A transistors-based, bidirectional flowmeter for neonatal ventilation: design and experimental characterization

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Abstract— **A bidirectional, low cost flowmeter for neonatal artificial ventilation, suitable for application in mono-patient breathing circuits, is described here. The sensing element consists of two nominally identical bipolar junction transistors employed as hot bodies. The sensor working principle is based on the convective heat transfer between the transistors, heated by Joule phenomenon, and the colder hitting fluid which represents the measurand. The proposed design allows the sensor to discriminate flow direction.**

Static calibration has been carried out in a range of flowrate values (from -8 L·min^{-1} up to +8 L L·min^{-1}) covering the ones employed in neonatal ventilation, at different pipe diameters (*i.e.*, 10 mm and 30 mm) and collector currents (*i.e.*, 500 mA, 300 mA, and 100 mA) in order to assess the influence of these two parameters on sensor's response. Results show that the configuration with a pipe diameter of 10 mm at the highest collector current guarantees the highest sensitivity (i.e., 763 mV/L·min^{-1} at low flowrate ± 1 L·min^{-1}) and ensures the minimum dead space (2 mL *vs* 18 mL for 30 mm of diameter). On the other hand, the 30 mm pipe diameter allows extending the range of measurement (up to ±6 L·min^{-1} *vs* ±3.5 L·min^{-1} at 10 mm), and improving both the discrimination threshold (<0.1 L·min^{-1}) and the symmetry of response. These characteristics together with the low dead space and low cost foster its application to neonatal ventilation.

I. INTRODUCTION

In neonatal ventilation, an accurate monitoring of gas volume exchanges is pivotal to minimize ventilator induced lung injury and hyperventilation or hypoventilation. Along with the commercial flowmeters (i.e., Fleisch and screen pneumotachographs, hot wire anemometers, ultrasonic flowmeters and variable orifice meters [1]), the growing interest in the control of breathing in preterm infants has motivated investigations, focusing on the development of flowmeters with different working principles, such as fiber optic-based [2,3], micromachined flowmeter [4], and non-compliant orifice meter [5], among others.

In this work we present the design and static calibration of a low cost, low dead space, bidirectional flowmeter, based on heat transfer between two (nominally identical) transistors and a colder hitting fluid. The choice of the transistors has been led by the following criteria: small dimension, low cost, and high maximum junction temperature. Besides, their small size may foster the development of miniaturized flowmeters, that are particularly required for preterm infants' breathing monitoring. Although, this solution involves some problems related to non-linear behavior of the transistors [6], it allows an easy integration in neonatal, disposable breathing circuit. The small dimension and the ability to discriminate flow direction are the main novelties of the proposed transducer with respect to similar approaches [7]. Firstly, the sensor working principle has been described, then it has been experimentally validated in a range of flowrates values usually delivered in neonatal ventilation (between -8 L·min^{-1} and +8 L·min^{-1}). Lastly, the influence of collector current and pipe diameter on sensor response has been assessed.

II. THEORETICALLY BACKGROUND

The sensor working principle is based on the convective heat transfer between the surface of the transistors, heated by Joule phenomenon, and the colder hitting fluid. In steady-state conditions, a hot element, placed in a fluid stream at temperature T_f, reaches a superficial temperature of equilibrium, which depends on the heat flow exchanged with the fluid. If this element is a transistor, the base-emitter junction temperature (T_{be}^S) can be obtained by the following equation:

$$I_C^2 \cdot R_{CE} = h \cdot S \cdot (T_{be}^S - T_f) = Q \tag{1}$$

where I_c is the collector current, R_{CE} the equivalent collector emitter resistance, h the heat transfer coefficient, Q the heat exchanged between the transistor and the fluid at equilibrium, and S is the hit exchange surface.

The heat transfer coefficient, h, depends on the system geometry, the physical properties of the fluid, and the fluid velocity. It can be expressed by the King's Law [8]:

$$h = A + B\sqrt{\rho v} \tag{2}$$

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where A and B are two calibration constants, ρ is the fluid density, and v is the mean fluid velocity.

The relationship between the base-emitter voltage, V_{be}, and the base-emitter temperature (T_{be}^{S}), can be considered as linear in a wide range of temperature:

$$V_{be}(T_{be}^{S}) \cong a + bT_{be}^{S} \tag{3}$$

The coefficients a and b are constants, and in particular b represents the thermal sensitivity of V_{be} (≈-2 mV·K^{-1}). Introducing (1) and (2) in (3) and solving for V_{be}, the relationship between the base-emitter voltage and v can be expressed as:

$$V_{be}(v) = a + b\left(\frac{Q}{S\left(A + B\sqrt{\rho v}\right)} + T_f\right) \tag{4}$$

In order to discriminate flow direction, the sensor is made of two identical transistors, placed in the center of the pipe cross-section (Fig.1): the front transistor is directly hit by the fluid, while the rear one is shielded by the PCB (Printed Circuit Board) where it is soldered on. Since the two transistors are nominally identical, the two constants a and b are considered equal. In steady state conditions, the two transistors reach different T_{be}^{S}, hence different V_{be}, because the fluid hits them with different speeds. In fact, the heat exchanged by the front transistor is bigger than the one exchanged by the rear transistor. As a consequence, the equilibrium temperature of the front transistor is lower than the one of the rear transistor. Therefore the two V_{be} are not equal, and their difference ΔV_{be} can be expressed as follows:

$$\begin{aligned} \Delta V_{be}(v_1, v_2) &= V_{be}^{1}(v_1) - V_{be}^{2}(v_2) = \\ &= b\left[\frac{Q_1}{S\left(A + B\sqrt{\rho v_1}\right)} - \frac{Q_2}{S\left(A + B\sqrt{\rho v_2}\right)}\right] \end{aligned} \tag{5}$$

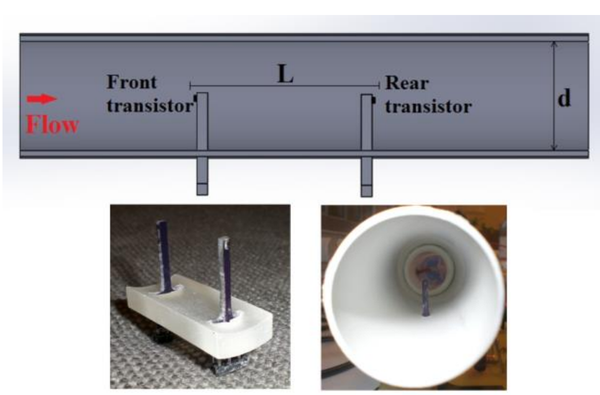

Fig. 1. Geometrical configuration of the sensing element. The transistors are placed on a PCB board, in line with the fluid stream, in correspondence with the duct center.

being Q_1 and Q_2 the heats exchanged between the transistors and the fluid, v_1 and v_2 are the speeds of the gas hitting the transistors T_{r1} and T_{r2}, respectively.

Assuming as simplifying hypotheses that: $Q_1=Q_2=Q$ (transistors are nominally identical and supplied by the same constant I_c),v_2 is negligible because the rear transistor is shielded by its own PCB, and $v_1 \approx 2 \cdot v$ (under laminar flow condition) where v is the gas speed averaged on the whole pipe cross-section, (5) becomes:

$$\Delta V_{be}(F) = \pm b\left[\frac{Q}{S\left(A + B\sqrt{\rho \frac{2F}{\Omega}}\right)} - \frac{Q}{SA}\right] \tag{6}$$

where Ω is the cross section of the pipe and $F=v \cdot \Omega$ is the volumetric flowrate. The sign of ΔV_{be} is determined by the direction of the gas flow.

By defining the following two additional constants:

$$k = \frac{bQ}{SA}, \quad c = \frac{B\rho^2}{\Omega^2} \tag{7}$$

we obtain the calibration function of the transducer:

$$\Delta V_{be}(F) = \pm kc\frac{\sqrt{F}}{A + c\sqrt{F}}. \tag{8}$$

III. Design and Manufacturing

In order to study the influence of pipe diameter on sensor sensitivity, we fabricated two prototypes with a minimum duct diameter of 10 mm and maximum one of 30 mm. These values meet the condition of laminar flow (Reynolds number<2100) in the whole range of interest (*i.e.*, F up to 8 L·min^{-1}), and assure a low dead space.

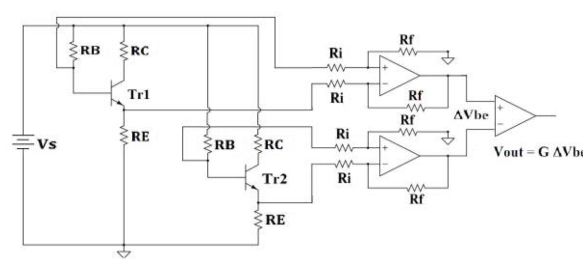

Fig. 2. Electrical schematic of the transducer.

The transistors have been soldered on two identical PCBs (1.6 mm thick), which are placed inside the duct 20 mm apart (Fig. 1). Their distance acts as thermal insulator, in order to minimize the mutual influence.

Two different sockets, one for each diameter, have been built using a rapid prototyping printer (Project 3000 by 3D Printer Inc.), and sealed on the duct to avoid air losses. Their function is to support the two PCBs inside the duct and to assure the positioning of the transistors at the center of duct cross-section, hit by the maximum gas speed. The two transistors used as hot sensing elements have been supplied by a constant current in common emitter configuration. For each transistor, the difference between the base and the emitter voltages (i.e., V_{be}^{1} and V_{be}^{2}) has been processed to obtain V_{out} as in Fig.2.

Among several off-the-shelf transistors, we have chosen two nominally identical NPN bipolar junction transistors (PBSS2515M by Philips) in a SOT883 package, with small dimensions (0.50 mm $\times$ 1.02 mm $\times$ 0.62 mm), maximum collector current of 500 mA, and a maximum junction temperature of 150 °C. The first stage of the analog circuit consists of two differential operational amplifiers (TL074CN, Texas Instrument), with unit gain; the second one consists on an instrumentation amplifier (INA101HP, Texas Instruments) with gain G=50, tuned by a resistive trimmer. Therefore, the output signal is $V_{out}=50 \cdot \Delta V_{be}$. Furthermore, the resistance values are: RB=267 Ω, RC=RE=1.8 Ω, and Ri=Rf=25 kΩ.

IV. EXPERIMENTAL SET UP

In order to calibrate the sensor prototypes (*i.e.*, 10 mm and 30 mm duct diameter), we have performed a set of trials with the experimental setup shown in Fig.3. We performed experiments at different values of flowrate (from 0.1 L·min^{-1} up to 8 L·min^{-1}) in the two flow directions and at three I_C values (*i.e.*, 500 mA, 300 mA, and 100 mA), in order to investigate the influence of diameter and I_c on sensor's response.

Gas temperature, T_f, has been monitored during all trials and can be considered almost constant (T_f =25±1°C for all trials).

Each trial was repeated five times to analyze the sensor's repeatability. All the results are reported as mean ± the uncertainty, calculated using a Student reference distribution with four degrees of freedom and a level of confidence of 95%.

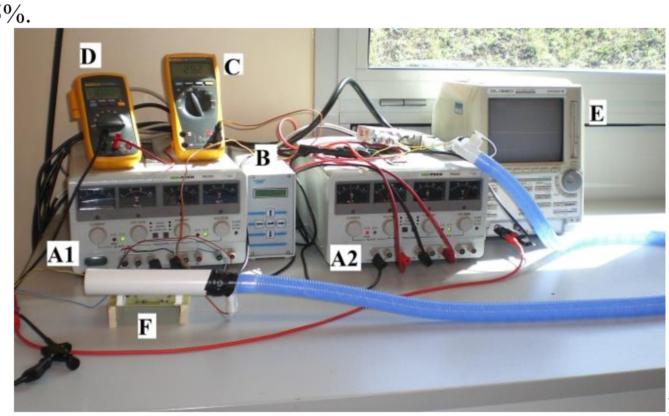

Fig. 3. Experimental setup. A1 and A2 power supply unit for amplifiers; B) air flow controller; C) thermocouple; D) multimeter; E) digital oscilloscope; F) flowmeter under calibration.

V. RESULTS AND DISCUSSION

The influence of I_C and d on sensor response has been experimentally assessed. In Fig. 4, the calibration curves for the two diameters and at the three I_c values are plotted.

Although the nonlinear response causes a decrease in the range of measurement, the proposed sensor is able to discriminate low flowrates. Fig.4 shows that the configuration with d=30 mm has a wider linear range than the one with d=10 mm. Moreover, the mean sensitivity is strongly influenced by I_c values: for d=10 mm, in the whole range of measurements at I_c=500 mA, it is four times bigger than the one at I_c=100 mA. The calibration curve is also influenced by d (*e.g.*, in the range of ±1 L·min^{-1}and at I_c=500 mA the mean sensitivity is 320 mV/L·min^{-1} for d=30 mm *vs* 763 mV/L·min^{-1} for d=10 mm). In order to analyze the sensor performance in terms of bi-directionality, the gas flow has been delivered in the two opposite directions to simulate inspiratory and expiratory flows. The bi-directionality has been quantitatively assessed by the following index (S_y), introduced in [5]:

$$S_y = \sum_{i=1}^{N} \frac{\left| \dfrac{\left|V_{out}^{\exp}(i)\right| - \left|V_{out}^{insp}(i)\right|}{\left|V_{out}^{\exp}(i)\right| + \left|V_{out}^{insp}(i)\right|} \right|}{N} \tag{9}$$

where $V_{out}^{exp}(i)$ represents the output voltage for the i-th flowrate value delivered in the direction of expiration, $V_{out}^{insp}(i)$ the output voltage for the i-th flowrate value blowing in the opposite direction; N is the number of different flowrate values used to calibrate the sensor (*13* in our case).

S_y is an asymmetry index and it varies between 0 and 1 by definition: the lower is its value, the better is the symmetry of sensor response.

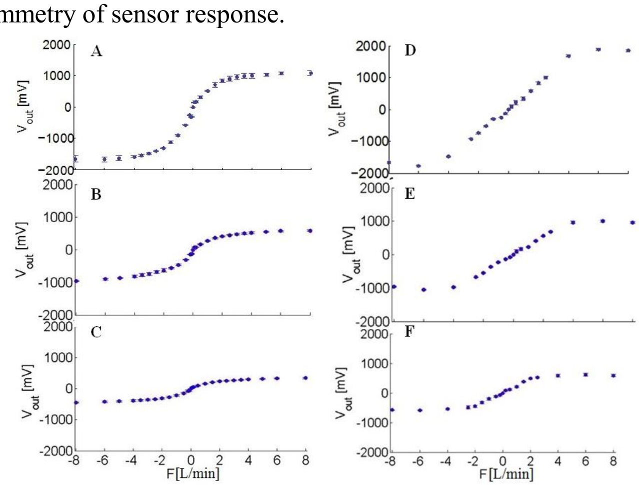

Fig.4. Calibration curves at different d and I_c: A) d=10mm and I_c=500mA; B) d=10mm and I_c=300mA; C) d=10mm and I_c=100mA; D) d=30mm and I_c=500mA; E) d=30mm and I_c=300mA; F) d=30mm and I_c=100mA.

In Table I, the following sensor characteristics for the different diameter and current values have been summarized:

i) range of measurement, *ii*) mean sensitivity calculated in the range ±1 L·min^{-1}, *iii*) asymmetry index, *iv*) discrimination threshold, *v*) dead space, calculated as $\pi \frac{d^2}{4} L$, where L=25.2 mm is the hypothetical distance between the two heat transfer surfaces of the transistors, as shown in Fig.1, and *vii*) accuracy as percentage of the full scale (FS).

The best performance in terms of sensitivity is obtained at the highest I_c value. Comparing values in Table I, the mean sensitivity in the range of ±1 L·min^{-1} increases of 10% from 100 mA to 300 mA, and of 40% from 300 mA to 500 mA, for d=30 mm. For d=10 mm, at 300 mA, the mean sensitivity is two times bigger than the one at 100 mA. The flowmeter with hot bodies supplied at their maximum collector current (*i.e.*, 500 mA) and with d=30 mm shows the best performance.

Its main advantages are: a high mean sensitivity in the whole range of measurement), a low discrimination threshold (<0.1 L·min^{-1}), a range of measurement (±6 L·min^{-1}) covering typical flowrates employed in neonatal ventilation, a good symmetric response (Sy=0.07), and a low accuracy (3%FS).

Table I. Characteristics of the flowmeter at different I_c and *d* values.

	d=30 mm			d=10 mm		
Ic [mA]	100	300	500	100	300	500
Measurement Range [L·min^{-1}]	±6	±6	±6	±2.5	±3.5	±3.5
Sensitivity [mV/L·min^{-1}]	206	230	320	190	370	763
S_y	0.04	0.04	0.07	0.18	0.25	0.24
Discrimination threshold [L·min^{-1}]	<0.1	<0.1	<0.1	>0.1	>0.1	>0.1
Dead Space [mL]	18	18	18	2	2	2
Accuracy [%FS]	7	5	3	7	4	7

Lastly the configuration with d=10 mm guarantees the lowest dead space (*i.e.,* 2 mL), lower or comparable to that of transducers typically used in neonatal ventilation, such as the pneumotachograph described in [9,10] (*i.e.*, 2 mL).

VI. Conclusion

In conclusion, the two configurations assure low dead space and are able to discriminate flow direction. Results show that both d and I_c strongly influence the sensor characteristics: the sensitivity improves with I_c and decreases with d; on the other hand the range of measurement is wider in the configuration with d=30 mm than in the one with d=10mm.

Thus, the proposed sensor exhibits promising results for application in neonatal ventilation; although further trials should be performed to experimentally assess the influence of other influencing factors, such as relative humidity. Moreover the sensor can be employed in other applications such as during nutritive sucking, where the respiratory monitoring can provide useful information regarding the integrity of the infant's central nervous system, and to perform early diagnosis of future neurodevelopmental disorder [11-13].

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