition system is designed with an embedded ARM based Cortex M0, NUC120 to control and communication with PC. For the temperature change of sensing area due to the flow, the output voltage of thermoelectric is weak and after amplification and low-pass filtering the signal is delivered to one of the channels of ADC, MCP3202. A chopper amplifier, AD8551 is used for its low offset and low temperature-drift. Without heating, the signal of temperature sensor is picked up to the second channel of ADC. After the ADC, the digital signals of two sensors are passed to the PC through the SPI interface of ADC.

![Figure 3. Architecture of sensing circuit for proposed ultra-low power thermoelectric-type anemometer.](image3)

3. Experiment and analysis

3.1. Experimental setup and calibration
A small wind tunnel is built and the flow velocity can be controlled under 0–5 m/s, while a standard flow meter is installed with outputs of flow velocity, flow temperature and humidity. The calibration curve is derived at room temperature 25 °C from the fitting function of data which are measured with thermoelectric sensor vs. flow velocities under different conditions of flow velocities, and shown in the figure 4. It is interesting to find the cooling of membrane temperature without heating due to the flow convection and the fitting curve shows a good behavior of squared function.

![Figure 4. Measurement of output voltage vs. flow velocity.](image)

**Figure 4.** Measurement of output voltage vs. flow velocity.

### 3.2. Results and discussions

The convective cooling of sensor for flow measurement can be also observed from the thermistor at the center of membrane. From figure 5 the thermistor of p+ Poly shows a positive TCR and is calibrated for the temperature from 35C–80 °C and the resistance varies from 730–760 Ω. After the calibration of thermistor, it is used to verify the reduction of temperature of sensing area during the flow and the measurement is carefully proceeded under a pulse reading of bridge circuit while is biased with 10 ms and reset to zero bias for 990 ms. It is also verified in another research that the pulse reading will cause no extra side-effect during the investigation of flow measurement.

![Figure 5. Temperature calibration of thermistor.](image)

**Figure 5.** Temperature calibration of thermistor.

It is obvious to see that from figure 6, the temperature of sensing area is gradually getting lower as the flow velocity increases. Because of the precision of thermistor calibration, the change of temperature is observed and quite small and the range of temperature change is from 41.95 ~ 41.6 °C while the velocity of flow is controlled from 0 ~ 5 m/s.
Figure 6. Investigation of temperature reduction vs. the increase of flow velocity.

4. Summary
A new thermopile with 32 pair central-symmetrical thermocouples is proposed in this work which is fabricated by using a standard TSMC 0.35 um CMOS process. The new approach of flow sensing technique without heating is proposed while the fluid passes through the thermopile, the fluid will take away the heat, so that a temperature difference is generated between the cold end and hot end of the thermocouple. The new approach for the anemometer of sensing flow velocity is realized and verified by our proposed thermopile which is proved to be a practical technique of flow sensing with ultra-low power consumption.

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