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Influence of gas temperature on the performances of a low dead space capillary type pneumotachograph for neonatal ventilation

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***Abstract*—The design and calibration of a pneumotachograph with capillary type resistance is here described. The pneumotacograph has been designed aimed to the measurement of flow rate in the neonatal ventilation range (±10 L/min) and is characterized by a low dead space (2mL).**

The calibration curve is quadratic and coefficient values for Rohrer equation have been obtained by fitting experimental data (R^2=0.99, MSE=1Pa^2). Sensitivity varies from about 25 $Pa \cdot L^{-1} \cdot min$ for flow rates lower than 4 L/min to about 58 $Pa \cdot L^{-1} \cdot min$ for flow rates higher than 7 L/min.

The influence of airflow temperature on Rohrer equation coefficients has then been analyzed. A gas temperature variation in the range 19-37°C corresponds to a 10% average output percent variation, being the discrepancy higher at higher flow rates. A linear dependence of Rohrer equation second order term coefficient from temperature has been hypothesized. By fitting experimental data with the proposed equation MSE decreases from 1Pa^2 to 0.3Pa^2 thus, increasing repeatability (<2%) in the overall flow rate and temperature range considered. The second order term coefficient in Rohrer equation increases with temperature of about 0.6%/°C.

Rohrer equation, corrected for gas temperature, allows then to increase the repeatability of the here proposed capillary type pneumotacograph, while maintaining a good sensitivity with low dead space.

I. INTRODUCTION

THE measurement of gas flow and volume is essential to most measurements of infants' respiratory function. Many devices are nowadays available for flow measurements and, among them, Fleisch pneumotachographs (FP) are widely used in mechanical ventilation [1]. FPs allow to obtain flow rate by the measurement of pressure drop across a linear resistance [2], or across a fine wire mesh [3] showing, in this last case, a quadratic relationship between flow rate and pressure drop.

As far as neonatal ventilation is concerned, especially for infants, the pneumotacograph is required to have a low dead space. In fact, a large dead space causes an unacceptable delay between pressure and flow waveforms [4] and infants' mechanic pulmonary alteration [5]. In literature, a FP with very low dead space (1.8 mL) is presented [6] showing mean sensitivity of about 4 $Pa \cdot L^{-1} \cdot min$. The American Thoracic Society recommends an error less than 3% in flow measurements [7] in order to avoid hyperventilation or hypoventilation and barotrauma. Small or predictable dependence on gas temperature and composition is a required feature for sensor: sensor's output mainly depends on gas viscosity [8], composition and temperature [9]. The contribution of gas temperature on sensor output is relatively repeatable in laminar resistance FPs. However, in order to obtain an adequate sensitivity at low flow rates, linear FPs length must be consistent, therefore increasing the dead space.

In this work, we present the design and calibration of a capillary type FP that represents a good compromise between sensitivity and low dead space. The relationship between flow and pressure drop is quadratic and calibration curve has been calculated on Rohrer second order model. Influence of gas temperature on sensor's measurement model has been accounted for and a linear equation for second order term coefficient has been proposed and experimentally validated.

II. INSTRUMENT DESCRIPTION

The FP resistance producing the pressure drop consists of twelve parallel capillary tubes with 1mm diameter and 16mm length.

The pressure static taps (4.8 mm of diameter) are placed symmetrically at a 3.3 mm distance from the middle of FP. The particular geometry of the above described flowmeter is characterized by a 2 mL volume. One of the FP edges angles fit standard endotracheal tube, whereas the other one is designed with a diameter (9 mm) to fit standard neonatal breathing circuits. The FP schematic is shown in fig.1.

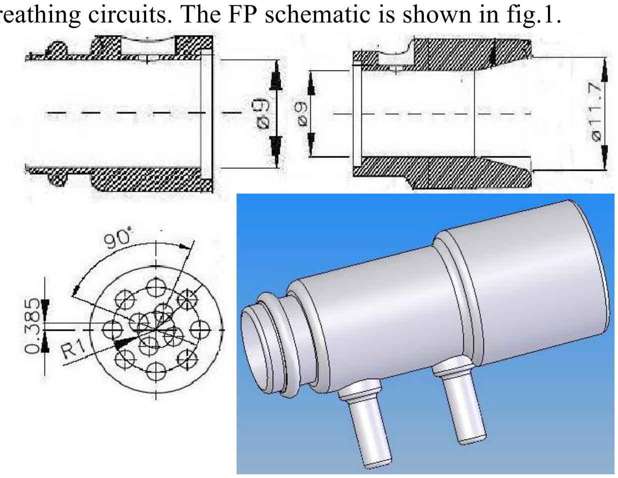

Fig. 1. FP schematic design of the capillary type pneumotacograph (dimensions in mm).

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III. THEORETICAL MODEL

As it is well known, the FP pressure drop on the overall resistance depends on gas physical parameters such as dynamic viscosity and temperature, on the geometric characteristics of the sensor and on the gas flow rate.

By assuming laminar flow, pressure-flow relationship in a FP capillary tube can be calculated from Hagen-Poiseuille's law [10]:

$$\Delta P = \frac{8\mu L}{\pi r^4}\phi \quad (1)$$

where:
ΔP is the pressure drop across the linear resistance,
μ is gas dynamic viscosity,
Φ is gas volumetric flow rate,
L is capillary length,
r is capillary radius.
Equation (1) can be rearranged in the following form:

$$\mu\Phi = K\Delta P \quad (2)$$

being K a constant depending only on FP geometric features [11].

However, with linear pressure-flow hypothesis, it is quite difficult to obtain FPs with a sufficient sensitivity and low deadspace for pulmonary ventilation measurement purposes. Thus, a polynomial calibration curve [12,13] is more commonly utilized and, in particular, a second order polynomial relationship, known as Rohrer equation [14,15], is frequently used as measurement reference model:

$$\Delta P = K_1\Phi^2 + K_2\Phi \quad (3)$$

where K_1 and K_2 are two constants calculated by fitting experimental data.

Equation (1) shows that one of the characteristic parameters of the pressure-flow relationship is the air dynamic viscosity and, as it is well known, this physical property depends on gas temperature and composition. However, limited researches have been found in literature concerning with the dependence of Rohrer equation coefficients from air viscosity and temperature. Among many, Kestin and Whitelaw report data regarding the dependence of air viscosity from temperature [16]. Values reported in [16] have been fitted with a linear relationship:

$$\mu = 0.4756T + 172.62 \quad (4)$$

being
μ the dry air dynamic viscosity [μP],
T the air temperature [°C].
These equations highlight the dependence of pressure drop across the resistance on the air temperature. As a consequence, K_1 and K_2 values for a generic gas, and in particular for air, increase with viscosity, and thus with temperature.

IV. EXPERIMENTAL SET UP

Experimental trials have been carried out in order to evaluate sensor performance and verify the mathematical model expressed by (3) and (4).

An air flow controller (Bronkhorst El-Flow, range 0.05–10L/min, accuracy ±0.2% of the setpoint value) has been used to generate a controlled flow rate ranging from 1 to 10L/min, see Fig. 2(G). Pressure drop across the sensor resistance have been measured by a pressure sensor (DC020NDR5 by Honeywell, range ±5kPa, accuracy ±0.2% full scale Fig. 2(D)). Sensor voltage output is shown on a oscilloscope, Fig. 2(B). The FP has been designed for bidirectional use, therefore bidirectional air flow has been generated. The gas flows from the air flow controller to the sensor through a duct provided with a heated wire, Fig. 2(F), to warm up the air in order to evaluate output sensitivity to temperature variations. A DC power unit, Fig. 2(C), supplies the heated wire and the pressure sensor. A sheathed type-K thermocouple, Fig. 2(H), has been placed upstream the sensor resistance, Fig. 2(E), to measure fluid temperature, displayed on a multimeter.

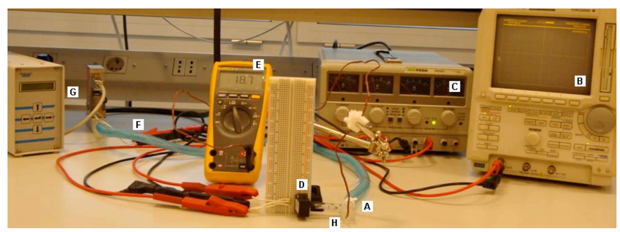

Fig. 2. Experimental setup for sensor calibration: A) FP; B) oscilloscope; C) DC power source; D) pressure sensor; E) multimeter to display air temperature value; F) duct with heated wire; G) air flow controller; H) type-K thermocouple

Three sets of measurements have been performed for static calibration. The first set has been performed with dry air at environmental condition, the air thermohygrometric conditions were T = 19±1°C and RH = 6±2%. Other two experimental trials have been carried out to evaluate temperature influence on the sensor calibration curve. The air thermohygrometric conditions were T = 28±1°C in the second set of measurements and T = 37±1°C in the third one; RH was always in the range 4÷8%.

V. RESULTS AND DISCUSSION

In the following, all results are reported as the mean ± the standard error calculated with a Student reference distribution (four degree of freedom and confidence of 95%).

Fig.3 shows the experimental data obtained from the first set of measurements along with the best fit, according to Eq. (3). Sensor response has been found slightly asymmetric as far as it concerns flow direction, although experimental data are fitted using a symmetric calibration curve. A maximum ΔP percent variation of 7% in correspondence of same flow rate in overall range has been found.

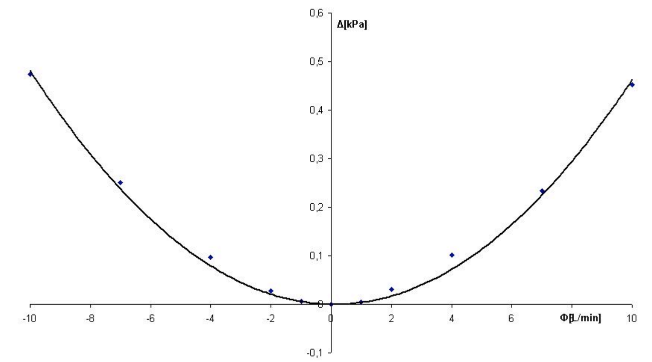

Fig. 3. Experimental data obtained from calibration and second order polynomial best fitting curve with air at 19±1°C temperature.

Using the least square mean error algorithm, Eq. (3) assumes the following expression:

$$\Delta P(19°C) = 0.0047\phi^2 - 0.0009\phi \quad (5)$$

This curve shows R^2=0.99 and a Mean Standard Error (MSE) equal to 0.2Pa^2.

The pneumotacograph shows a repeatability value lower than 2% in the whole calibration range. Sensitivity is not constant and varies from about 25 Pa·L^{-1}·min for flow rates lower than 4 L/min to about 58 Pa·L^{-1}·min for flow rates higher than 7 L/min.

Fig. 4 shows data obtained at different air flow temperature values (T=28°C and T=37°C), compared with the previously reported results obtained at air temperature T=19°C. MSE is equal to 0.4 Pa^2 at a 28°C gas temperature, 1 Pa^2 at 37°C.

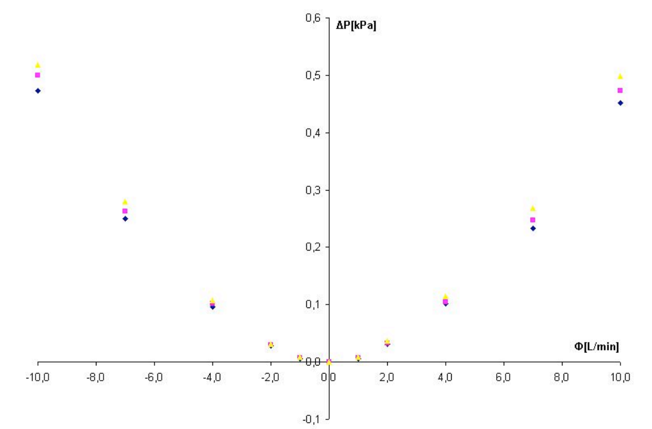

Fig. 4. Experimental data obtained from calibration using air at 20°C (rhombus dot), 28°C (square dot), 37°C (triangle dot).

When higher air temperature are set (28°C and 37°C), repeatability is about 2% in overall range. It can be seen that sensor output is different from the first set of experiments, as the resistance increase with the temperature. The ΔP variation, if air temperature increases from 20°C to 37°C, is higher than 10% at highest flow rates.

Using the standard least-square-fit technique, Rohrer's equations have been found:

$$\Delta P(28°C) = 0.0050\phi^2 - 0.0011\phi \quad (6)$$

$$\Delta P(37°C) = 0.0052\phi^2 - 0.0007\phi \quad (7)$$

As it can be seen in Table I, K_1 and K_2 values increase with temperature.

TABLE I
K_1 AND K_2 VALUES CALCULATED FOR THREE AIR TEMPERATURE VALUES

	$K_1 \left[\frac{Pa}{(L/min)^2}\right]$	$K_2 \left[\frac{Pa}{(L/min)}\right]$
T=19±1°C	4.7	-0.9
T=28±1°C	5.0	-1.1
T=37±1°C	5.2	-0.7

From the observation of Table I it emerges that K_1 increases with temperature whereas K_2 does not show a regular dependence from temperature. As temperature increases from 19°C to 37°C, a percent K_1 variation of about 10% is shown.

The sensor calibration curve obtained for air at 19°C applied to the measurement of an air flow rate at 37°C would then cause an error of about 10% at highest flow rates.

We hypothesized then a linear relationship between K_1 coefficient and temperature:

$$K_1(T) = AT + B \quad (8)$$

and utilized Eq. (8) to minimize the measurement error as a function of temperature. Thus, by substituting Eq. (8) in Eq. (3) and solving for ΔP we obtain:

$$\Delta P = (AT + B)\phi^2 + K_2\phi \quad (9)$$

A, B and K_2 values have been obtained in order to minimize MSE between the curve represented by (9) and the entire set of experimental data. Thus, the following equation for K_1 coefficient has been obtained:

$$K_1 = 2.778*10^{-5}T + 4.170*10^{-3} \quad (10)$$

By substituting Eq. (10) in Eq. (9) we obtain the calibration curve as a function of temperature:

$$\Delta P = (2.7778*10^{-5}T + 4.17*10^{-3})\phi^2 - 9*10^{-4}\phi \quad (11)$$

By utilizing Eq. (11) for fitting all experimental data we obtained MSE = 0.2Pa^2 at a 19°C and 28°C gas temperature and a MSE = 0.3Pa^2 at 37°C. MSE values as a function of gas temperature is represented in Table II both when using Eq. (10) and without using it. Accuracy is <2% in overall range at three different temperatures.

TABLE II
MSE AS A FUNCTION OF GAS TEMPERATURE OBTAINED BY DATA REGRESSION WITH EQ. (5) AND WITH EQ. (11)

	T=19°C	T=28°C	T=37°C
MSE obtained with (5) [Pa^2]	0.2	0.4	1
MSE obtained with (11) [Pa^2]	0.2	0.2	0.3

A linear dependence of K_1 coefficient with temperature appears then to be suitable to obtain low MSE values in the temperature range considered.

VI. Conclusions

A capillary type pneumotachograph has been described and calibrated for air flow measurement at different temperatures.

The pneumotacograph is characterized by a low dead space and a good sensitivity in the whole measurement range. The Rohrer equation, corrected for gas temperature, allows to increase the accuracy of the pneumotacograph whereas maintaining the sensitivity. The proposed correction makes the sensor suitable for infant ventilatory flow rate measurements.

The linearity of second term coefficient is hypothesized and found suitable for the here presented flow sensor. However, more research is still needed to extend such a result to wider temperature and flow rate ranges.

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