Journal of Applied Fluid Mechanics, Vol. 9, No. 5, pp. 1991-1996, 2016.
Available online at www.jafmonline.net, ISSN 1735-3572, EISSN 1735-3645.
DOI: 10.18869/acadpub.jafm.68.235.24600

Liquid Flow Meter based on a Thermal Anemometer Microsensor

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(Received January 24, 2015; accepted October 14, 2015)

ABSTRACT

An analytical model of a thermal anemometer sensor is developed. A thermal anemometer microsensor utilizing doped polycrystalline silicon is created. A liquid flow meter prototype based on a thermal anemometer microsensor is designed. Results of the flow meter testing are presented.

Keywords: Thermal flow sensor; Heat mass transfer; Liquid flow meter; MEMS.

NOMENCLATURE

a_f	coefficient of thermal diffusivity of fluid
c	specific heat capacity
D	inner diameter of cylindrical channel
H	coefficient of heat transfer
J_s	quantity of heat lost
L	length of the rod
Nu	Nusselt number
P	electric power
Pr	Prandtl number
Q	volume flow rate of fluid
q_h	quantity of heat generated or absorbed per unit of time per unit of volume
Re	Reynolds number
R_T	resistor's resistance under temperature T
S	area of contact
T_0	temperature corresponding to normal climate conditions
t	time
U	average velocity of liquid
V	voltage
α_R	temperature coefficient of resistance (TCR)
λ	coefficient of thermal conductivity
ρ	density of the rod material
ν_f	kinematic viscosity of fluid

1. INTRODUCTION

Correct measurement of transferable liquid volume in a system is certainly of both practical and theoretical interest. In theoretical aspect the major interest lies in the verification of the existing physical models, while practical uses include measuring water flow rate in water supply and cooling systems, process liquid flow control, gauging petrol volume at filling stations, etc. Liquid flow meters are widely used in engineering, power industry, transportation, housing and utilities services, medicine, mining, and construction.

Modern industry produces a significant number of liquid flow meter types based on different physical measuring principles (Lin 2011; Sridhara and Raghunandan 2010). Flow meters based on a thermal flow sensor (Elwenspoek 1999) have a number of advantages in comparison to sensors based on other measuring principles. The main advantages are as follows:

- high sensitivity;
- low level of output signal drift;
- no mechanically moving parts;
- high precision of measurements;
- no direct contact between the sensitive element and the fluid.

The general principle of flow measurement using thermal flow sensors consists in the dependency of convective heat transfer intensity on the fluid flow velocity. Thermal flow sensors can be divided by the principle of measurement into three basic groups: time of flight (TOF) sensors, thermal anemometers, and calorimetric sensors.

A review of thermal flow sensors for liquid and gas flow measurement was presented in our previous work (Sazhin 2013). One of the main conclusions of the review was that in the present day fast-evolving methods of forming micro- and nanoscale surface structures with enhanced service characteristics considerably expand opportunities for creating new sensor designs and their area of application. In particular, miniaturization of the sensors yields new possibilities to use them, significantly reducing manufacturing costs and energy consumption.

The present study is based on the most common thermal anemometer measuring principle. This choice is due to a number of factors, including three key advantages. First, the thermal anemometer principle is preferable for diagnosing large mass fluid flows such as liquid, as opposed to the calorimetric principle which is normally used for diagnosing gas flows. Second, the thermal anemometer measuring principle is simple enough for practical realization, while the time of flight and calorimetric principles are quite demanding to sensor topology. Last but not least, practical realization of thermal anemometer measuring principle meets the sensor durability requirements. For example, a calorimetric sensor in the form of a thin membrane can't withstand possible hydraulic shocks in the liquid flow.

Currently thermal anemometry is one of the most common experimental methods in measuring fluid flow rate and velocity. There is a large number of practical realizations of this method, from hot wire anemometers to hot film anemometers (Bruun 1996). One particular realization method involves determining the dynamics of the cooling process of an electrically heated element due to exchanging heat with the fluid. The heat transfer rate, in turn, depends significantly on the flow rate of the fluid. As electrical resistance of most materials considerably depends on temperature, the element's resistance should be measured in order to determine its temperature. Indeed, a resistor's resistance R_T under temperature T can be expressed as $R_T = R_{T_0}\left[1+\alpha_R\left(T-T_0\right)\right]$, where α_R is the temperature coefficient of resistance (TCR) and R_{T_0} is the resistor's resistance under temperature T_0, which corresponds to normal climate conditions. Thus, having defined the resistor's resistance R_T, one can derive the resistor's temperature T from the following formula: $T = T_0 + \alpha_R^{-1}\left(R_T/R_{T_0} - 1\right)$.

Thermal anemometers can be operated in three modes: constant power, constant temperature, and temperature balance. The first mode involves heating up a temperature-sensitive resistor with constant electric power and measuring its temperature. The characteristic time of the measuring process in this mode (the response time) is determined by heat capacity of the resistor's material and the intensity of exchanging heat with the environment.

In the second mode, the resistor's temperature is maintained constant, while the supplied electric power required for temperature stability is measured. In this mode thermal anemometers operate much faster than in the constant power mode.

The third mode involves measuring temperatures of two temperature-sensitive resistors located upstream and downstream within the fluid flow. The ratio of electric powers supplied to each resistor for maintaining zero-difference of the resistors' temperatures depends on the fluid flow rate.

Due to easy realization and rapid response, the constant temperature mode is more preferable for measurements based on the thermal anemometer principle.

The purpose of this study is the development of a relatively simple and applicable for engineering calculations analytical model of a thermal anemometer sensor for measuring fluid flow in the channel. The study's practical objective is to design and build a liquid flow meter based on a thermal anemometer microsensor.

2. ANALYTICAL MODEL

Let us consider a temperature-sensitive element (resistor) as a thin rectangular rod, which is positioned on the surface of a cylindrical channel of inner diameter D, in which liquid is moving with average velocity U. The temperature-sensitive element, that has electric resistance R, is heated up with direct electric current, for which purpose voltage V is supplied to it.

For calculating the temperature field in a solid body $T=T(x, y, z, t)$, the following differential equation of heat conduction (Carslaw and Jaeger 1959) is commonly used:

$$\frac{\partial T}{\partial t} = \frac{\lambda}{\rho c}\nabla T + \frac{q_h(x,y,z,t)}{\rho c}, \qquad (1)$$

where t is time; ρ, c, and λ are the density, specific heat capacity, and the coefficient of thermal conductivity of the rod material, respectively; q_h (x, y, z, t) is the quantity of heat generated or absorbed per unit of time per unit of volume.

Let us examine the operation of a temperature-sensitive element in the constant temperature mode where the element's temperature is maintained constant and the supplied electric power $P = V^2/R$ necessary for constant temperature is measured. Since the common practice is to calculate the mean integral temperature of the temperature-sensitive element, there is no need to precisely calculate the temperature field in the element. For that reason we consider the element's temperature to be uniform throughout the volume, i.e., not depending on the coordinates, and having the value close to the mean integral one. This significantly simplifies the heat conduction equation, which now for the entire temperature-sensitive element looks like this:

$$P - H(U)\cdot S\cdot\left(T - T_w\right) - J_s = 0, \qquad (2)$$

where H is the coefficient of the heat transfer between the liquid and the rod that depends on the liquid flow velocity U; S is the contact area of the temperature-sensitive element with the liquid; T_w is temperature of the liquid; J_s is the quantity of heat lost by the element as a result of thermal contact with the substrate per unit of time.

It is quite difficult to correctly calculate J_s due to the indeterminacy of heat contact between the temperature-sensitive element and the substrate. In practice heat contact with the substrate is minimized using modern technological methods and materials (Nassiopoulou 2005; Pagonis, Kaltsas and Nassiopoulou 2004). In order to avoid the need for calculating J_s, it makes sense to use the differential method of measurement. To this end, the frame supporting the two temperature-sensitive elements should be designed in such a way as to hold one element immersed in the liquid flow in the channel and the second element, a duplicate of the first one, in almost motionless liquid.

Both temperature-sensitive elements should have approximately similar thermal and physical characteristics, so that under the same conditions the same amount of heating produces equal J_s values for each element. Subtracting Eq. 2 for one element from the same for the other yields the following expression:

$$\Delta P = P_1 - P_2 = \left[H(U) - H(U=0)\right] \cdot S \cdot (T - T_w) \quad (3)$$

where P_1 and P_2 are electric powers supplied to the temperature-sensitive elements placed in moving liquid and liquid at rest, respectively. As it follows from the Eq. 3, having determined the dependency of the coefficient of heat transfer H on the average velocity of liquid flow U, one can calculate the value of U.

To solve the problem of heat transfer in its entirety in order to determine the coefficient of heat transfer H, we need to use Navier - Stokes equations together with the equation of energy transfer. Solving these equations is a complex task, therefore in practical calculations methods of the similitude theory are used.

The similitude equation for heat transfer in forced movement of fluid looks like $Nu = f(Re; Pr)$, where Nu, Re and Pr are the similitude criteria: Nusselt, Reynolds and Prandtl number, respectively. When fluid flows over a rod under a uniform temperature positioned on the surface of a cylindrical channel of diameter D, a similitude equation can be written as a system of equations for each flow regime as follows (Incropera *et al*. 2007):

$$Nu = \begin{cases} 0.664 Re^{\frac{1}{2}} Pr^{\frac{1}{3}} & \text{for laminar regime,} \\ (0.037 Re^{\frac{4}{5}} - A) Pr^{\frac{1}{3}} & \text{for mixed regime} \\ 0.037 Re^{\frac{4}{5}} Pr^{\frac{1}{3}} & \text{for turbulent regime,} \end{cases} \quad (4)$$

where $A = 0.037 Re_{cr}^{\frac{4}{5}} - 0.664 Re_{cr}^{\frac{1}{2}}$ and Re_{cr} is critical Reynolds number. The similitude criteria in this system of equations can be expressed as $Nu = H\,L/\lambda_f$, $Re = UD/\nu_f$ and $Pr = \nu_f / a_f$, where λ_f is the coefficient of thermal conductivity of the fluid; ν_f is its kinematic viscosity; a_f is the coefficient of thermal diffusivity; and L is the length of the rod.

A transition from laminar to turbulent flow regime can happen when the critical Reynolds number Re_{cr} is reached. When $Re < Re_{cr}$, the flow proceeds in laminar regime; when $Re > Re_{cr}$, the turbulence may emerge. The critical Reynolds number value for a fluid flow in a cylindrical channel is $Re_{cr} \approx 2300$. A developed turbulent regime comes about with $Re > 1 \cdot 10^4$, and the range of Re values from $2 \cdot 10^3$ to $1 \cdot 10^4$ corresponds to a mixed flow regime. The relation between average velocity U of fluid flow in a cylindrical channel and volume flow rate Q through the channel can be expressed as follows:

$$U = 4Q / (\pi D^2) \,. \quad (5)$$

In order not to complicate engineering calculations, it is common practice to use the approximation formula for determining the heat transfer coefficient $H = a + b\sqrt{U}$, where a and b are constants consistent with the data obtained as a result of a given experiment. Using this formula in Eq. 3, we can get a simple relation between differences in electric powers supplied to the temperature-sensitive elements in moving and motionless liquid, and the average velocity of liquid flow, as $\Delta P = b\sqrt{U} \cdot S \cdot (T - T_w)$.

Since the temperature-sensitive element operates with its temperature maintained constant, then, considering Eq. 5, we can arrive at the following relation:

$$\Delta P = k \cdot \sqrt{Q} \,, \quad (6)$$

where k is a free parameter that can be determined by processing the experimental data using the least squares method.

Analyzing the system of Eq. 4, we may presume that the best possible fit with the experimental data can be achieved using the following relation:

$$\Delta P = k \cdot Q^{\gamma} \,, \quad (7)$$

where parameter γ is within the range from $\frac{1}{2}$ to $\frac{4}{5}$.

The same way a voltage calculation formula can be deduced from Eq. 2. In order to maintain constant temperature of the sensitive element in liquid flow, the voltage needed can be determined as follows:

$$V = \left(\alpha Q^{\gamma^*} + \beta\right)^{\frac{1}{2}} \,, \quad (8)$$

where α and β are the free parameters, γ^* is the value obtained by processing the experimental data

(a) **(b)**

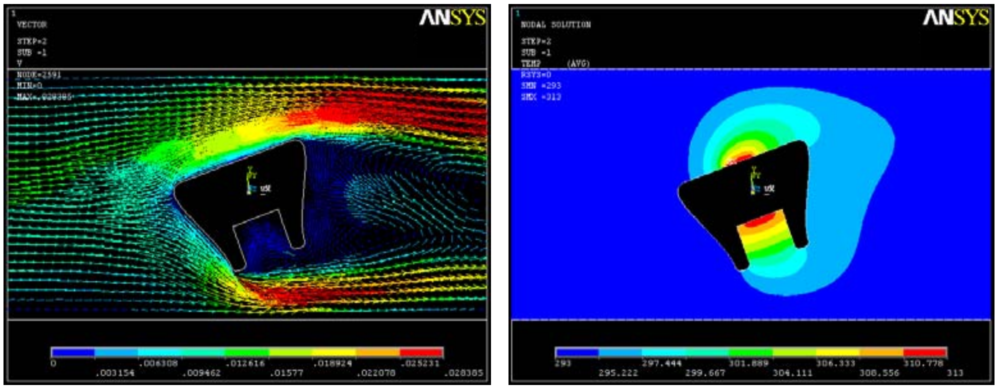

Fig. 1. Distribution of velocity (a) and temperature (b) of water flowing over the holding frame inclined at a 20 degrees angle towards the flow with a velocity of $1{\cdot}10^{-2}$ m/s.

using the least squares method with Eq. 7 as the approximation formula.

3. LIQUID FLOW METER

The basic element of a liquid flow meter is a thermal anemometer microsensor. For this study, temperature sensitive resistors were made of polycrystalline silicon by gas-phase deposition under lowered pressure. The produced film resistors were approximately 1 μm thick. The sensor's topology, created using photolithography, is comprised of a measuring resistor with 150 Ohm resistance, two resistors with high resistance (approximately 3.2 kOhm) for measuring the ambiance temperature, and a system of conductors and lands for connecting the resistors to external circuitry.

To increase the resistors' temperature coefficient of resistance α_R of resistors, polysilicon doping was performed so as to ensure the highest value of α_R while keeping the linear nature of the dependency between resistance and temperature sufficiently high. The resulting temperature coefficient of resistance α_R was approximately $1{\cdot}10^{-3}$ (K^{-1}).

For protection from aggressive environment, the resistors are covered with a thin layer of silicon nitride. The technological process of producing polycrystalline silicon-based microsensors is described in our other work (Sazhin 2013).

The manufactured prototype of a liquid flow meter consists of the following components:

- two thermal anemometer microsensors;
- microsensors holding frame;
- external circuitry for valid signal record, amplification, and processing;
- meter housing for setting the other components securely in place and waterproof sealing.

In order to determine the best configuration and placement of the holding frame in the channel so as to allow for the differential measuring method, a numerical simulation of the problem was carried out using the Finite Element Method (FEM) and ANSYS simulation software (www.ansys.com). As an example of the simulation results, Fig. 1 shows the distribution of velocity (a) and temperature (b) of water flowing over the holding frame inclined at a 20 degrees angle towards the flow with a velocity of $1{\cdot}10^{-2}$ m/s.

Based on the simulation results, the microsensor holding frame was manufactured so as to hold the first microsensor on the surface of the frame where the liquid flow velocity is close to the average velocity in the channel, and the second microsensor – in a recessed groove where, according to the performed simulation, the liquid can be considered motionless.

Tests of the flow meter prototype were carried out in compliance with the differential measuring method in constant temperature mode. Tap water under normal conditions was used. The volume flow rate Q of water flowing through the tube with the inner diameter of 25 mm, in which the flow meter was positioned, was measured by timing the flow filling up a 10-liter container.

Fig. 2 demonstrates the amounts of electric power of P_1 and P_2, supplied to the first and second temperature-sensitive resistors, respectively, for maintaining the constant temperature difference $T - T_w = 5$ K depending on the water volume flow rate Q. As it follows from Fig. 2, the amount of electric power P_1 significantly depends on water flow rate Q, unlike the amount P_2 that almost doesn't depend on Q. Thus, the results of the computational simulation were consistent with the experimental data, allowing us to claim that the holding frame designed according to the results of the computational simulation was effective for using within the differential measuring method.

Unfortunately, in this study there was opportunity to obtain closely matching thermal and physical characteristics of the two microsensors positioned in moving and motionless liquid, respectively. Indeed as it follows from Fig.2, in case of no water flow (Q = 0) the electric power amounts supplied to the resistors for maintaining the same temperature difference are different.

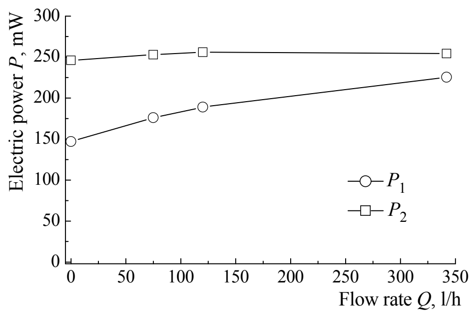

Fig. 2. Amounts of electric power P_1 and P_2 supplied to the temperature-sensitive resistors, located on the surface of the holding frame and in the recessed groove, respectively, for maintaining constant temperature difference T - T_w = 5 K depending on the water volume flow rate Q.

In fact, precisely matching characteristics would have been difficult to achieve within this work due to it being a research effort. If and when microsensors become a mass production article, their thermal and physical characteristics will be nearly identical. The integral technology of microsensor manufacturing (Sazhin 2013) for air mass flow sensor (Sazhin 2014) can attest to that. Indeed, this technology involves chemical and micromechanical batch processing of plates with hundreds of sensors on each plate, accomplished within one manufacturing process, which makes it possible to achieve uniformity of the microsensors' characteristics. At this stage of designing the liquid flow meter, the uniformity of thermal and physical characteristics of the microsensors is not essential. One of the study's main objectives is verification of the obtained results.

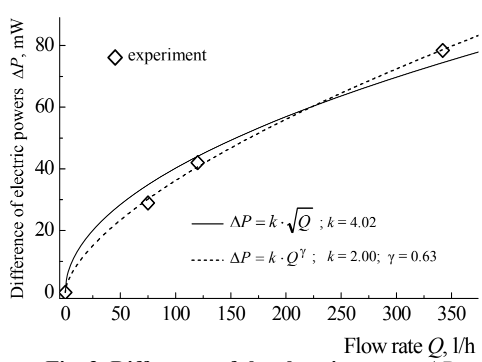

Fig. 3. Difference of the electric powers ΔP supplied to the temperature-sensitive element in moving and motionless water as a function of the water volume flow rate Q.

To verify the analytical model developed in the course of this work, a comparison of the model results to the experimental data was made. One result obtained by using the analytical model is represented in the formulas Eq. 6 and Eq. 7 that express the relation between the difference of the electric powers ΔP supplied to the temperature-sensitive elements in moving and motionless liquid, and volume flow rate Q of the liquid in the channel. Since the microsensors used in the experiment have different thermal and physical characteristics, in order to make a valid comparison we must use experimental data obtained from one sensor as follows: $\Delta P = P_1(Q) - P_1(Q = 0)$.

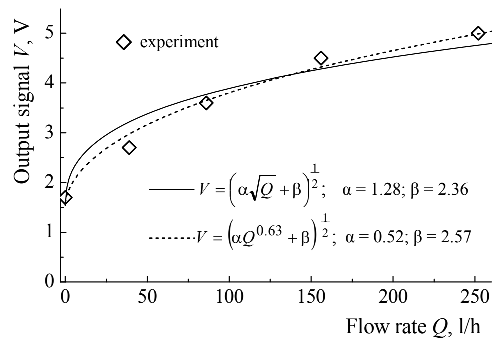

Fig. 4. Voltage V (output signal of the flow meter) required to be supplied to the temperature-sensitive element in water flow for maintaining its temperature constant as a function of the water volume flow rate Q.

Fig. 3 demonstrates a comparison of the results of analytical model with the corresponding experimental data. As it was suggested, the best fit with the experimental data was obtained using Eq. 7. The increase of coefficient γ from 0.5 to 0.63 indicates the presence of turbulence in the water flow. Indeed, as it follows from Eq. 4, value γ = 0.5 describes the fluid flow in laminar regime. In the present experiment, the complex shape of the holding frame, in particular, may have caused the flow's turbulization.

Equation 8 of the analytical model represents the amount of voltage V that must be supplied to the temperature-sensitive element in fluid flow for maintaining its temperature constant as a function of fluid volume flow rate Q. Fig. 4 shows experimental and theoretical dependence of voltage V (output signal of the flow meter) on the flow rate value Q of water in the channel. As it follows from the Figure, the consistency can be observed between the results of the analytical model and the experimental data. As in previous case, the best fit was obtained with γ = 0.63.

4. CONCLUSION

The main results of performed work are the following:

- an analytical model of a thermal anemometer sensor;
- a thermal anemometer microsensor based on doped polycrystalline silicon for a liquid flow

meter;

- a prototype of a liquid flow meter;

- the flow meter test results.

Based on the results, the following key conclusions can be drawn.

– The developed analytical model of a thermal anemometer sensor adequately describes obtained experimental data.

– The microsensor is simple and compact in design, all-purpose and reliable in operation. The microsensor's design and manufacturing technology allow for simple mass production and improvements.

– The suggested design of the holding frame allows to use the differential method of flow measurement.

– Tests performed on the prototype of a liquid flow meter using the differential measuring method showed that the output signal level is sufficient for carrying out measurements of liquid flow rate in a wide range of values.

Generally, the obtained results are important for the design, production, and optimization of liquid flow meters.

ACKNOWLEDGEMENTS

The support by the Ministry of Education and Science of the Russian Federation through the base part of the State task for high educational institutions (the research project #2189) is gratefully acknowledged. This work was partly supported by Act 211 Government of the Russian Federation, contract № 02.A03.21.0006.

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