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# Design and Analysis of an Instrumentation System for Precise Flow Measurements

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***Abstract*—The contribution of this research is in suggesting the design of an electronic anemometer incorporated into an instrumentation system for precise flow measurements. The flow sensor employs thermistors imbedded in a Wheatstone bridge. To achieve very high accuracy of flow measurements, a feedback assembly is applied. It reduces the measurement error, making it negligible and keeps signal equilibrium at a specific low flow rate. A proper signal conditioning may link the achieved data to a process control and a display. Analysis of the anemometer circuit and testing it in real environment proves its effectiveness in improvement the accuracy of measurement of very low flow rates.**

***Keywords—Flow; Anemometer; Error; Sensors; Accuracy; Measurement; Thermistors; Feedback; Equilibrium; Signal conditioning;***

## I. INTRODUCTION

In most industrial applications measurement of very low flow rates is required with fair accuracy. Fluid flow measurements are used in many cases, such as industrial process control, water supply systems, fluid pipeline systems and irrigation systems. Fluids like natural gas, petroleum, oxygen and any other fluid may flow to customers or industrial processes on a continuous basis. Precise online measurement of the quantity of supply is essential either for payment purposes or for a precise process control.

The conditions under which the flow occurs result in many types of flow measurement methods. Apart from the numerous mechanical flow meters, there are also different patented versions of thermal anemometers. All of them stand on the concept that fluid carriers cool down a sensor and the cooling off varies as the fluid flow changes [1]. These transducers are designed to measure the velocity at a point in the flow area. Most of these anemometers have the disadvantages of either the complexity of their structure, or they introduce an error of measurement.

The present research has the objective to suggest a design of an anemometer that can measure low flow velocity with much greater accuracy. The flow sensor consists of two identical thermistors, connected in a Wheatstone bridge configuration. One of them is exposed to the flow, while the other is in a closed chamber, protected from the flow. The bridge is balanced with no flow at all. Then both sensors are subjected to the same ambient temperature. When flow is applied, the exposed thermistor changes its resistance and the developed output voltage of the Wheatstone bridge is proportional to the flow velocity. The instrumentation system at this state is an open-loop configuration. It can measure successfully the flow rate, but with a considerable error, due to the difference in the self-heating effect in the two thermistors embedded in the bridge [2]. To achieve very high accuracy of flow rate measurements, a feedback arrangement within the sensor system is applied. It reduces considerably the measurement error, bringing it to negligible values, at the same time maintaining signal equilibrium at a specific low flow velocity.

## II. DESIGN AND ANALYSIS OF AN OPEN-LOOP FLOW MEASUREMENT SYSTEM

An instrumentation open-loop anemometer system for measurement of flow velocity is shown in Figure 1. It consists of a Wheatstone bridge and a signal conditioning circuit. Thermistors are positioned as two of the Wheatstone bridge arms. The first thermistor, with resistance $R_{T1}$, is exposed to the flow under measurement. The second thermistor, having a resistance $R_{T2}$, is placed in a closed chamber that is protecting it from the flow and is positioned in the vicinity of the first thermistor.

The Wheatstone bridge is balanced when there is absence of flow [3], [4]. At this condition, the two thermistors operate at exactly the same temperature and therefore they have same resistances, as seen in this case from Figure 1, $R_{T1} = R_{T2} = 3.747\text{k}\Omega$.

When positioned in a flow environment, the temperature of the exposed thermistor reduces and its resistance $R_{T1}$ increases to $R_{T1} = 5.97\text{k}\Omega$ as seen from Figure 1 and from the characteristic shown in

Figure 2. As a result, the Wheatstone bridge becomes unbalanced and its output voltage is subjected to proper signal conditioning provided by the operational amplifiers *OA1* to *OA4*. The purpose of the signal conditioning is to buffer the signal obtained from the Wheatstone bridge and also to provide a proper amplification [4], [5].

The operational amplifiers *OA1* and *OA2* are voltage followers with very high input resistances protecting the exact resistor settings of the Wheatstone bridge. The amplifier *OA3* operates as a difference amplifier, while *OA4* is an inverting amplifier. Depending on their settings, the output voltage of the instrumentation system can be displayed directly in terms of the flow velocity.

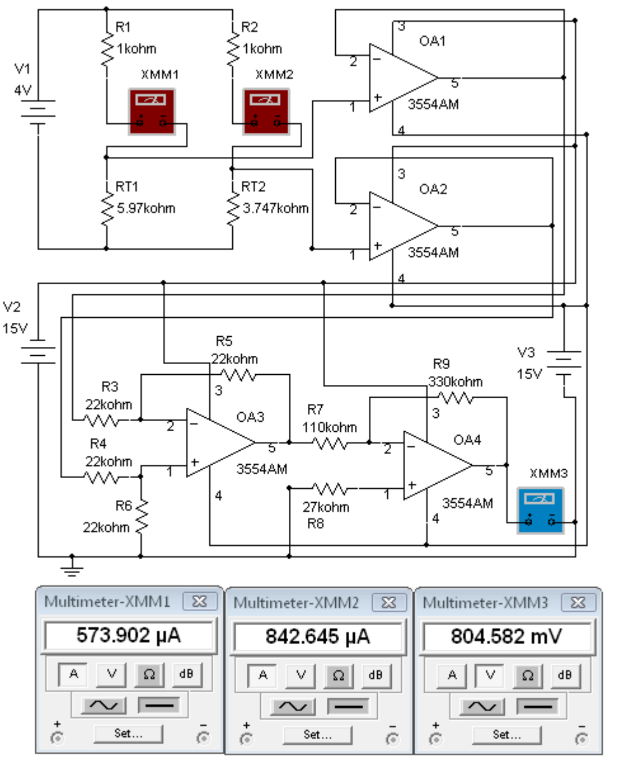


*Figure 1: Open-Loop Flow Measurement System with Thermistor $R_{T1}$ Exposed to Flow*

The power ($P = I^2 R_T$) dissipated in a thermistor will heat it up above the actual temperature under measurement. The self-heating temperature rise in thermistors is considered as the *Self-Heating Error* [3], [4], [5] and can be found from the power dissipated by the thermistor and its corresponding dissipation constant as follows:

$$\Delta T = \frac{I^2 R_T}{P_D}, °C \qquad (1)$$

where

- $\Delta T$ is the rise of temperature in the thermistor as a result of the self-heating effect in [°C]
- $I$ is the current via the thermistor in [A]
- $R_T$ is the thermistor resistance in [Ω]
- $P_D$ is the thermistor dissipation constant in [W/°C]

Suppose that the two identical thermistors used for the case have resistances $R_T$ = 3747Ω at 20°C and their dissipation constant is $P_D$ = 5mW/°C. Hence, in absence of flow, if the Wheatstone bridge is balanced at 20°C, both thermistor sensors will have equal resistances $R_{T1} = R_{T2} = R_T$ = 3747Ω. At this condition, the currents via both thermistors are equal, $I_1 = I_2$ = 842.645 µA, as seen from the electronic circuit shown in Figure 1. The *Self-Heating Errors* due to power dissipation in both thermistors are determined as:

$$\Delta T_1 = \Delta T_2 = \frac{I^2 R_T}{P_D} = \frac{(0.842654 mA)^2 \times 3747\Omega}{5\, mW/°C} \approx 0.532°C \qquad (2)$$

Since the thermistors *Self-Heating Errors* in this case are equal, they do not affect the balance of the bridge and therefore the output voltage of the bridge is measured without any error.

Further, if the thermistor $R_{T1}$ is exposed to flow, its temperature decreases, for instance, from 20°C to 10°C causing increment of its resistance from $R_{T1}'$ = 3747Ω to $R_{T1}''$ = 5970Ω, as shown in Figure 1. Also, as seen from the thermistor characteristic in Figure 2, the operational point A is shifted to point B.

The *Self-Heating Error* of the sealed thermistor do not change and still is $\Delta T_2$ = 0.532°C.

But considering that now $I_1$ = 573.902 µA, the *Self-Heating Error* of the exposed to flow thermistor changes and can be determined as:

$$\Delta T_1 = \frac{I^2 R_T}{P_D} = \frac{(0.573902 mA)^2 \times 5970\Omega}{5\, mW/°C} \approx 0.393°C \qquad (3)$$

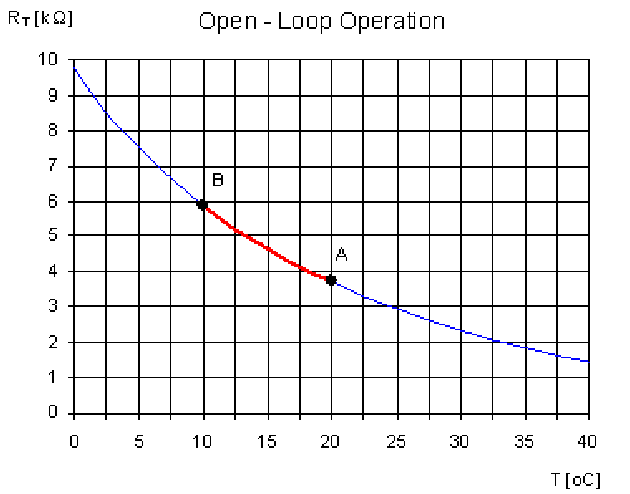


*Figure 2: Open-Loop Operation of the Thermistor Sensor*

In this case, the difference of the *Self-Heating Errors* of the two thermistors is:

$$\Delta T = 0.532°C - 0.393°C = 0.139°C \qquad (4)$$

This difference will cause an error in measurement. The bridge output voltage $V_o$ = 804.582 mV, as shown in Figure 1, is in fact larger than its real value and therefore the flow rate will be displayed also as larger value than the real one.

## III. Design and Analysis of a Precise Closed-Loop Flow Measurement System

To reduce the error of measurement, the output of the bridge can be involved in a negative feedback that keeps the operating temperatures of both thermistors at very small difference. In this case, the thermistor exposed to the measured fluid flow, is supported by a copper plate around which is wound an insulated thin copper wire. This wire operates as an additional heater to the exposed thermistor and its resistance is represented by $R_H$, as seen from Figure 3.

In absence of fluid flow both thermistors will be at same temperature and have equal resistance values. At this state, the Wheatstone bridge will be completely balanced and there will be no heating-up current via the wire wound around the copper plate.

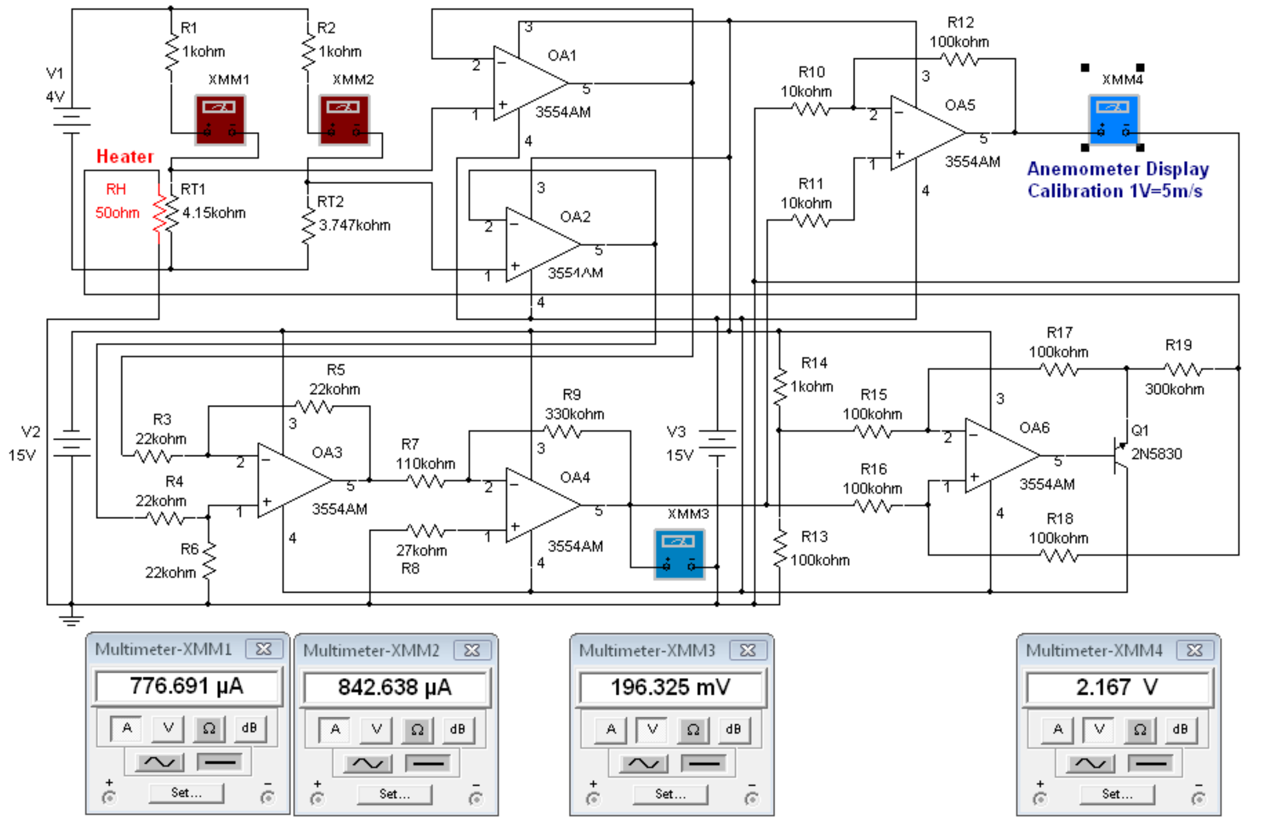


*Figure 3: Closed-Loop Precise Flow Measurement System with Thermistor $R_{T1}$ Exposed to Flow and Heat Compensated*

When the sensor mounted on the copper plate is exposed to flow, its temperature decreases and its resistance $R_{T1}$ increases. The increment in resistance results in a Wheatstone bridge unbalance. Its output voltage is conditioned and fed back to the coil with resistance $R_H$ wound around the copper plate. The coil and therefore the copper plate heats up the exposed to flow thermistor, in this way reducing its resistance $R_{T1}$, bringing it back very close to its original value.

As seen from the characteristic on Figure 4, there is an attempt the operating point to shift from A to B, but due to the feedback signal it moves back to point C, corresponding in this case temperature to 17.5°C and accordingly to thermistor resistance $R_{T1}$ = 4150Ω.

Finally, the developed negative feedback brings the sensor temperature to equilibrium. Now the two thermistors operate at very close temperatures and the error of measurement due to the different self-heating effects in the two thermistors is reduced to a negligible value. In the closed-loop system, the operational amplifier OA5 provides proper calibration for the display that is made in terms of flow rate, while the circuit of the amplifier OA6 insures the appropriate signal conditioning and the required current for the heater $R_H$ [6], [7], [8].

The *Self-Heating Error* of the thermistor sealed in the closed chamber do not change and still is $\Delta T_2$ = 0.532°C. At the same time, the *Self-Heating Error* of the exposed to flow thermistor can be determined as:

$$\Delta T_1 = \frac{I^2 R_T}{P_D} = = \frac{(0.776691 mA)^2 \times 4150\Omega}{5\, mW/°C} \approx 0.501°C \qquad (5)$$

In this case the difference of the *Self-Heating Errors* of the two thermistors becomes:

$$\Delta T = 0.532°C - 0.501°C = 0.031°C \qquad (6)$$

This result for the difference of the *Self-Heating Errors* in the operation of the closed-loop flow measurement system is about four times smaller compared with the case of the open-loop system.

As seen from Figure 4, the effect of the error reduction is due to the fact that now the temperature change of the exposed thermistor $R_{T1}$ is only from 20°C to 17.5°C that is just 2.5°C. This causes smaller increment of the thermistor resistance, which now is from $R_{T1}' = 3747\Omega$ to $R_{T1}'' = 4150\Omega$. As a result, the currents via the two thermistors are now closer in value, $I_1 = 776.691\mu A$ and $I_2 = 842.645\ \mu A$, as seen in Figure 3.

It is visible from Figure 4 that in the feedback flow measurement system, the change in the thermistor $R_{T1}$ temperature is four times smaller compared with the case of the open-loop system. It is obvious that the smaller the temperature difference between the chamber-sealed thermistor and the exposed to flow thermistor is, the smaller will be the difference of the *Self-Heating Errors* $\Delta T$ and therefore the smaller will be the error of measurement.

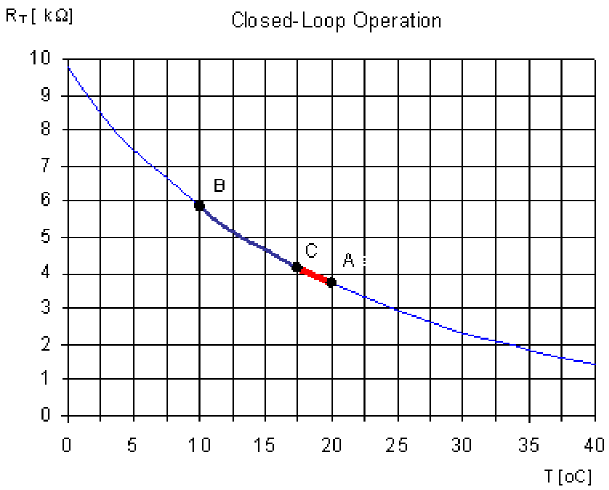


*Figure 4: Closed-Loop Operation of the Thermistor Sensor*

The reduction of the $\Delta T$ to very small values can be achieved due to the high sensitivity of the thermistor sensors. By adjusting the gain of operational amplifier OA4, the difference between the *Self-Heating Errors* $\Delta T$ of the exposed to flow and the sealed thermistors incorporated into the closed-loop flow measurement system may become even a hundred times smaller. This practically reduces the error of measurement to a negligible value close to zero. It is apparent that by implementing the negative feedback and correcting the temperature of the sensor exposed to flow, a very high accuracy in the measurements of low flow velocity can be achieved.

The introduced negative feedback in the flow measurement system also affects significantly its output voltage. By comparing the meter readings of the output voltage from the OA4, seen from Figure 1 and Figure 3, it is noticeable that this voltage is reduced almost four times, from 804.582 mV to 196.325 mV.

The meter, connected at the output of the OA5 has the purpose of displaying the flow rate. In this case, as seen from Figure 3, the meter calibration is 1V = 5 m/s and since the meter reading is 2.167V, the corresponding flow rate is 10.835m/s. The scale of this meter can be calibrated to read directly the flow rate.

## IV. Conclusion

The objective of the presented research is to develop an electronic anemometer that can measure flow rate with very high accuracy. There is a combination of several major factors that contribute to the achievement of these objectives. First, the employment of thermistors as high sensitive sensors plays an important part in this development. Further, connecting the thermistor sensors in a Wheatstone bridge configuration, improves the detection of very small resistance changes caused by the observed and measured flow velocity. The proper signal conditioning brings the output bridge voltage to the proper desired level. Finally, the implemented negative feedback plays the major role in eliminating the error of measurement. A phenomenon, known as temperature reduction of the environment is used in this case.

The research procedure is following two main stages. Initially, an open-loop system of flow rate measurement is developed and explored. It operates as expected, but due to the difference in currents via the two thermistors in the Wheatstone bridge and the resulting different self-heating effects in each one of them, an error of measurement cannot be avoided.

This brings the idea of introducing a negative feedback that can keep the temperature of operation of the two thermistors very close and therefore to reduce significantly the error due to the difference in self-heating effect of the sensors. Depending on the proper tuning of the signal conditioning units, the temperature of operation of the two thermistors can be made so close, that the error becomes negligible small. At the same time, always a small temperature difference of the thermistors is maintained and the resulting signal is amplified to keep the feedback operational and to display the measurement in terms of flow rate.

The operation of the electronic anemometer circuit has been initially simulated with the aid of the software package MULTISIM. Further, a laboratory model was produced and examined. Its operation proves the expected results. The developed in this research instrumentation system for precise flow measurements can be applied successfully in many industrial applications, especially where it is required to measure very low flow rates with very high accuracy.

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