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High sensitivity calorimetric sensor for flow measurements

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Industrial mass flow controllers (MFC) are limited to high-sensitivity measurements. Two methods for mass fluid flow detection and measurement are presented in this work. The flow sensor consists of a temperature sensor and a reference thermistor to accurately detect laminar flows with high sensitivity. The thermistor is self-regulated maintaining a positive temperature coefficient (PTC) due to the utilization of resistive Joule heating. This, in turn, ensures constant power dissipation to the fluid. Measurement of transient fluid flow is achieved through variations in the enthalpy advection to the fluid. The relationship between the enthalpy advection and the fluid flow is found to be in agreement with the first-order model for high sensitivity response to temperatures. Finally, we have shown superior sensitivity of the measured flow in comparison with that of the available commercial MFC devices.

Keywords: Thermal response test, ground thermal properties, borehole heat exchangers

INTRODUCTION

Positive temperature coefficient (PTC) semiconductors are prepared from oxide materials such as $BaTiO_3$, through ceramic technology or films. Depending on the material composition the thermal resistance can be changed linearly or non-linearly with respect to the surface contact with a substance flow, liquid, or gas. Linear PTC thermistors are used for a wide range of temperature sensing applications and non-linear PTC thermistors are typically used for low-range temperature sensors [1, 2], anemometers [3, 4], liquid level detectors [5] and heating elements [6]. Another intrinsic characteristic of a PTC thermistor is the Joule heating effect. When a current flows in the PTC resistive thermistor it gets hot, and the generated heat results in an internal temperature increase. Due to the variable thermal resistance of PTCs and in order to maintain constant temperature at the PTC, its current varies in accordance with the thermal load of the flowing fluid. This phenomenon is called self-regulated heating. PTC thermistors are widely used as analogue thermal switches in electro-mechanical appliances and as controllers in the food, chemical, medical, and automotive industries. The main challenge in applying PTC thermistors as flow sensors lies in the non-linear dependence of their thermal resistance and in correlating their physical dimensions to the liquid or gaseous flow. The self-regulated heating phenomenon is widely used in flow level detection, anemometry and voltage and current limiters heavy duty electrical appliances.

These PTC-based self-regulated heaters provide high sensitivity at a relatively low cost and complexity, compared to the discrete solutions. Since the signal from a thermistor depends on the fluid temperature a second PTC is positioned next to the sensor, outside the flow (liquid or gas) to measure the fluid temperature. In our study we investigated the convection of fluid mixtures in order to determine their flow rates. For this purpose, we assumed uniform concentration of each fluid at the probe surface and in the continuous phase far from the probe [7]. The aim of this work was to design a method for measuring a wide range of fluid flows based on heat advection from the PTCs to the fluid, develop a mathematical model for determining the flow rate and carry out analysis of other various methods for signal conditioning to increase measurement efficacy.

HEAT TRANSFER

Application of the first law of thermodynamics to an infinitesimal Newtonian fluid of uniform composition with constant properties, may be used to measure fluid velocity [8]:

$$P_{diss} = I_t^2 R_t = h(v) A_s (T - T_\infty) \qquad (1)$$

where:

P_{diss} - Power dissipated by Joule heating, W;
I_t – Current through the thermistor, A;
R_t – Thermistor's resistance, Ω;
h(v) – Heat transfer coefficient, W/m^2K;
A_s – Surface area, m^2;
T – temperature at the solid fluid interface, K;
T_∞ - Fluid temperature far from the probe, K;

The relation suggested by King [8] for the fluid velocity is given by:

$$hA_s = a + bv^n \qquad (2)$$

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where a and b are constants given by the dimensionless Reynolds and Prandtl numbers. These constants depend on the fluid and system properties and the power n of the fluid in Eq. (2) typically equals to 0.5 for a laminar fluid flow. PTC thermistors resistance increases with the increase of temperature and is described by an exponential relation Eq. (3). The relationship between thermal resistance and temperature in turn, yields a model of the PTC temperature, relative to the heat dissipated by Joule heating to the fluid, as shown in Eq. (5).

$$R(T) = R_0 e^{b(T-T_0)} \tag{3}$$

$$h \sim v^{0.5} \tag{4}$$

$$R(v) = R_0 e^{-\frac{b^2}{2}v^2 - T_0 + T_f} \tag{5}$$

where:
$R(v)$- PTC resistance, Ω;
R_0 – PTC reference resistance, Ω;
b – PTC temperature coefficient;
v – Fluid velocity, m/s;
T_0 – PTC reference temperature, K.

The PTC resistance is highly dependent on variation of the fluid velocity due to the forced convection. For precise measurements of the fluid velocity, the fluid temperature is determined at a reference point of the PTC in the exponential resistance zone. Calibration of the fluid velocity/temperature relationship in the exponential resistance regime of the PTC, is the basis for all measurements. It is important to set the reference point of the thermistor in the exponential regime in order to maintain high sensitivity and set reference points at the limits of the working conditions.

Constant power configuration

In Fig. 1, the control volume of the proposed model is presented. A reference thermistor T_{s1} measures the fluid temperature while a PTC heated thermistor T_{s2} detects the thermal load of the fluid, trying to maintain a constant temperature [9]. The relation between the two signals can be observed using a Whitson balanced bridge, shown in Fig. 2, in order to digitize its open-circuit voltage. An instrumentation amplifier can be used to match the signal obtained from the bridge and the analog-to-digital converter (ADC), to increase its efficiency [10]. On one hand, the current flow through T_{s1} needs to be minimal in order to avoid temperature reading error due to the Joule heating, and on the other hand, T_{s2} draws increased currents in order to maintain a constant temperature difference between the fluid and the probe. These constraints prevent a proper balanced bridge operation; therefore a second PTC could not be applied as T_{s1} reference temperature sensor. A second resistive negative temperature coefficient (NTC) thermistor can be applied and satisfy the above constraints. NTC temperature reading can be calculated using the well-known Steinhart-Hart equation [11].

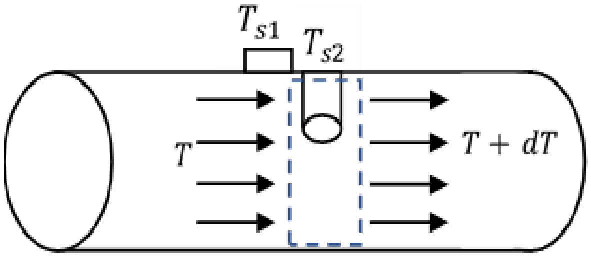

Fig. 1. Schematic structure of the flow sensor

$$\frac{T_{s1}}{T_{s2}} = \frac{R_1}{R_2} \tag{6}$$

Following Eq. (6) for a balanced bridge, the relation between the PTC and NTC for fluid temperature (T_{S1}/T_{S2}), equals the relation between R_1 and R_2, where R_1 is used to limit the NTC current and reduce self-heating errors, and R_2 can be selected with low values to enable high power dissipation in the probe. That results in a highly resistive NTC thermistor compared to the PTC.

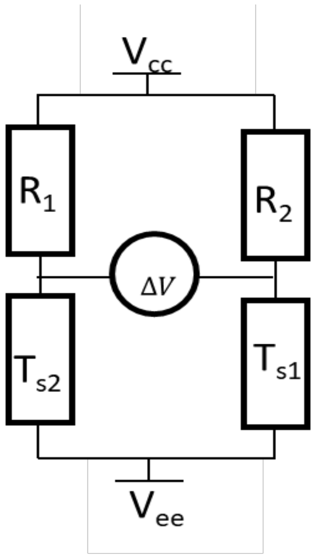

Fig. 1. Resistors bridge for accurate sensor reading

The proposed procedure is suggested for the measurements of Eq. (4) constants:

- Measurement of the PTC resistance temperature curve, and the I-V curve.
- Measurement of the PTC Curie temperature and the corresponding resistance.

- Measurement of the PTC zero velocities temperature and corresponding resistance.
- Determination of the constants according to both reference fitting points.
- Measurement of the NTC resistance with constant fluid temperature.
- Balancing the bridge using either the NTC or replacing it with a constant resistor of the value calculated above.

The main drawback of the proposed model is the lack of temperature compensation in case the fluid temperature varies, and high-power consumption.

Transient response

Another proposed approach for measuring the fluid velocity is by means of the rate of enthalpy advection over the cross-section of the PTC thermistor. As the PTC self-regulates the power dissipated to the fluid, the transient step response of the PTC to the heating signal is proportional to the thermistor and fluid mechanical properties, heat capacity, and mass transfer coefficients. Starting from the energy balance of Eq. (7), a first-order differential equation is obtained Eq. (8):

$$P_{diss} = h(v)A_s(T\text{-}T_\infty) + mc\frac{dT}{dt} \quad (7)$$

where:

m - probe mass, Kg;
c – specific heat, J/K;

$$mc\frac{dT}{dt} + hA_sT = P + hA_sT_\infty \quad (8)$$

The solution of Eq. 8 is in the exponential trend as in Eq. (9):

$$T(t) = K(1\text{-}e^{\frac{t}{\tau}}) \quad (9)$$

where:

$$\tau = \frac{mc_p}{hA_s} \quad (10)$$

$$K = \frac{P + hA_sT_\infty}{hA_s} \quad (11)$$

As obtained from Eq. (9), the time constant and the maximum temperature are both dependent on the fluid velocity, as presented in Eqs. (10, 11). It can be noted that high thermal response can be achieved by reducing the probe thermal mass, by decreasing its dimensions.

MEASUREMENT SYSTEM

In the experiment, a cylindrical stainless probe, a PTC thermistor (TDK Electronics B59010D1135B040) was taken as the enthalpy sensing element. Its diameter is 2 mm and the length exposed to fluid is about 3 mm. The stainless probe NTC (Littlefuse USP7806) was used to measure the fluid temperature. During the measurement the PTC was heated with constant voltage and thus constant power. The heat was then transferred to the flowing fluid – N_2, since the gas density is known, it is more convenient to measure the mass flow rate. As shown in Fig. 2 a Wheatstone bridge was used in the flow measurements to obtain the electrical resistance change in time and the temperature change with time. The sensors were inserted in a T shape connector as shown in Fig. 3 and thermal epoxy was used for sealing. Using a 15 VDC power supply the maximum power dissipation was measured at 300 mW.

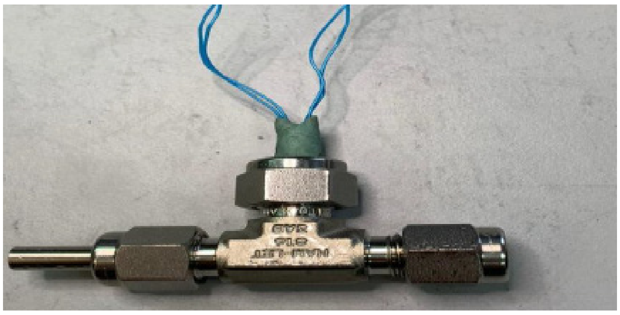

Fig. 2. Assembly of two thermistors in T shape ¼” Swagelok connector

RESULTS AND DISCUSSION

Various flows were applied using a mass flow controller (MFC) and the system response for both constant power and transient conditions were measured. For constant power dissipation, the measurement was taken after verifying that the system had reached thermal equilibrium, resulting in a data acquisition (DAQ) system for display. The results obtained are shown in Fig. 4.

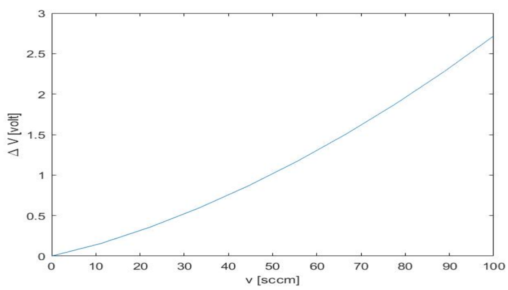

Fig. 3. Voltage difference obtained from the Wheatstone bridge in response to the variation of the fluid velocity

High sensitivity was achieved even for a low flow rate up to the highest resolution of the industrial MFC. Transient response was measured using an operational amplifier (OA) in order to indicate that the balanced bridge has crossed its reference voltage (0.69V) of the full bridge voltage. In Fig. 5. the measured temperature difference between the probe and the fluid is displayed for various flow rates. The expected behavior of the increased response time, while the fluid flow increases, may indicate a high sensitivity at the lower flow rates. When the PTC behaves exponentially poor response is obtained for higher flow rates.

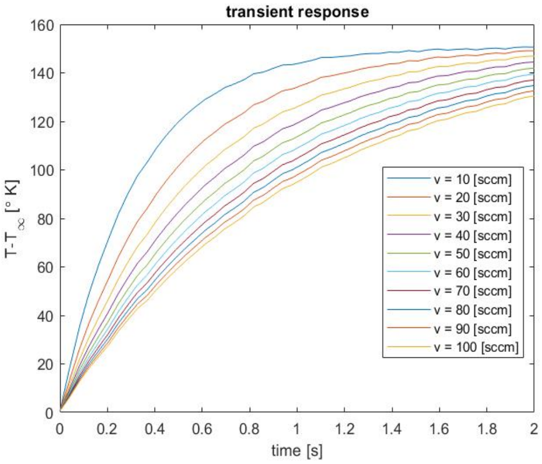

Fig. 4. Transient response of PTC for different mass flow rates

The results presented in Fig. 6 indicate the increase of thermal constant time as a function of the flow rate in the sensor.

CONCLUSIONS

Two methods were proposed for measuring the fluid velocity by a thermal flow meter. A PTC was suggested for the measurements due to the exponential response of the fluid's Curie temperature, relative to the velocity. This enables the detection of low velocities. Due to the self-regulation of the PTC, no external current source is needed to maintain the hot wire at constant temperature and thus the circuit implementation is easier in comparison with conventional resistive thermal flow sensors. As the resistive heater method suffers from high power consumption, the self-regulated PTC method is favourable due to transient response for low power working conditions. The results obtained in the experiments show high sensitivity in comparison with an industrial MFC.

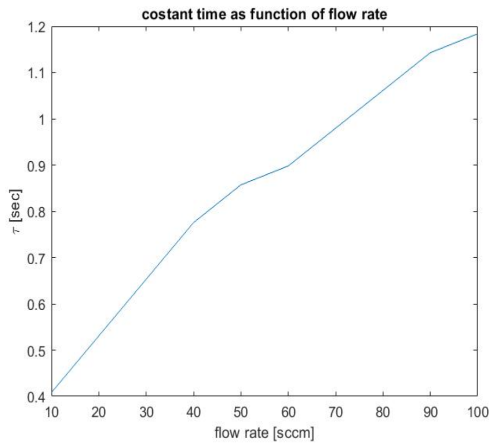

Fig. 5. Thermal constant time as function of flow rate

NOMENCLATURE

A_s – Surface area, m^2;
b – PTC temperature coefficient;
c – Specific heat, J/K;
h(v) – Heat transfer coefficient, W/m^{2}K;
I_t – Current passing through the thermistor, A;
m - Probe mass, kg;
P_{diss} - Power dissipated by joule heating, W;
R_t – Thermistor's resistance, Ω;
$R(v)$- PTC resistance, Ω;
R_0 – PTC reference resistance, Ω;
T – Temperature at the solid fluid interface, K;
T_∞ - Fluid temperature far from the probe, K;
T_0 – PTC reference temperature, K;
v – Fluid velocity, m/s.

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