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Prototype of Calorimetric Flow Microsensor

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Abstract. An analytical model of calorimetric flow sensor has been developed. The results of the application of this model are utilized to develop a calorimetric flow microsensor with optimal functional characteristics. The technology to manufacture the microsensor is described. A prototype of the microsensor suitable to be used in the mass air flow meter has been designed. The basic characteristics of the microsensor are presented.

Keywords: thermal flow sensor, mass flow rate, heat and mass transfer, mass flow meter, MEMS.
PACS: 47.80.-v; 47.60.Dx; 44.15.+a; 47.61.Fg**.**

INTRODUCTION

So-called thermal flow sensors [1] holds a special place among modern microelectromechanical systems (MEMS), their general operation principle is based on the dependency of the intensity of convective heat transfer on the velocity of the moving medium (fluid). The study of patents database shows an increasing interest in recent years for the development of new thermal flow microsensors design, which is based on the use of technologies to form micro- and nanoscale surface structures (see, for example, [2]). Indeed, due to fast-evolving methods of surface microstructure formation with enhanced exploitation characteristics a significant progress has been reached in the majority of critical industrial technologies and in microsensor manufacturing technology as well. In particular, miniaturization of sensors has given new possibilities for their practical use, by significantly reducing manufacturing costs and consumed electric energy.

Application field of thermal flow microsensors are: automobile [3, 4], chemical [5] and electronic industries [6], medical [7], aerospace applications [8], air conditioning and ventilation [9] as well as other fields. Thermal flow microsensors are used in Micro Total Analysis System (μTAS) which recently has been significantly developed [10].

According to measuring principle the thermal flow sensors can be classified into three main categories: time of flight (TOF) sensors, thermo anemometric and calorimetric sensors.

The method to measure fluid velocity or fluid flow rate by using TOF sensors consists in determining the time delay of thermal pulse. The heater undergoes the pulse heating and after some time (time of flight) temperature sensitive element located downstream the fluid flow, registers the pulse. Obviously, the time of flight depends on the velocity of the fluid.

Thermo anemometers are among the most common sensors to diagnose the fluid flow rate, they have quite a number of practical applications. In particular, the substance of one of them is to determine the dynamics of the electrically heated element that cools down as a result of heat exchange with the fluid. The heat exchange rate, in turn, depends significantly on the flow rate of the fluid. Since the electrical resistance of the most materials depends significantly on the temperature, the resistance of the material is measured to determine the temperature.

The principle of the calorimetric sensor is based on the change of the temperature field near the heated element through fluid flow. The difference of temperature between the temperature sensitive elements situated symmetrically downstream and upstream with reference to the heater, is determined by the flow rate of the fluid.

In this paper we will focus on the calorimetric flow microsensor, since its practical implementation can combine all three mentioned principles of measuring the velocity and the flow rate of the fluid. Fig. 1 illustrates the physical principle to diagnose the gas flow in a channel using a calorimetric sensor. The sensor is mounted securely inside the channel either on the surface or at some distance. The measuring part of the sensor is a thin membrane that is situated on a massive substrate. The membrane has heater and temperature sensitive elements, number of which can be two or more.

From a theoretical point of view, to describe the heat and mass transfer process in internal gas flow is quite challenging. Indeed, the process of heat and mass transfer in channels depends on multiple factors such as the regime of the gas flow [11], the type and the size of the channel [12;13], the chemical composition of the channel's

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surface and the kind of gas [14-16], temperature distribution on the surface [17], roughness of the surface [18] and the pressure ratio [19]. The heat and mass transfer is also influenced by the macroscopic and physical properties of the gas.

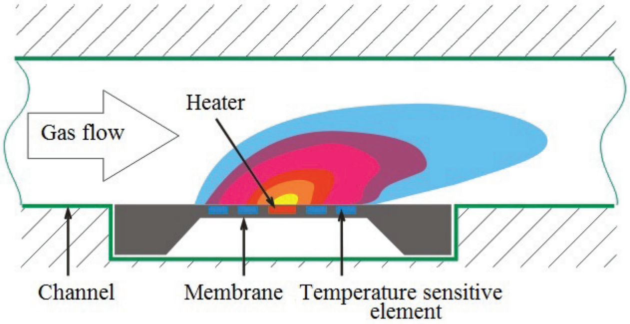

FIGURE 1. The physical principle for diagnostics of gas flow in a channel using a calorimetric sensor.

There is no doubt for a more accurate and precise study of the heat and mass transfer process it is preferable to use numerical methods, such as the Finite Element Method (FEM), which is free from a number of assumptions and simplifications inherent in the analytical approaches. However for better understanding of the issue and recommendations to develop the design of sensor, an analytical model is also highly critical.

The analytical model of the calorimetric sensor suggested in [20] is a frequently used model. According to this model, the temperature of the membrane equals to the temperature of the environment at an infinite distance from the heater. However in reality the temperature of this membrane equals the temperature of the environment at a finite distance from the heater, where it is connected to the massive substrate.

The theoretical purpose of this study is to develop a realistic analytical model of the calorimetric flow sensor suitable for engineering calculations. The results of such calculations may be provisional data of the functional characteristics of the sensor, identification of the most crucial parts of the system, comparison of several alternative designs, system optimization and calculation of operating regimes. The practical goal of this study is to develop and design a calorimetric microsensor with functional and technological characteristics as close as possible to the optimal ones.

ANALYTICAL MODEL

Let's consider a membrane in the form of a thin rectangular plate with cross section S and perimeter p with a heater and temperature sensitive elements located on it. The plate is assumed to be so thin that the temperature at all points of the cross section can be considered equal, allowing us to use a one-dimensional formulation of the task.

Consider the plate located on the X-axis, along which the gas flows with velocity U. The length of the plate in the x-direction is $2L$, the length of the heater is $2l$. Electrical power P is applied upon the heater. Temperature sensitive elements are located in $-L<x_s<-l$ and $l< x_s <L$ areas.

In order to calculate the steady-state temperature distribution in the plate, we can use a differential equation of heat conduction for an element volume, bounded by the sections passing through x and dx perpendicular to the X-axis:

$$\frac{\lambda}{\rho c}\frac{\partial^2 T}{\partial^2 x} - U\frac{\partial T}{\partial x} - \frac{Hp}{\rho c S}\left(T - T_{amb}\right) + \frac{P}{2l\rho c S} = 0\,, \tag{1}$$

where $T=T(x)$ is the temperature of the plate; T_{amb} is the temperature of the ambient environment; H is the coefficient of the heat exchange between the gas and the plate, ρ, c and λ are the density, specific heat capacity and the coefficient of thermal conductivity of the plate material, respectively.

In practice, one of the main problems of studying the heat transfer process in the "fluid – solid" system is determining a correct heat exchange coefficient H, which depends on many factors. In particular, fluid flow regime has a significant effect on the efficiency of the heat exchange, since it determines the mechanism of the heat transfer. In the laminar flow of the fluid the particles move without mixing so the heat transfer along the normal to the direction of motion is carried out by thermal conductivity. In the turbulent flow, the particles move randomly;

motion direction and velocity of individual particles are continuously changing and the heat transfer along the normal to the average flow direction is carried out both by thermal conductivity and by convection, where convective heat transfer can significantly exceed heat exchange by thermal conductivity.

To solve the problem of the heat transfer in full, in order to determine the coefficient of heat exchange, a joint solution should be found for the equations of continuity, motion (Navier-Stokes) and energy transfer. Solving these equations simultaneously is quite complicated, so it is practical to use methods of the similarity theory.

In order to not excessively complicate engineering calculations, an approximation formula to calculate the heat exchange coefficient is frequently used $H = a + b\sqrt{U}$, where a and b are the constants, determined from the condition of the best agreement with the data of certain experiment. In most practical cases the heat exchange coefficient is determined experimentally.

Using the approach suggested in [21], the solution of equation (1) is as follows:

$$\begin{cases} -L \le x < -l: \; T - T_{amb} = \left(T_{(-l)} - T_{amb}\right)\exp\left(\dfrac{U\rho c(l+x)}{2\lambda}\right)\dfrac{sh(\xi(L+x))}{sh(\xi(L-l))}, \\[2ex] -l \le x \le l: \; T - T_{amb} = \dfrac{\left(T_l - T_{amb}\right)\exp\left[-\dfrac{U\rho c(l-x)}{2\lambda}\right]sh(\xi(l+x)) + \left(T_{(-l)} - T_{amb}\right)\exp\left[\dfrac{U\rho c(l+x)}{2\lambda}\right]sh(\xi(l-x))}{sh(2\xi l)} + \dfrac{P}{2lHp}; \\[2ex] l < x \le L: \; T - T_{amb} = \left(T_l - T_{amb}\right)\exp\left(-\dfrac{U\rho c(l-x)}{2\lambda}\right)\dfrac{sh(\xi(L-x))}{sh(\xi(L-l))}, \end{cases} \quad (2)$$

where $\xi = \left[(U\rho c/2\lambda)^2 + (Hp/\lambda S)\right]^{\frac{1}{2}}$.

Figure 2 presents qualitative result of the calculation of steady-state temperature distribution in the membrane T=T(x) while the heater is in the mode of constant temperature for different gas flow velocity U = 0, 0.01 and 0.1.

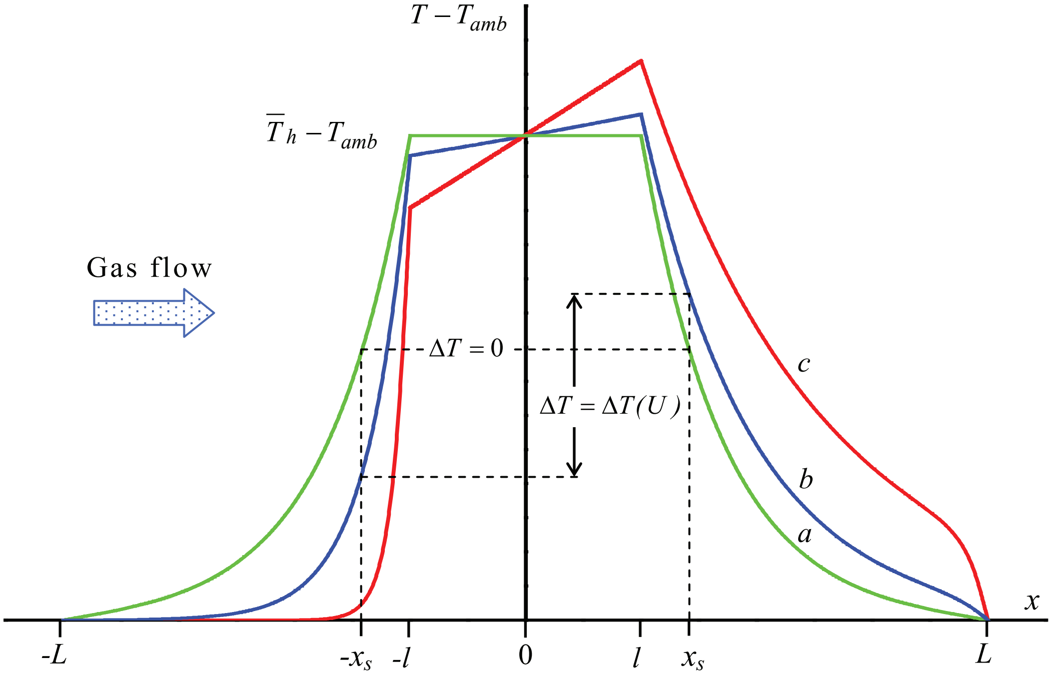

FIGURE 2. Steady-state temperature distribution in the membrane T=T(x), while the heater is in the mode of constant temperature for different gas flow velocity U = 0 (a); 0.01 (b) and 0.1 (c).

The temperature difference between the temperature sensitive elements located symmetrically downstream and upstream with reference to the heater is defined as:

$$\Delta T = T(x_S) - T(-x_S),\ (x_S > l). \tag{3}$$

As follows from Fig. 2, in the absence of directed gas flow ($U = 0$) the steady-state temperature distribution in the membrane $T=T(x)$ is presented as an even function and the temperature difference $\Delta T = 0$. The directed gas flow ($U \neq 0$) changes the temperature distribution in the membrane, both in areas downstream and upstream with reference to the heater and in the heating element; and the temperature difference $\Delta T \neq 0$. The temperature difference increases with the increase of velocity of the gas. The figure also shows that the temperature of the sensitive element located downstream close enough to the heater can exceed the average temperature of the heater.

MICROSENSOR

The thermal flow sensor must meet fairly strict functional, technological and mechanical requirements. The important functional requirements are high level of the valid signal, rapid response and low energy consumption. The sensor must be fairly durable and reliably protected from damage and contamination. The surface of the sensor must be chemically passive. The sensor manufacturing technology must contain the maximum number of standard microelectronic production operations.

In this study the equipment used for creating the sensor is defined by requirements for manufacturing integrated microcircuits. Manufacturing is performed in the microelectronic production in clean rooms and using standard equipment for the micro-electromechanical systems formation.

The microsensor is formed on the monocrystalline silicon plate. The manufacturing technology is integral, i.e. micromachining batch of plates containing hundreds of sensors on each plate is carried out in one manufacturing process, which makes possible to achieve uniformity of the parameters of the microsensor and low manufacturing cost of a single microsensor in a mass production.

Initially, a raw plate undergoes hydro mechanical and chemical treatments to remove technical contamination. At this stage, using the method of double-sided lithography two-way labels are formed. Labels are used to combine topologies of opposite sides of the plate in the process of photolithography in subsequent operations.

At the next stage the oxidation of the plate up to 1.2-2.0 μm in thickness on both sides is performed in order to obtain the etching mask membrane and insulation of the electrical circuit from the substrate. Afterwards a silicon nitride layer around 0.15 μm thick is applied to the surface of the planar side of the plate.

The following layer applied on a planar side of the plate is a doped polycrystalline silicon in order to form electric conductors, resistance of which depends on the temperature. For this purpose by gas-phase method the surface of silicon nitride is coated with 1 μm thick polycrystalline silicon; then polysilicon layer is alloyed with a dope. Alloying is performed according to a regime which ensures the highest Temperature Coefficient Resistance (TCR) with a sufficiently high level of linear dependency between resistance and temperature. The configuration of heating and four temperature sensitive resistors located on the membrane, as well as one resistor on the edge of the sensor used for measuring air temperature, are formed in this layer. The conductors system in order to put this configuration in the external circuitry for recording and processing the valid signal is also formed at this stage.

The electrical circuit in the polycrystalline silicon layer is formed by using the photolithography method. The sizes of the heater and the temperature sensitive resistors, as well as their location on the membrane, are determined on the basis of preliminary theoretical calculations according to developed analytical model and features of the available technology and equipment.

After this 0.2 μm thick silicon nitride is deposited on the formed surface of the planar side of the plate. Thus, the conductive layer is "packed" into impermeable cover of silicon nitride and is not under the threat of chemical effect of the environment and the technological reagents.

At the final stage the plate undergoes micromachining. With the use of previously formed labels a photolithography process is carried out in order to obtain the topology of the plate's surface as a whole, in particular lines for scribing and membranes etching masks are formed. In the membrane area on the non-planar side of the plate the monocrystalline silicon is etched to 10-20 μm thickness, which is sufficient to provide mechanical strength to carry out further operations.

At this stage bonding areas are formed by vacuum deposition of aluminum to subsequently put microsensor in external circuitry. To divide into individual crystals, on each of which a separate microsensor is formed, diamond scribing of the plate is performed.

The final step is the complete removal of the monocrystal silicon in membrane area to reduce the "parasitic" effect of the substrate and to remove the mechanical stresses conditioned by differences in the temperature of various materials' films formations. Thus, the bearing element of the membrane is nitride and oxide of silicon. As a result the total thickness of the membrane with circuitry located inside is less than 2 μm.

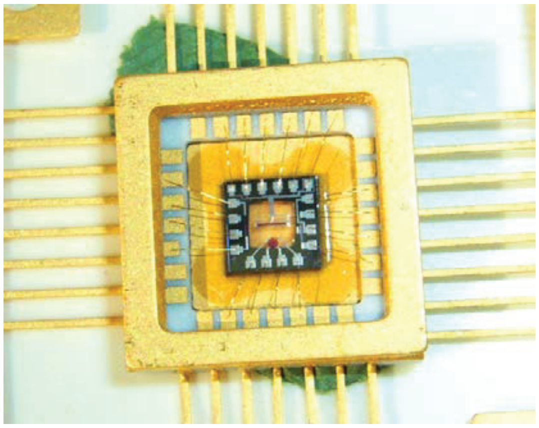

FIGURE 3. Microsensor in a testing case.

Figure 3 presents a microsensor in a testing case. The figure shows that the membrane is so thin that the gilded cover underneath it can be clearly seen. According to the measurements a typical resistance under normal climate conditions is: about 500 Ω for the heater and 4000 Ω for the temperature sensitive resistors. The resistors' temperature coefficient of resistance (TCR) α is $1.3 \cdot 10^{-4}$ (K^{-1}).

CONCLUSION

The main results of the performed study are the analytical model of the calorimetric flow sensor and a prototype of microsensor for mass air flow meter.

The developed analytical model of the sensor is suitable for engineering calculations. The design and manufacturing technology of the microsensor enable mass production, subsequent device assembly and reliable operation as well. The obtained results are important for the development, production and optimization of the thermal flow microsensors. The next stage of the research is the development and design of the mass air flow meter for automobile industry based on the calorimetric flow microsensor presented in this paper.

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