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An experimental study on MEMS-based gas flow sensor for wide range flow measurements

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The paper describes an experimental analysis of thermal MEMS sensor, the gas flow velocity sensor, based on both thermo-anemometric (for the gas flow velocities less than 1 m/s) and calorimetric (for the gas flow velocities exceeding 1 m/s) measurement methods. It was found that fixing the flow sensor on the wing fairing inclined at nonzero angle relative to the gas flow direction allows measuring the wide range of flow velocities varied from 0 m/s to 10 m/s with about 3% accuracy, which is enough for different sensor applications. The optimized design of analog circuit scheme for better sensor's signal processing is also presented.

Keywords—MEMS; gas flow velocity sensor; flow meter; wing fairing; sensor signal processing.

I. INTRODUCTION

There are many different methods of measuring gas flow, based on different physical principles. Each of the methods has its advantages and disadvantages. In this work we will discuss on the promising type of these sensors - thermal MEMS gas flow sensor [1-4]. The operation principle of thermal gas flow velocity sensor is shown in Figure 1.

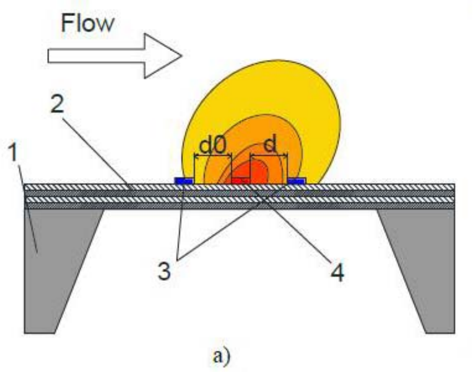

Figure 1. The principle of operation of the thermal gas flow sensor.

Sensor consists of 4 platinum thermistors: 2 sensing elements, heater resistor and resistor for the temperature control. Sensing elements and heater are located on thin dielectric membrane to reduce heat conduction through substrate. The membrane consists of 4 dielectric layers of silicon oxide and silicon nitride with total thickness of 1.2 microns. In turn, thermistor for the temperature control stands aside membrane and heating elements. The sensor dimensions are 3x9x0.46 mm.

II. THE PROPOSED DESIGN OF THE GAS FLOW SENSOR. THEORY AND EXPERIMENT

The thermistor outputs of the gas flow sensor were glued and welded to the printed circuit board (Figure 2). The sensor chip with the thermosensitive elements on the thin multilayer membrane is shown in Figure 3.

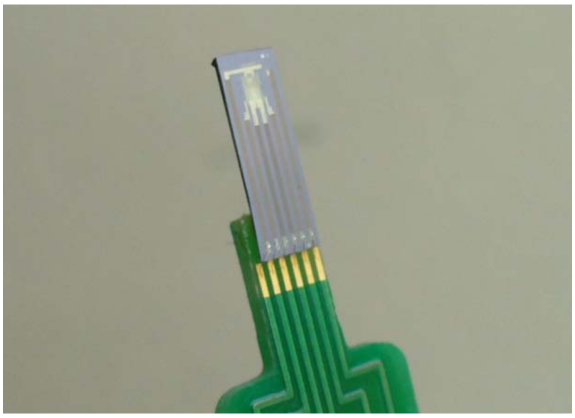

Figure 2. Gas flow sensor on the printed circuit board.

Since the heat transfer through the thin membrane is very small, even small flows, flowing through the heater, create a temperature gradient in the surrounding gas, the so-called thermal cloud (Figure 1).

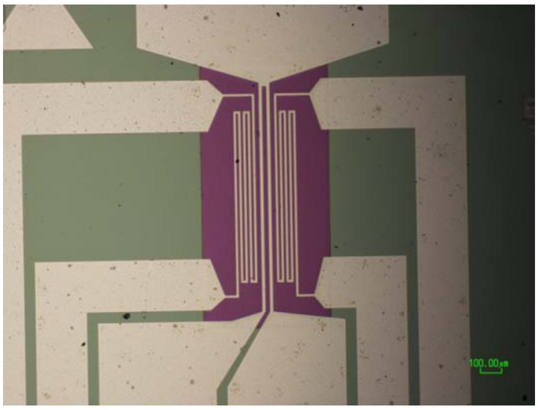

Figure 3. Overview of the sensor chip.

The dependence of the increment in the temperature of the heater from the current is shown in Figure 4. It can be seen from the graphs that at the input current of 12 mA the heater temperature rises up to 130 °C at zero flow rate and the gas temperature of 25 °C, while the temperature increment will be only 100 ° C when the flow velocity is 5 m/s under the same conditions.

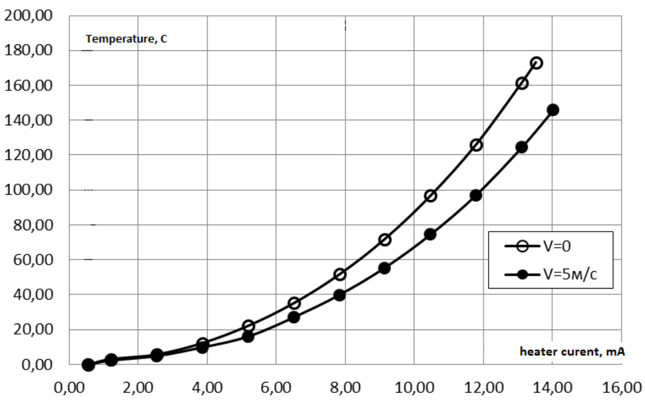

Figure 4. The dependence of the temperature increment of the heater of the flow velocity sensor from the input current flowing through it at an ambient temperature of 25 °C.

The gas flow leads not only to a decrease in the temperature of the heater, but also to the displacement of the thermal cloud and the appearance of the temperature difference between the platinum thermistors (Figure 1).

To increase the sensitivity of the thermal sensor for measuring the wide range of gas flow velocity, it is necessary to ensure laminarity of the gas flow around it and eliminate the flow vortices. The gas flow near the location of the thermal sensor presented in Figure 5 was calculated using SolidWorks simulation software [5]. It is easy to see that the gas flow is significantly distorted, especially in the cavity beneath the membrane. To eliminate the turbulence, a wing fairing was used.

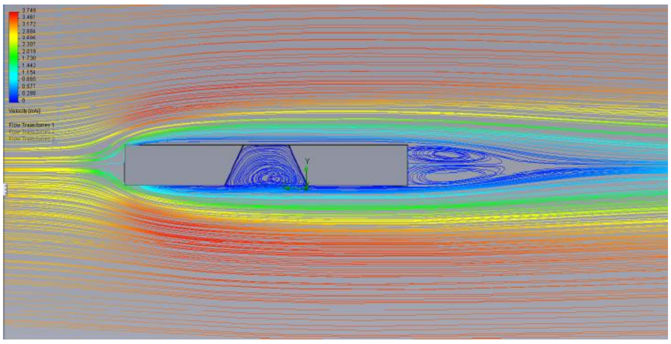

Figure 5. The simulated gas flow near the location of the gas flow velocity sensor.

Figure 6 shows the results of simulating the gas flow near the sensor fixed on a wing fairing inclined at an angle of 30° relative to the flow direction, where the influence of flow vortexes is minimized. It is important to note that turning the wing noncollinearly to the flow increases the sensitivity of the gas flow velocity sensor.

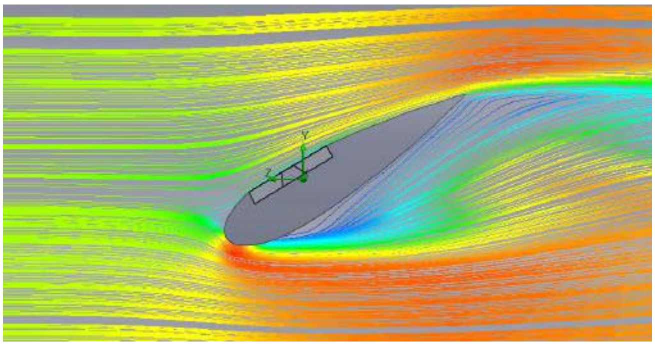

Figure 6. The simulated gas flow near the location of the gas flow velocity sensor attached to the wing fairing, inclined at an angle of 30 ° relative to the flow direction.

Figure 7 shows the experimental dependence of the temperature difference on the wing inclination angle with respect to the flow direction. According to these experimental results, the optimal inclination angle for the wing profile equal to 30° was chosen.

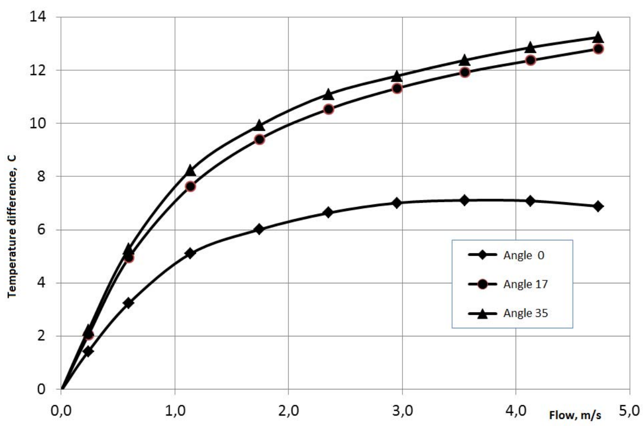

Figure 7. The temperature difference between thermistors located before and after the heater at various angles of the inclination of the wing profile relative to the flow direction.

It can be seen that in this case the temperature difference increases twice and is about 12°C at the flow velocity of 4 m/s.

III. THE SCHEME FOR ANALOG PROCESSING OF SIGNALS OF THE GAS FLOW VELOCITY SENSOR

Two methods of measuring the gas flow velocity, using a calorimetric or anemometric approach, are widely used. In the calorimetric method, the gas flow velocity is determined from the temperature gradient within the thermal cloud (Figure 1), the higher the flow velocity, the greater the displacement of the thermal cloud and the higher the temperature difference between thermistors. This method requires the laminar flow of the gas (the absence of substantial twists) so that the thermal cloud does not dissipate, which is done at low flow rates. Figure 6 shows that the temperature difference between thermistors decreases with increasing the flow velocity and the calorimetric method becomes poorly informative at the gas flow rates of more than 3-4 m/s, even when the angle of inclination of the fairing wing is optimal. The anemometric method is based on measuring the temperature drop of the heater at nonzero gas flow velocity.

The method, on the contrary, is informative at high speeds, while the results become distorted at low flow rates, which is caused by the influence of convective gas flows near the heater. Figure 8 shows the voltages of the electrical signals «InOut» and «In» responsible for the temperature difference between thermistors and the increase in heater temperature correspondingly after their pre-amplification.

A detailed consideration of the «In» voltage signal, determining the temperature change of the heater in the range of low gas flow rates (less than 0.1 m/s), indicates that the heater temperature increases, since the gas flow shifts the temperature cloud to the gas flow velocity sensor (speed converter) that reduces the heat sink from the heater caused by convective heat transfer. Thus, to measure gas flow velocities up to 10 m/s, both measurement methods must be used [6].

At velocities less than 1 m/s, a calorimetric method based on measuring the temperature difference between thermistors should be used, while at flow speeds, exceeding 1 m/s, an anemometric method based on measuring the temperature drop of the heater proved to be more suitable.

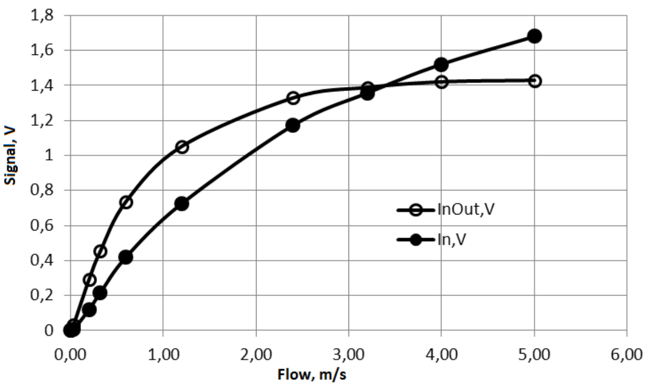

Figure 8. The comparison of calorimetric (InOut) and anemometric (In) signals for measuring the gas flow rate.

The electrical circuits of analog processing of the signal coming from the flow velocity sensor can differ both in its design and in the ways of feeding the measuring bridges and the subsequent amplification of signals: 1) the measuring bridges are powered by current or voltage sources, 2) the heater power supply is continuous or pulsed, 3) the single heater is used or thermistors server as a heating element.

Layouts of the various circuit designs of the gas flow sensor were developed. A circuit of the gas flow sensor was chosen for measurements in which the measuring bridges are powered by current sources, and the measuring thermistors are used as a heater [7]. Compared to others [8,9], this circuit has better noise immunity and does not require the specific parameters of operational amplifiers used, since the currents of about 100 µA or less are not used to power the bridge of thermistors. At high currents, the thermistors located on the membrane of the gas flow velocity sensor will be markedly heated by the input current.

The circuit provides three signals from the measuring bridges: «InOut» signal (showing the temperature difference between thermistors), «In» signal (showing the temperature drop of thermistor located first along the direction of the gas flow) and «Sr» signal from thermistor located not on the membrane but on the crystal array on which the flow sensor is based (in other words, showing the ambient temperature).

The circuit can provide both continuous and pulsed power to the flow sensor. The transient process of signal formation in the resistor corresponding to «Sr» signal is set faster than in the other resistors. The time delay is about 2-3 ms. The «InOut» signal between thermistors is set no longer than 18-20 ms. The «In» signal from the first thermistor is set the longest time. The setting time of this signal (In) is 20-24 ms. Moreover, the lower the flow velocity, the longer this signal is set.

The studies were carried out on a special test bench with the use of an automated workstation and the LabVIEW software environment [10]. The voltage signals «In», «InOut», «Sr» from the sensor thermistors in the case of pulsed power supply are shown in Figure 9, where «In» signal is shown by green line, while the red and blue lines presents «InOut» and «Sr» signals correspondingly.

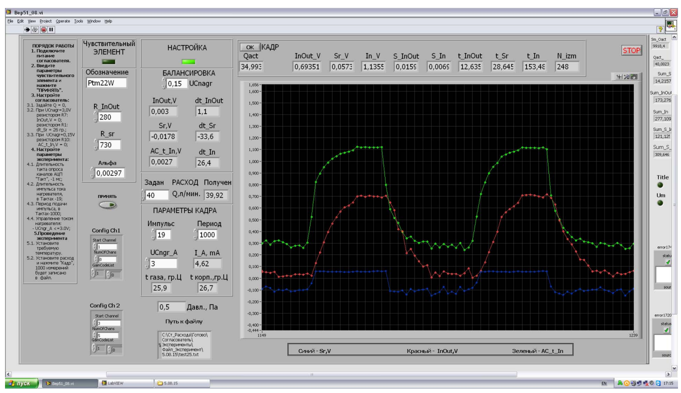

Figure 9. The screen of «In», «InOut» and «Sr» output signals of the gas flow velocity sensor powered by the pulsed supply (obtained using LabVIEW software environment [10]).

IV. CONCLUSIONS

It was shown that using calorimetric at low flow velocities (from 0 m/s to 1 m/s) and using thermo-anemometric at flow velocities more than 1 m/s allows to measure flow from 0.05 m/s to 10 m/s at accuracy 3%. It was also shown that by implementing fairing wing to a sensor it is possible to increase output signal more than twice.

ACKNOWLEDGMENTS

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