Hot-wire anemometer for spirography

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Abstract—*The use of a constant temperature hot-wire anemometer flow sensor for spirography is reported. The construction, operating principles and calibration procedure of the apparatus are described, and temperature compensation method is discussed. Frequency response is studied. It is shown that this hot-wire flow transducer satisfies common demands with respect to accuracy, response time and temperature variations.*

Keywords—*Hot-wire anemometer, Spirometer, Respiratory gas flow measurements*

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1 Introduction

THE PRINCIPLE of the constant temperature hot-wire anemometer has been known for over 80 years (KING, 1915) and has been thoroughly studied (KOVASZNAY, 1954; COMTE-BELLOT, 1976). Furthermore, there has been analysis of its dynamic behaviour, temperature compensation and feedback control theory (FREYMUTH, 1967*a*, *b*, 1977, DAVIS, 1970, PERRY and MORRISON, 1971). Constant hot-wire anemometers are widely used for flow measurement, particularly for measuring velocity fluctuations in turbulent flows. The hot-wire sensor has several advantages that make it very suitable in spirometry; the output of the transducer is a direct measure of true mass flow, the response is very fast and it is possible to construct transducers for a very large diapason of respiratory air flows. Despite this, there is a very limited number of spirometers using this principle. Since 1986, research has been carried out to develop constant-temperature hot-wire flow transducers for respiratory gas flow measurement.

In our present study, the construction and operating principle of a constant temperature hot-wire anemometer flow sensor are described. There have been preliminary reports on this apparatus (LAMP *et al.*, 1994, KINGISEPP *et al.*, 1996).

2 Operating principle

A simplified schema of the hot-wire anemometer for spirography is presented in Fig. 1. It consists of a flow transducer and corresponding electronic circuits for data acquisition and the computer interface. The electronic circuitry can be divided into four functionally independent parts: flow and temperature measurement circuits, A/D convertor together with digital circuitry for linking with a computer ISA bus, and a thermostat for heating the flow transducer. All the electronic circuits are mounted on a computer add-in card except the thermostat, which is placed in the handle of the flow transducer.

The flow transducer has a tubular flow channel, where the flow and temperature sensors are placed. The channel is profiled to ensure uniform flow distribution over its cross-section. Grids are used at either end of the flow channel to make the flow distribution more uniform; they also protect the sensors from contamination and mechanical damage. The part of the flow channel where the sensors are situated is made of Plexiglass. The rear part of the flow channel is made of aluminium and is heated to 35°C to prevent condensation of water vapour.

The flow and temperature sensors are identical. They are made of 20 μm platinum wire, wound on an 8 mm long glass capillary. As the lengths of the sensors are about half the flow channel diameter, they effectively integrate the flow and temperature profile across the flow channel. Therefore, it is not necessary to ensure and maintain a defined flow profile over the full dynamic range. It is sufficient that the flow profile is symmetrical.

The flowmeter uses standard constant-temperature hot-wire anemometer connection, where flow sensor R_f is one arm of a Wheatstone bridge. The bridge is connected to the servo amplifier to keep the temperature of the flow sensor constant. The output variable is the bridge voltage U_B, which is a function of gas velocity.

A simplified schema of the flowmeter is shown in Fig. 2. The flow sensor R_f and resistors R_1, R_2 and R_3 form a Wheatstone bridge. The bridge is balanced at temperature T_1 of the flow sensor. Any imbalance in the bridge is detected by the differential amplifier, amplified by the power amplifier and fed back to the bridge to keep it balanced. The signal from one arm of the bridge is put through the D/A convertor, which is used as a potential divider. This makes the temperature T_1 digitally controllable. The bridge voltage U_B is level-shifted and fed to the A/D convertor input. The temperature of the flow sensor T_1 is set to 250°C; this ensures a fast enough response, together with good long-term stability. The parameters of the circuit are chosen to give an output voltage range of 0–10 V at a flow range of 0–14 l s^{-1}.

Fig. 3 shows the schema of the thermometer circuit. The temperature sensor R_t is in a current-driven bridge. The output of the bridge is amplified by a differential amplifier. Potentiometer RP_1 is used to balance the bridge and RP_2 to set the gain of the circuit. The output voltage of the circuit is a linear function of the temperature. The circuit is set to give an output voltage range of 0–10 V when the temperature changes from 0 to 50°C.

The hot-wire sensor is incapable of detecting the direction of the flow. To overcome this problem, the temperature of the flowing gas is continuously measured by an additional sensor

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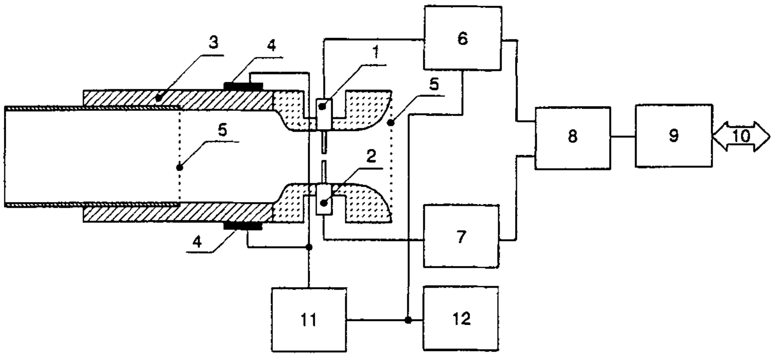

Fig. 1. *Schema of the hot-wire anemometer. 1 = flow sensor, 2 = temperature sensor, 3 = flow channel, 4 = heating elements, 5 = mesh grids, 6 = flow measurement circuitry, 7 = thermometer circuits, 8 = A/D convertor, 9 = digital interface circuits, 10 = PC ISA bus, 11 = thermostat, 12 = power supply*

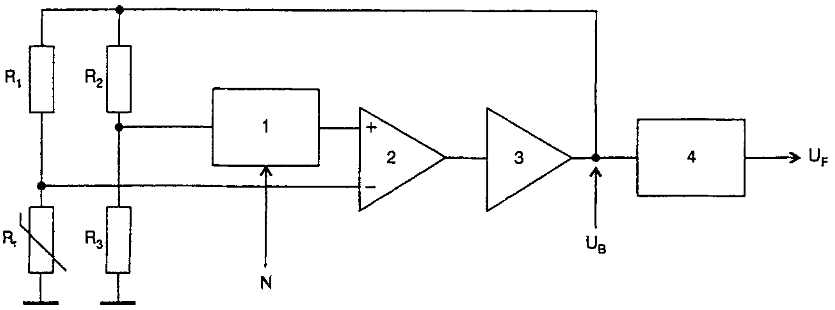

Fig. 2 *Flowmeter (simplified circuit). 1D/A convertor, 2 = differential amplifier, 3 = power amplifier, 4 = level shifter, R_f= flow sensor, N = control code, U_B = bridge voltage, U_F = flowmeter output voltage*

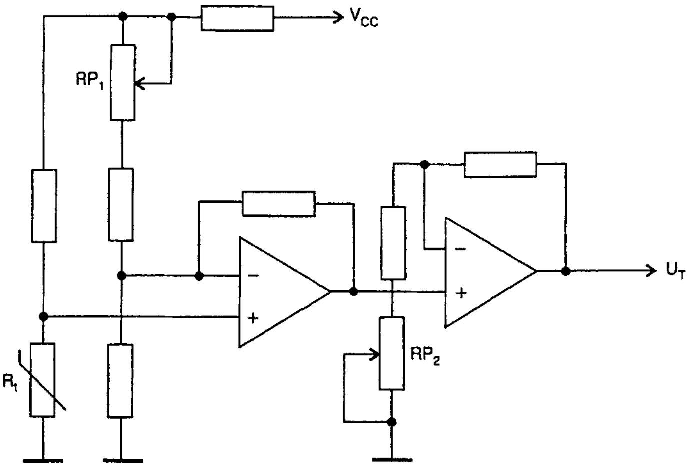

Fig. 3 *Thermometer circuit*

and considered by the software program. The obtained temperature values are compared with the flow readings, and a special algorithm is used to determine the direction of gas flow. This algorithm uses the rapid temperature fall at the beginning of expiration and the temperature rise at the beginning of inspiration, together with the minimum of the air flow readings, to determine the starting points of the respiratory phases.

3 Effect of gas composition and temperature

A flow transducer for spirography must be insensitive to variations of gas temperature and composition, or at least their effects must be compensated. Expired air composition is affected by humidity, oxygen and carbon dioxide. LUNDSGAARD *et al.* (1979) investigated the influence of humidity and gas composition on different calibration setups. No detectable effect of gas humidity was reported. Calibration curves for air, pure argon and carbon dioxide were obtained, and mixtures of air and argon were investigated. However, the gas mixtures investigated were not very similar to expired air.

Owing to the difficulties in building a setup for experiments with gas mixtures that would be close to expired air, we used a mathematical model for estimating errors due to humidity and gas composition. As the geometry of the hot-wire sensor used is too complex for analytical expression, we used the well known model for a simple cylindrical hot-wire (HINZE, 1959). The voltage of the hot-wire is

$$U^2 = R_w(R_w - R_e)(A + Bu^n) \tag{1}$$

The coefficients A and B are described by

$$A = 0.42(\lambda\pi l/\beta)Pr^{0.2} \tag{2}$$

$$B = 0.57(\lambda\pi l/\beta)Pr^{0.33}(d/v)^n \tag{3}$$

where U is the sensor voltage; R_w is the sensor operating resistance; R_e is the sensor resistance at gas temperature; u is the gas velocity; $n = \sim 0.4$, λ is the gas thermal conductivity; l is the sensor length; β is the sensor wire temperature dependency coefficient; Pr is the Prandtl number ($Pr = c_p\mu/\lambda$, where μ is the dynamic viscosity, c_p is the gas specific heat capacity at constant pressure); d is the sensor diameter; v is the kinematic viscosity ($v = \mu/\rho$, where ρ is the gas density).

All gas parameters are at 'film' temperature $(T_w + T_e)/2$, where T_w is the temperature of the hot-wire and T_e is the temperature of the flowing gas.

At first, the parameters c_p, λ, μ and v for normal room air at a temperature of 24°C and for expired gas mixture were calculated according to WILKE, 1950; LINDSAY and BROMLEY, 1950. It was assumed that air exhaled by humans contains 3.5 vol% carbon dioxide and 17.5 vol% oxygen. Humidity was assumed to be 100% and temperature 33°C. Numerical values of gas constants and parameters were taken from REID *et al.*, 1977.

Parameters for normal room air were used in eqns. 1, 2 and 3, and for a given velocity the hot-wire voltage was calculated. Parameters for expired gas mixture were then substituted in eqns. 1, 2 and 3, and the flow velocity was found that gave the same hot-wire voltage.

Our calculations show that if a hot-wire anemometer is calibrated with room air (0.03 vol% carbon dioxide and 20.95 vol% oxygen) and then exhaled gas is measured, the anemometer would underestimate flow by ~ 1%. Such a small error is, in practice, not significant. The calculations were repeated for various velocities of gas flow. No significant dependence on velocity was observed.

The bridge voltage is also dependent on the gas temperature. Various methods have been proposed to compensate for this dependence (LUNDSGAARD *et al.*, 1979; LEMIEUX and OOSTHUIZEN, 1985). Some methods use a temperature sensor in the other arm of the bridge, and others determine the temperature dependence of the parameters of the transfer equation. The latter method is not suitable in our case because an adequate analytical expression for the transfer function is difficult to obtain due to the complex geometry of the sensor. An identical temperature sensor could be placed in the other arm of the bridge to achieve temperature compensation but then direct measurement of temperature would be lost.

Our experiments showed that, when temperature variations were small compared to the overheat of the hot-wire, the output voltage of the bridge was a near linear function of the temperature. Its use for temperature compensation is explained below.

4 Calibration

4.1 *Calibration setup*

The hot-wire anemometer was calibrated using the calibration setup shown in Fig. 4. The calibration setup consists of a 300 l barrel that acts as an air source of controlled temperature. Room air enters the barrel through the air inlet near the bottom, and passes the heater element and thermistor. The signal from the thermistor is fed to the temperature controller, which controls the heating element to give the required air temperature. The mixing van ensures a uniform air temperature in the barrel.

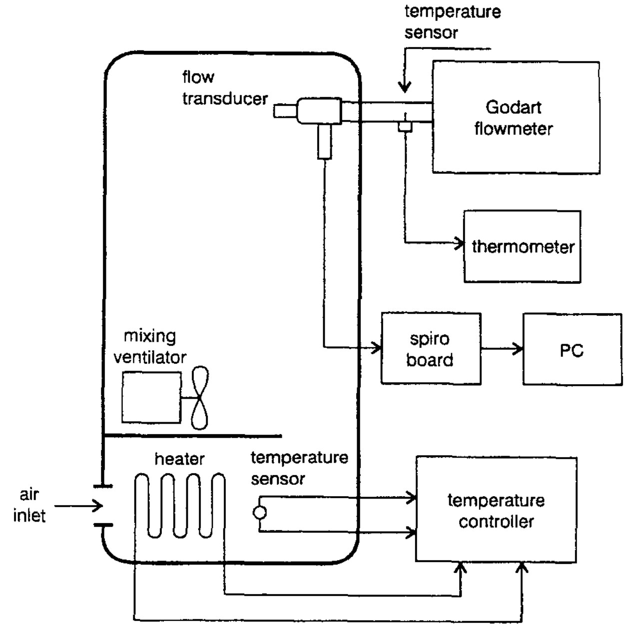

Fig. 4 *Hot-wire anemometer calibration setup*

The air of predetermined temperature passes through the flow transducer to the flowmeter setup*. The measuring range of the flowmeter is 10–720 l min^{-1}. The flowmeter is of the differential pressure type, and its readings are dependent on the air density and viscosity. Therefore, a separate temperature sensor is placed at the flowmeter input. The temperature readings were recorded during calibration, and they were used together with the air pressure values to correct the readings of the flowmeter. To calibrate the thermometer, the flow transducer and Hg thermometer are placed in a heat insulated box and are heated with the flow transducer's internal thermostat.

The Hg thermometer readings were recorded together with the thermometer output voltages. 8–10 points are usually recorded for calibration. As the thermometer output voltage is linearly related to the temperature, the temperature range of the calibration is not critical and is usually in the range 18–40°C. From obtained data, the coefficients of the linear function are calculated. These coefficients are used by the computer program to calculate instantaneous temperature values.

4.2 *Calibration procedure*

Using the calibration setup described above, the flowmeter output voltage U_F is determined (Fig. 2) as a function of the flow rate at a constant flow temperature in the range 10–720 l min^{-1}. For each flow transducer, a set of three calibration curves were obtained; the first near the lowest operating temperature (15°C), the second at normal room temperatures (around 24°C), and the third near the temperature of exhaled air (35°C). A typical set of calibration curves for a hot-wire flow sensor is shown in Fig. 5. From the obtained curves, a flow matrix consisting of 96 coherent values of flowmeter output voltage U_F and flow rate was obtained, and this matrix was included in the spiro-analyser software. To calculate the temperature-compensated flow values, the com-

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*Type 59007, Godart, N.V. Holland

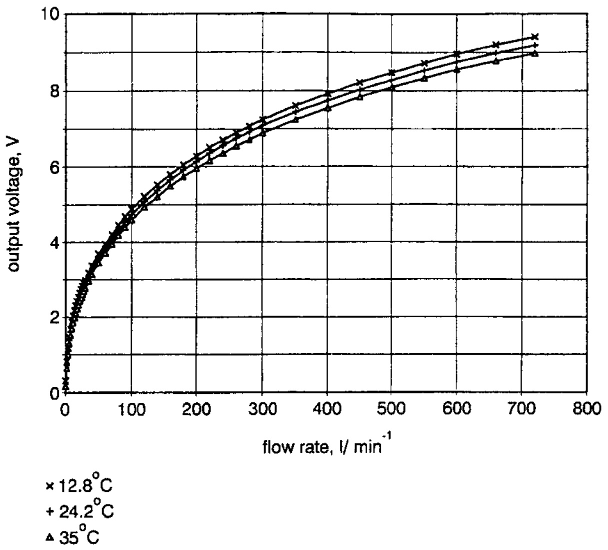

Fig. 5 *Typical calibration curves of the hot-wire anemometer*

puter program uses linear interpolation between the points of the flow matrix.

The obtained calibration curves are valid for a steady flow. To compensate for dynamic effects, a 3 l hand-driven air pump was used. The flow transducer was connected to the air pump and four in-out cycles were performed. The software computed the volume of each stroke, and displayed them and average errors for both flow directions on the monitor.

The described procedure was provided with the different flow patterns to compensate for the slight non-linearity of the transducer. In practice, three sets of strokes with different flows are performed and corresponding errors are recorded: slow, medium and fast strokes with peak flows about 1..2 l s^{-1}, 4..5 l s^{-1} and 10..12 l s^{-1}, respectively. For example, the values −2.2, −2.5 and −3.8% (typical) were found. From these values the overall correction factor 1.029 is determined giving +0.7% volume error at slow flow maneuvre and −0.9% volume error at fast flow maneuvre. From the overall 2.9% error, about 2% may be systematic error from the flowmeter, and the rest is due to the dynamic effects and transducer non–linearity. Volume errors of >2..3% (at slow and medium flow patterns) are rare and could be caused by uneven winding of the Pt wire on the flow sensor. However, if the linearity error of the sensor does not exceed limits, the sensor can be used; otherwise it is rejected. Volume errors, compensated in this fashion, are usually in the range 1–3%; with 1.5% as a typical mean.

The application software enables the user to check the calibration of the flow transducer in a similar fashion and to compensate possible errors if necessary. This time, unlike the initial calibration, the application software calculates the correction factors itself and uses them, if instructed to do so.

4.3 *Verification of dynamic response*

To determine the frequency response of the flow transducer, the following setup was used. The 3 l air pump was modified to give an electrical output pulse for every displacement of 1.5 cm^3. The pump was connected in series with the transducer, and the electrical pulses were fed into the serial port of the transducer's computer. The electrical pulses were read optically from the pump's shaft, and the first signal of the pump triggered the recording of the flow transducer output. The output signals from the pump and the flow transducer were then recorded simultaneously, and a point-to-point comparison of pump and flow transducer output signals was made for various patterns of air movements.

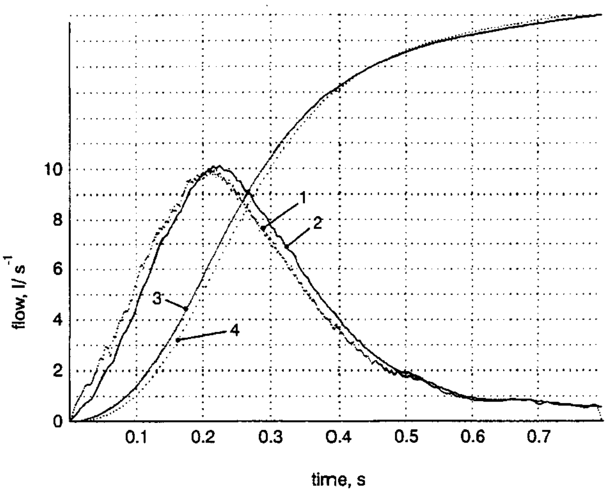

Fig. 6 *Point-to-point comparison of pump flow and flow transducer readings: 1 = pump flow, 2 = flow transducer output, 3 = integrated volume of the 3 l pump, 4 = integrated volume of the flow transducer; the scale of the volume curves is not shown, but curve 3 ends at the volume of 3 litres*

Typical results from one experiment are shown in Fig. 6, where curve 1 shows flow values of the pump and curve 2 the flow transducer readings. Curves 3 and 4 show the integrated volumes of the pump and flow transducer, respectively. Fig. 6 also shows that the flow transducer's output is delayed about 10–20 ms from real flow, but the shapes of the curves are nearly identical.

To determine the frequency response of the flow transducer, standard object identification software was used†, which gives approximately optimal IV estimate to ARX (extended autoregressive) model. Using this function and obtained data, the −3dB frequency of the transducer was calculated to be 75 Hz. The dynamic response of the flow transducer complies with the standard requirements (QUANJER *et al.*, 1993) for measuring all flow-volume loop parameters.

5 Conclusions

We conclude that our constant temperature hot-wire anemometer can be successfully used as a flow transducer for spirography. The use of fast temperature measurement and real time computing has made it possible to detect the flow direction, and thus the main drawback of the hot-wire transducer has been overcome. A single transducer can be used for measuring the air flow from 0 to 15 l s^{-1}.

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† Mathlab's function IV4 MathWorks, Inc.

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