

Development of multiple velocity and temperature probe sets for ventilated spaces

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A b s t r a c t. Development of a low-cost computer-based system for multi-point measurement of velocity and temperature has been completed. The principle is based on hot-wire anemometry. A typical probe consists of a cold thermistor for flow temperature detection and a hot thermistor for flow velocity detection. The later is self-heated by a thermal potentiometer circuit. The change in resistance of the thermistor is related to the airflow. The designed probes were calibrated with reference to known parameters. The system developed can monitor and analyze 48 velocities and temperature sets in a ventilated space. System development and results are presented.

K e y w o r d s: velocity, temperature, ventilation, probe, thermistor

INTRODUCTION

Thermistors have found widespread application in measurements of temperature and especially fluid flow. For measuring the fluid flow as a flowmeter, a thermoresistive device is electrically heated to a temperature (T) higher than that of the surrounding medium (T_a) and then placed in the flow stream which draws from the device an amount of heat proportional to the flow. The change in resistance of the thermoresistive device is directly related to the airflow which in turn is directly related to the resulting temperature of thermistor. Self-heated thermistors have been used by previous researchers for fluid flow measurements. Okamoto *et al.* (1993) developed a digital anemometer consisting of a cold thermistor for flow temperature and a hot thermistor for flow velocity detection. The latter is self-heated by a thermal bridge. They found a linear digital output by comparing the voltage across the self-heated thermistor with the characteristic waveform generated by direct digital synthesizing. Oliverira *et al.* (1995) developed an experimental prototype of an anemometer with a pulse width

modulated (PWM) excitation voltage. They used a thermistor placed in one arm of a Wheatstone bridge as a flow detection sensor heated by a PWM voltage. A negative feed-back circuit substituted the thermal power absorbed by the fluid from the heated sensor maintaining it at a constant temperature. The pulse width contained information about the fluid velocity and, using a timer counter, the velocity information was found in digital form without use of a conventional A/D converter. No report on the performance of their system was provided.

A multi-point temperature and velocity measurement system was developed by Zhang *et al.* (1996) for studying air flow patterns and temperature distribution in ventilated spaces. Their system measured up to 32 points using thermistors as measuring elements. The system consisted of multi-head temperature and velocity sensors, on-line data analysis, graphical presentation of temperatures and velocities, and the option of data logging. A relative error of less than 3% for velocity was reported and temperature measurements were reported as accurate to within 0.05°C in the range of $0\text{-}45^\circ\text{C}$. The system developed with this research used the procedures successfully demonstrated by the work of Zhang *et al.* (1994).

SYSTEM DESIGN AND INSTRUMENTATION

Probe assembly

The configuration of one typical temperature and velocity probe is illustrated in Fig. 1. It is constructed with two matched thermistors, two military grade resistors, and necessary wiring. For temperature sensing, a 10 K ohms resistor was connected in series with one thermistor to form a potentiometer circuit with 0.5 volt as the power supply. For

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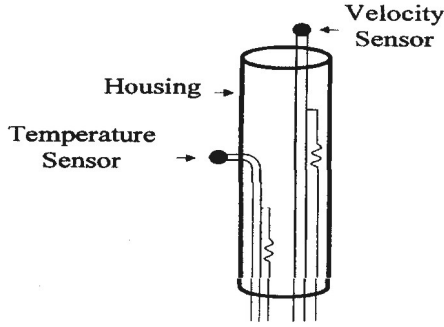


Fig. 1. Schematic of a typical temperature/velocity probe.

velocity sensing, a 392 ohms resistor and a second thermistor with a 12 volt power supply were connected in series. A flexible plastic tube (7 mm diameter and 15 cm long) was used for the housing of probes. All wires were passed through the tubing with the velocity thermistor at the top of the housing and the temperature thermistor located to the side with the head outside and 25 mm below the velocity thermistor. In this configuration, both sensor heads were exposed to open air space during measurement.

Hardware

The data acquisition system consisted of a CR-10 data logger, three AM416 multiplexers (both from Campbell Scientific Inc.; Logan, Utah), a 12V constant voltage power supply (SOLA Model 83-12-218-03, Newark Electronic Inc.), and a built-in PC-Board with 16 - 4 position DIP switches. The CR-10 was linked to a microcomputer via a 9-pin serial data interface for communication. The AM416 multiplexer had 16 sets of differential channels in which each set was used for one probe. A total of 48 probes were constructed and connected in a batch of 16 to each multiplexer.

Software

The system software is supported by a program written using the PC208E software package (Campbell Scientific Inc, Logan, Utah). Language of the program is in CSI format. The software has the ability of scanning all three multiplexers at a frequency of 10 scans s^{-1} . The data are sampled, averaged, and stored in CR-10 final storage location and then downloaded to the computer in the form of text for further analysis.

Methodology

When a thermistor is placed in a potentiometer circuit with a known input voltage (V_s) and circuit resistance (R_o), the output voltage of thermistor (V_t) can be measured. From the following equation, the resistance of the thermistor (R_t) in the circuit is determined:

$$R_t = \frac{R_o V_t}{V_s - V_t} \quad (1)$$

The corresponding temperature of the thermistor can be determined by use of the Resistance - Temperature (R-T) curve that is based on the calibration of an individual thermistor. The R-T data supplied from the thermistor manufacturer (RTI Electronics Inc.; Anaheim, CA) were Least-Squares fit to the Steinhart-Hart equation which is written explicitly in T as Eq. (2):

$$1/T = C_0 + C_1 (\ln R_t) + C_2 (\ln R_t)^3 \quad (2)$$

where: C_0 , C_1 and C_2 were determined by regression method. The thermistors selected for this application are an NTC type ACCU-CURVE series ACC-001 with 2252 Ohms @ 25°C. The ACC-001 spherical thermistor has a diameter of 1.5 mm with a dissipation and thermal time constant of $1mW \text{ } ^\circ C^{-1}$ and 10 s, respectively. Typical R-T characteristics of the thermistors are shown in Fig. 2. The result of regression analysis with Eq. (2) showed an R^2 of 0.9999 and standard error of T of $0.07512^\circ C$.

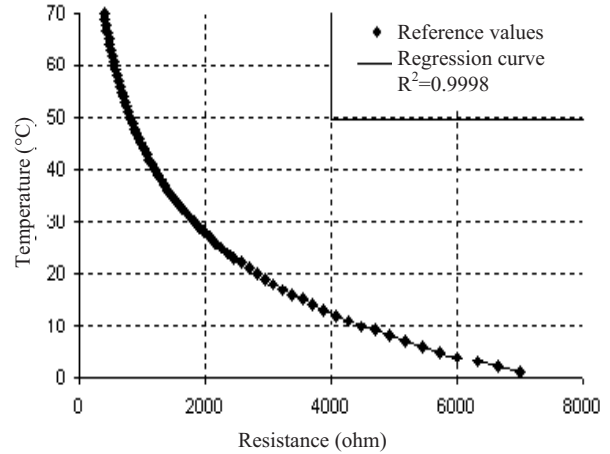


Fig. 2. Typical Resistance - Temperature curve for thermistor.

Theory of operation

Rusmussen (1961) developed the basic theory for the behavior of thermistors in a moving fluid. If a thermistor is heated above the ambient temperature due to electrical energy input, an energy balance on the thermistor yields as follows:

$$C \frac{dT_v}{dt} = P - K(T_v - T_a) \quad (3)$$

where: C is the heat capacity ($J \text{ kg}^{-1} \text{ } ^\circ C^{-1}$), T_v is the temperature ($^\circ C$), P is the supplied energy to the thermistor (mW), and K is the dissipation factor of the thermistor ($mW \text{ } ^\circ C^{-1}$), T_a is the surrounding fluid temperature ($^\circ C$) and t is time (s).

Taroni and Zanarini (1975) have studied the response of thermistors in detail. In a steady state condition, Eq. (3) reduces to:

$$P = K(T_v - T_a). \quad (4)$$

The dissipation factor, K , of a given thermistor depends on the relative speed and properties of the fluid, and also the orientation of the thermistor relative to the air flow. Now, for a fixed orientation and with the range of ambient temperature fluctuation limited to that for which the variation in fluid properties is negligible, K is only a function of fluid speed. Therefore, the thermistor can be calibrated as a flowmeter by experimentally determining the relationship between dissipation factor, power input, and the temperature difference ($T_v - T_a$). So, Eq. (4) can be re-written as:

$$I^2 R_v = Ah(T_v - T_a) \quad (5)$$

where: R_v , A , and I are resistance, surface area, and current passing through the thermistor respectively. The convection heat transfer coefficient, h , is related to the thermodynamic properties of the fluid, typically presented as the *Nusselt* number (hd/k) (where: h is heat transfer coefficient, d is diameter, and k is thermal conductivity). The relationship between *Nusselt* number and other thermodynamic fluid properties and characteristics of the flow around the thermistor have been studied by Olivari and Carbonaro (1993). Typically, by dimensional analysis one must have:

$$Nu = f(Re, Pr). \quad (6)$$

The general form of non-dimensional heat transfer relationship, at fixed *Prandtl* number is:

$$Nu = a + b Re^n. \quad (7)$$

Now, replacing Nu in Eq. (5) by (7) and noting that Re is a function of V , the Eq. (5) can be re-written as:

$$I^2 R_v = (a + b V^n) (T_v - T_a). \quad (8)$$

In the above equation, a represents the natural convection term and $b V^n$ the force convection term. After rearranging, Eq. (8) can be written as:

$$V^n = A + B \frac{I^2 R_v}{(T_v - T_a)}. \quad (9)$$

This is the basis for the system presented in this paper. I and R_v may be determined by Eq. (1), T_v and T_a are known by Eq. (2), A and B are the intercept and slope of the regression equation and their values are determined in the calibration procedure for each thermistor.

Calibration of probes

Calibration experiments were performed for each set of temperature-velocity probe at the Air Dispersion Laboratory in the Agricultural and Biosystem Engineering De-

partment at Iowa State University to determine all required calibration coefficients. For temperature calibration, a Copper-Constantan thermocouple sensor was employed as reference. An Omni-directional anemometer (Model 8470, TSI Inc.) was used for velocity calibration. The temperature and velocity thermistors were calibrated simultaneously in a plenum chamber constructed for this purpose. The experimental plenum chamber (Fig. 3) consisted of three sections including: (1) a rectangular sheet metal cross section of 30x50 and 40 cm long; (2) a pyramidal sheet metal section at 50 cm in length with 30x50 cm at one end and converged to 15 cm in diameter at the other end; and (3) a PVC duct with 15 cm in diameter and the length of 60 cm. On the pyramidal section, sheet metal work was done to converge from rectangular to circular cross section. The plenum was equipped with a 20 cm diameter axial fan wired in a circuit with a variable speed controller. Two air straighteners were mounted inside the rectangular cross section to reduce the air swirling at the outlet. The temperature inside the plenum was controlled by two spring type heaters installed between the fan and the air straighteners. One of the heaters was wired to a variac for temperature variation control.

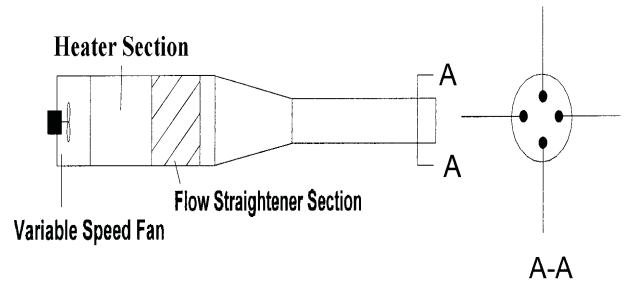


Fig. 3. Set up for probe assembly calibration.

The probes for calibration (10 per batch) were mounted uniformly and radially along the duct circle at 5 cm to the outlet end of the plenum with the probe heads toward the center of duct section. The calibration was carried out for temperature in the range of 20-45°C in steps of 2°C. The velocity at each temperature setting varied from 0 to 5 m s⁻¹ in steps of 0.3 for 0 to 2 and 0.5 for 2 to 5 m s⁻¹ under isothermal conditions. The values of A and B for each thermistor were obtained through the regression analysis.

RESULTS AND DISCUSSIONS

For each experiment conducted during the calibration procedure, data scanning started after 15 min so that a steady state condition was achieved. The true velocity and temperature along with the output voltages for each batch of 10 probes were recorded with a scan rate of 2 s and averaged over a period of 3 min. Equation (1) was used to convert the output voltages of each thermistor to resistance and then, using the R-T Eq. (2), the temperatures of both thermistor

heads were determined. Regression analysis for each temperature thermistor was carried out by regressing the measured temperature over the true temperature as shown in Fig. 4. An R^2 ranging from 0.9957 to 0.9987 with standard errors of 0.3192 to 0.4847°C and the variance ranging from 0.59 to 1.3°C were found. Equation (9) was used for calculation of measured velocities based on the temperature and output voltages of the velocity thermistor. A comparable optimum n -value of 0.485 was used in Eq. (9) for all the velocity thermistors through their entire range. The values for A and B were found for each probe from analysis of data and used in Eq. (9). The regression analysis for the relationship between V and other obtained parameters in Eq. (9) showed good agreement with R^2 ranging from 0.9750 to 0.9946 with standard errors ranging from 0.0451 to 0.0164 m s^{-1} , respectively. The measured and true velocities for a typical probe are shown in Fig. 5. It is noted that the line drawn through data in Figs 4 and 5 is more likely a 1:1 line for the base of comparison. Figure 6 is a presentation of standard error for a typical probe showing that, as the velocity increases, the error in measurement decreases.

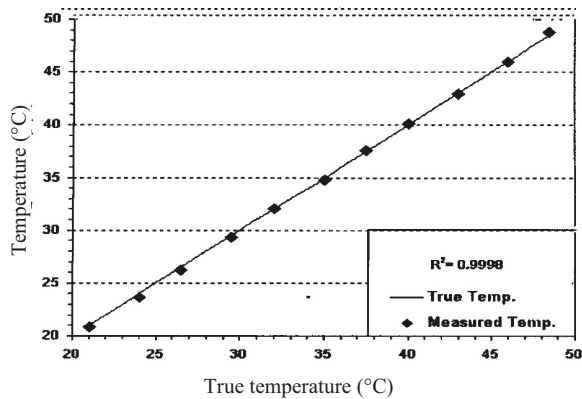


Fig. 4. Measured temperature plot for a typical probe.

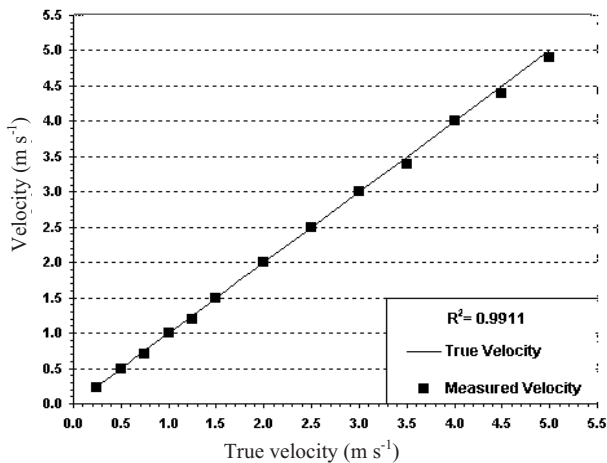


Fig. 5. Measured velocity plot for a typical probe.

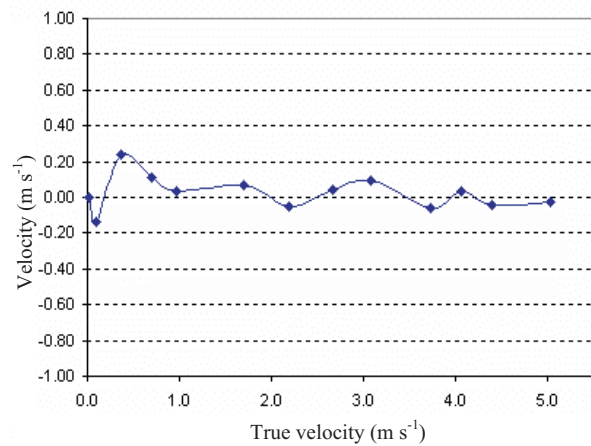


Fig. 6. Standard error for a typical probe.

CONCLUSIONS

1. For the measurement system developed, 96 thermistors were used as the measuring elements. The system can handle measurements of velocity and temperature for 48 locations.
2. The accuracy of temperature over the range of 20 to 45°C was better than 0.048°C. For the velocity at low temperature, an accuracy of better than 0.24 m s^{-1} was obtained. This range of flow velocity would cover the velocity of airflow in ventilated spaces. At higher temperature, the system performed better with an increase in accuracy to 0.11 m s^{-1} .
3. The system can be operated on a microcomputer and present on-line monitoring and graphs for airflow pattern, temperature distribution, and air flow velocity studies in greenhouses, nursery buildings and basic ventilation systems.
4. A good application of the system developed is for controlling the temperature and velocity in automated greenhouse systems due to its high performance/cost ratio.

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