Conference Paper

New Approach for Airflow Measurement Using Thermal Resistance Simulation

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Abstract

This paper presents a new model-based approach to detect and compensate errors of positive temperature coefficient (PTC) sensors used for airflow measurement. From modeling and simulation, it can be shown that the thermal resistance of the sensor at self-heating mode was influenced by air flow magnitude. The sensor of type EPCOS-AG B59010 in a steel case, length 20 mm, diameter 2 mm was characterised over the flow rate range between 0 and 6 m/s and modeled to determine coupling thermal resistance interaction R_{th} between the medium surrounding and sensor's structure. Soiling caused by dust transported with the air on the sensor surface changing in the thermal resistance has observed and simulated in an experiment using a cylindrical sheath of PTFE – *Polytetrafluorethylen* with known heat conductivity λ_S = 0.24 W/Km and diameter D. Parameters of model were then calibrated by evaluating current-voltage I(U)-characteristic at air velocity of v = 0m/s, and recalibration is then also used to correct the model parameters for v ≠ 0m/s. Result shows the soiling has exceeded critical thickness at D/d = 9 wherein the thermal resistance tends to be constant meaning cleaning sensor surface or replacing are needed.

Keywords: airflow measurement, PTC sensor, thermal resistance, soiling, simulation

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1. Introduction

There is a variety of airflow sensors on the market which meet specific application especially for commercial and private purpose [1]. The ceramic PTC thermistor is considered as an ideal sensor for monitoring the airflow and has several advantages such as simple structure and rugged. For long-time application, the sensor has disadvantages due to their longterm stability and soiling on its surface, so that it has to be recalibrated.

Positive temperature coefficient (PTC) thermistor sensors are constructed from sintered metal oxide ceramic and its electrical resistance change with temperature. They are sensitive but highly non linear. Their sensitivity, reliability, ruggedness and ease in use, have made them popular for research applications but less commonly used for industrial applications. Furthermore, the raw signal from the thermistor is extremely non-linier [2].

This paper presents a new approach model-based method of automatic self-control of PTC airflow sensors using thermal resistance measurement. The parameters of the

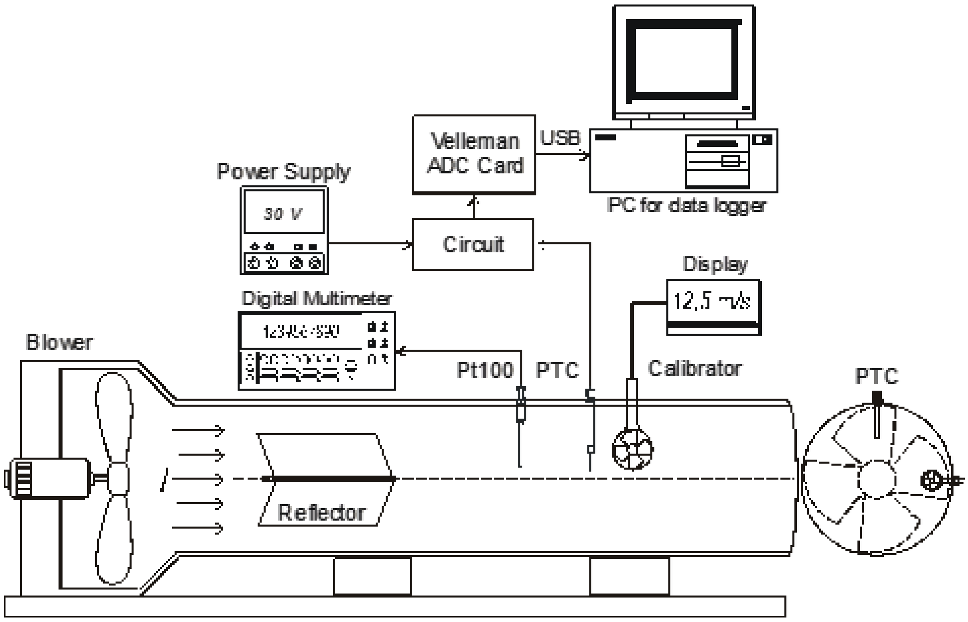

Figure 1: Schematic diagram of the airflow measurement system.

model were also determined from the sensor's current-voltage curve (I-U-characteristics) at certain defined states, and are used to correct the measured data. With this self-calibration procedure, failure due to soiling on sensor's surface can be detected and effectively compensated to enhance the reliability and accuracy measurement especially in hostile environments.

2. Materials and Methods

2.1. Design and Construction of The Experiments

Airflow measurement experiments were carried out in an experimental setup for calibration consisting of a wind tunnel with an air reflector and a blower, a calibration circuit, an anemometer calibrator and a personal computer for data acquisition as shown schematically in Fig. 1. The tunnel was constructed using a PVC pipe (∅ 10 cm; length 150 cm). For appropriate measurement of airflow, a blower with a 12V_{DC} operating voltage was used for generating a homogeneous and constant air current in wind tunnel. The velocity of the air entering the wind tunnel was varied by changing the operating voltage, from 0 m/s to a maximum speed. A stand of a scale and a holder were provided on the table with an additional anemometer to allow observation of the airflow profile in two dimensions over the entire tube cross section. An anemometer of the Electronic Wind Speed Indicator was used to measure the airflow independently of the incident flow direction.

The PTC sensor was attached at the front of the wind tunnel for characterization. Due to the heat dissipation of the blower motor, the ambient temperature T_M of the measured airflow in the tunnel increased and resulted in the shift of the sensor's I(U) curve. This ambient temperature was measured with a metal-housed temperature sensor PT100 and subsequently used for modeling of the I(U)-curve in order to obtain the parameters of the sensor and the parameters related to air velocity. A computer equipped with an Analog to Digital Card (ADC) type Velleman drived by a program PC Lab-2000 has been used for data acquisition of the air velocity, whereas curve modeling and graphic processing has been done using the program MathCad, Sigma Plot and Table Curve.

2.2. Heat Transfer and Airflow Measurement

The airflow was measured using the PTC Top of Form

Sensor type EPCOS-AG (Cat. Nr. B59010), enclosed in the stainless steel housing and suitable particularly well for airflow monitoring. In self heating mode, the sensor is heated and responds to a change in external cooling conditions due to airflow by changing its power consumption [3, 4]. The electrical power input is equal to the power lost to convective heat transfer,

$$I^2 \left(R_{T0} \cdot e^{B\left(\frac{T_S - T_C}{T_S}\right)} + R_0 \right) = \frac{1}{R_{th}} \left(T_S - T_M \right) \cdot \tag{1}$$

where I is the input current, T_S and T_M the temperatures of the sensor and fluid respectively and R_{th} the thermal resistance that indicates the heat coupling between sensor and its surrounding medium. Parameters R_{T0} denote sensor resistance at the specified temperature T_0, R_0 initial resistance, B proportional to the activation energy and T_C the Curie temperature. Such parameters show the behaviour of the sensor during operation. According to [5], thermal resistance R_{th} as a function of fluid velocity vwas determined by means of the following equation,

$$R_{th} = (a + b.v^c)^{-1} \tag{2}$$

where a, b, and c are coefficients R_{th} obtained from calibration (c ~ 0.5). Combining Eq. 1 and Eq. 2 allows us to eliminate the thermal resistance and solving for the fluid velocity,

$$v = \left\{ \left[\left(I^2 \cdot R_{T0} \cdot e^{B\frac{T - T_C}{T}} + R_0 \right) \left(T_S - T_M \right)^{-1} - a \right] / b \right\}^{1/c} \tag{3}$$

Using the formal Steinhart-Hart equation [6] for the temperature dependence of the electrical resistance with three parameters, the air velocity then can be measured with a relative error < 3 %.

2.3. Sensor Calibration

In Fig. 2, a simple electrical circuit for calibration the I(U) characteristic of PTC sensor in the self-heating mode is shown. The sensor was calibrated in still air (v = 0 m/s) and in at a different air flow ($v \neq$ 0 m/s). To obtain the thermal resistance and sensor parameters, the I(U) characteristic was modeled after Eq. 1.

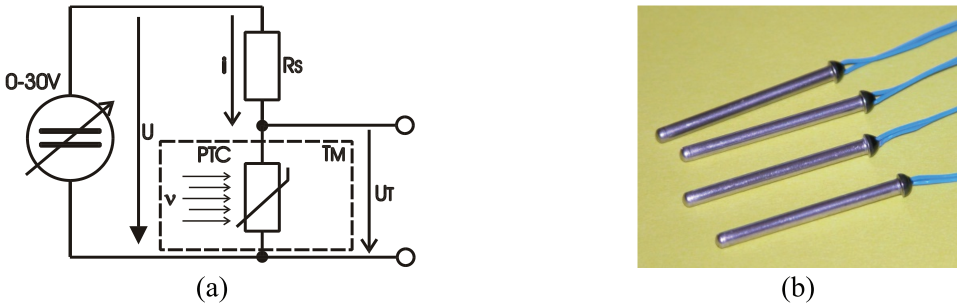

Figure 2: Simple circuit for characterisastion of PTC sensor (a) and sensor B59010 in (b).

Heat conductivity (λ_S)	0,24 W/Km
Density (ρ)	2,15 g cm^{-3}
Specific heat (c)	1,01 kJ kg^{-1} K^{-1}
Temperature max. (ϑ)	260 °C
Diameters of PTC (d)	2 mm
Diameters of sheath (D)	3 … 8 mm

Table 1: Characteristic of the cylindrical sheath with L = 22 mm.

The sensor output data can then be kept within the specification through continuous re-calibration, a necessary maintenance will be signaled only if the deviation from the reference exceeds a threshold.

2.4. Simulation of Soiled Sensor

For long-time applications the airflow sensor is successively soiled by dust transported with the air, thus changing the heat transfer to medium. Soiling increases the diameter of the sensor from the initial value d to D. The changing of the thermal resistance is observed using a cylindrical sheath with known heat conductivity λ_S and diameter D, as shown in Fig. 3 and Table 1. For the measurements, a Teflon (PTFE – *Polytetrafluorethylen*) sheath was used with following physical characteristics:

An increasing in the diameter of cylindrical sheath changes the overall thermal resistance $R_{th,overall}$. As a result, the function of fluid velocity v according to King's law has been extended in order to fit more data set for obtaining better results as follows [7]:

$$R_{th,overall} = R_{W,S} + \frac{1}{2\pi L\lambda} \cdot \ln\left(\frac{D}{d}\right) + \frac{1}{\left(a_0\left[1 + a_1 \cdot \left(\frac{D}{d}\right)^{0.5}\right]^2 - b_0\sqrt{\left(\frac{D}{d}\right) \cdot v + b_1 \cdot \left(\frac{D}{d}\right)^{1.6} v^{1.6}}\right)} \tag{4}$$

In Eq. 4, the thermal resistance $R_{th,S}$ describes the heat transfer of the thermal source (sensor material) to the surface of the sensor, and it is exemplar specific and temporally constant. The second term in Eq. 4 describes the thermal resistance through heat conduction of the sensor soiling and the third term depicts extended King's law.

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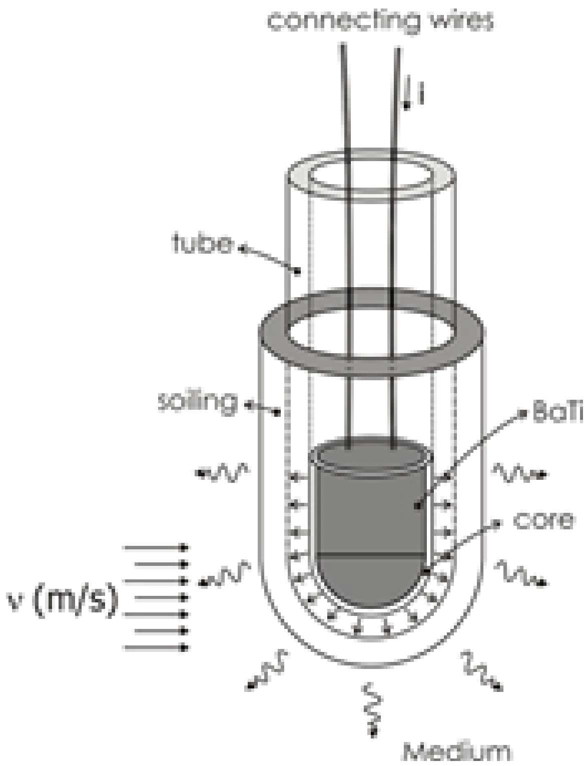

Figure 3: Simulation of soiled sensor of EPCOS-AG B59010 with a cylindrical teflon sheath.

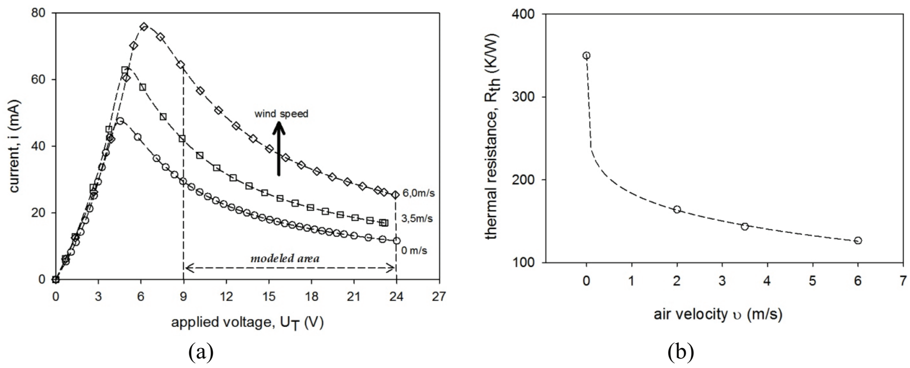

Figure 4: The I(U)-characteristic of the sensor at various air velocities and modeled area (a) and the thermal resistances decrease against the increasing of velocities in (b).

3. Results and Discussion

3.1. Modeling of the I(U)-Curve

The current-voltage curve (I-U) of the observed sensor at various velocities obtained in the present work ranged from 0 to 6.0 m/s, see Fig. 4. There was a current shift toward higher levels with the increase of the velocities due to more heat transfer to the environment. It led the sensor to compensate in order to retain the equilibrium state. This is caused by a better thermal conductivity flowing - than in still air. The changing in the current shifts the voltage-current characteristic of the sensor (I-U curve) and results in the changing of the heat transfer, thus its thermal resistance.

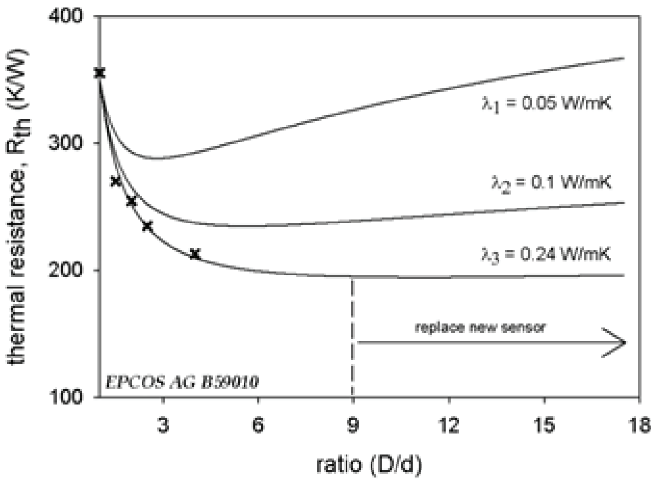

Figure 5: Variation of thermal resistance at different diameter ratio (D/d), measured at constant temperature of 30∘C.

The thermal resistance and the sensor parameters were obtained from the modeling of the I(U)-curve at a given range according and the results showed that the thermal resistances in still air (R_{th} = 350K/W at v = 0 m/s) and at various air velocities (R_{th} = 126.7K/W at v ≠ 0 m/s) are differed clearly from one another, or decreased around 63% at v = 6 m/s, while the sensor parameters R_{T0} = 32.67Ω, R_0 = 4.99 10^{-7}Ω, B = 73,88 and T_C = 378.53K are remain constant since there were no recrystallization of the sensor material.

3.1.1.

3.2. Self-Calibration of the Sensor Parameter

The "effective" diameter D of the soiled sensor is time-dependent. According to Eq. 5, a larger D has influence on the thermal resistance and also on the sensitivity of R_{th}. Fig. 5 represents the simulation of thermal resistance for v = 0 m/s as a function of the diameter ratio, D/d after Eq. 4.

In Fig. 5, the thermal resistance of was simulated at various diameter coating. At the beginning of the soiling, the thermal resistance in air was very large, since air has a low thermal conductivity. Thereby the total resistance is determined by the boundary of layer-resistance. With increasing sheath diameter, the thermal resistance decreases as teflon sheat has a better thermal conductivity than air. In Fig. 5, it appears that for λ = 0.24 W/mK the thermal resistance after (D/d) ≈ 9 is no longer decrease and tends to remain constant. In this case, the soiling has exceeded critical thickness and the PTC thermistor sensor must be cleaned or changed.

From the known type-specific thermal parameters such as a_i and b_j in Eq. 4, the exemplary-specific electrical parameters $R_{T0,}R_{0,}B$, T_C and R_{th} are estimated from the sensor with known D prior to the first use. The "effective" diameter D is calculated with an assumed value of λ (the influence of λ is small and all relevant soiling matters have very similar thermal conductivity values.)

4. Conclusion

In this work, a model-based method of self-control of PTC air-velocity sensors has been presented to determine sensor parameter and thermal resistance used for airflow detection. The sensor's I(U)-characteristics is corrected at certain defined states, i.e. when v = 0 m/s, and used to correct the measured data, also when $v \neq 0$ m/s. With this self-calibration procedure, errors like contamination of the sensor surface by dust, ohmic bridges, shortcuts and ageing of the electrical parameters, are detected and effectively compensated, without the need to take several additional measurements.

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