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Gas pre-warming for improving performances of heated humidifiers in neonatal ventilation

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Abstract— **Adequate temperature and humidification of gas delivered must be performed during long term neonatal ventilation to avoid potential adverse health effects. Literature shows that performances of heated humidifiers are, at least in some cases, quite poor.**

In this study, a novel approach to gas conditioning, consisting of gas warming upstream the humidification chamber, is presented. Gas pre-warming, in combination with a control strategy based on a mathematical model taking into account a number of parameters, allows to significantly improve the heated humidifier performances.

The theoretical model has been validated and experimental trials have been carried out in the whole volumetric flow-rate (Q) range of neonatal ventilation (lower than 10 L·min^{-1}). Experimental results (temperature values ranging from 36 °C to 38 °C and relative humidity values from 90 % to 98 % in the whole range of Q) show values very close to the ideal thermo-hygrometric conditions.

The proposed solution allows to avoid vapor condensation at low flow rates and decrease of relative humidity at high flow rates.

I. INTRODUCTION

DURING invasive artificial ventilation, the upper airways are bypassed by endotracheal or tracheostomy tube. Therefore, gases delivered to patients need to be warmed and humidified in order to minimize adverse health effects due to dry gas, particularly critical in neonatal ventilation (moisture and heat loss, loss of ciliated epithelium, reduction in surfactant activity) [1]. Recommended gas thermo-hygrometric conditions for intubated neonates are still subject of debate however, they should have values very close to those observed in normal lung conditions during spontaneous breathing [2]: temperature value close to the systemic one (37 °C) and saturated (RH almost 100 %) [3].

The most widely used humidifiers in long-term neonatal ventilation are Heated Humidifiers (HHs) and Heated Wire Humidifiers (HWHs) [4]. Previous studies described the influence of several parameters (e.g., ventilator settings as minute volume [5], [6] , inlet chamber gas temperature, T_1, and environmental temperature [7]) on the performances of HH and HWH. Schena *et al.* [8] and Verta *et al.* [9] proposed novel control approaches to improve HH performances.

Commercially available HWHs warm and humidify gas through two steps: 1) the gas delivered by mechanical ventilator passes through a humidification chamber where water is heated by an electrically powered plate; 2) the gas leaving the humidification chamber is further warmed along the breathing circuit inspiratory limb connecting with the "Y" piece, through heat produced by a heating wire. This second step is absent in the HH. Some humidifiers can be controlled in both HWH and HH modalities [10], [11]. The main drawback using "HH mode" is the decrease of gas temperature along the breathing circuit between the humidification chamber and the "Y" piece. On the other hand, a temperature increase in "HWH mode", causes a decrease of gas relative humidity.

The control strategy implemented in a HH, by adjusting the power delivered to the heating plate, causes the weakening of performances. In our opinion, this is due mainly because the value of just one variable is used as feedback (e.g., gas temperature at the exit of the chamber).

In this study a novel approach for humidification process is introduced: delivered gas is "pre-warmed" along the tract connecting the mechanical ventilator with the HH. The pre-warming treatment, that increases T_1, is implemented to obtain an outlet chamber gas temperature (T_2) equal to about 37 °C with an outlet relative humidity (RH_2) slightly lower than 100 %. The aim is to obtain gas at ideal thermo-hygrometric conditions immediately after the humidification chamber, therefore not requiring an additional increase of temperature along the breathing circuit. In the inspiratory limb, a heated wire is used only to maintain the gas temperature constant.

The pre-warming treatment has been theoretically assessed, and implemented in the heated humidifier SCH 1000 PLUS (Ginevri srl). Its performances, adopting the control strategy described in a previous work [9], are evaluated at flow rate values typical of neonatal ventilation.

II. THEORETICAL BACKGROUND

As it well known, RH depends also on gas temperature (T) and it can be expressed as:

$$RH = \frac{1.61 \cdot P_t}{P_s} U \qquad 1$$

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where P_t is gas total pressure, P_s is saturation pressure of water vapor and U is absolute humidity of the gas. The dependence of P_s with T can be expressed by the following simplified formula [12]:

$$P_s = 611.21 \cdot \exp\left(\frac{17.502 \cdot T}{240.97 + T}\right) \qquad 2$$

where T and P_s are expressed in celsius degree and in pascal respectively.

Introducing (2) in (1) RH can be related to T:

$$RH = \frac{2.634 \cdot 10^{-3} \cdot P_t}{\exp\left(\frac{17.502 \cdot T}{240.97 + T}\right)} U = \alpha(T) \cdot P_t \cdot U \qquad 3$$

being:

$$\alpha(T) = \frac{2.634 \cdot 10^{-3}}{\exp\left(\frac{17.502 \cdot T}{240.97 + T}\right)}$$

$\alpha(T)$ decreases if T increases, in the typical gas temperature range of mechanical ventilation (e.g., from 20 °C to 40 °C). This consideration spotlights that gas temperature at humidification chamber outlet should be equal to the recommended temperature at the "Y" piece. In fact, if gas was heated along the tract between the chamber and the "Y" piece, RH would decrease; if gas was cooled, the water vapor would condensate, causing the risk of the endotracheal tube occlusion.

Figure 1 shows the RH variations of saturated gas (RH=100%) at different initial temperatures, (T_i equal to 31 °C, 34 °C and 37 °C), as a function of positive ΔT increments ranging from 0 to 5 °C.

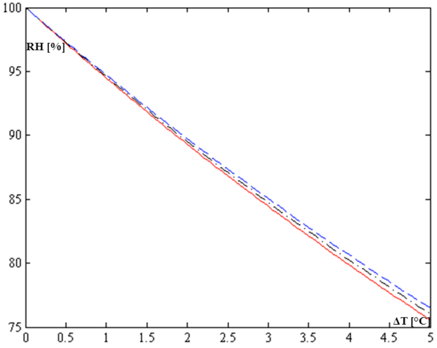

Fig. 1. RH of saturated gas as a function of gas temperature increase (ΔT). Continuous line: initial gas temperature T_i=31 °C; dotted line: T_i=34 °C; dashed line: T_i= 37 °C.

Numerical simulations show that a temperature increase of 5 °C causes a RH decrease greater than 20 % for all three initial gas temperatures; moreover, a gas temperature increase from 37 °C to 40 °C, typically performed in HWHs, causes a RH decrease of about 15 %. Simulations also show a negligible influence of T_i value on the RH decrease.

In order to cope with the above mentioned issue, we introduce the gas pre-warming, along the tract between the outlet of pulmonary ventilator and the humidification chamber inlet, through a heated wire. The power dissipated by a heated wire is controlled in order to warm up the gas at a defined value of T_1. The aim is to obtain T_2 values of about 37 °C and RH_2 values of about 95 % at humidification chamber outlet. Therefore, another heated wire maintains the gas temperature constant along the tubing connecting the humidification chamber outlet to the patient.

The control law implemented by the SCH 1000-PLUS is based on the adjustment of plate temperature from the HH panel. In a previous study we developed a mathematical model of gas conditioning. It showed that RH_2 depends on several factors: T_1 and T_2, RH_1, T_W, and Q. The dependence can be expressed by following equation [9]:

$$U_2 = \frac{\left\{-Q\left[C^U_{P,2}(T_2 - T_0) - C^U_{P,1}(T_1 - T_0)\right] + Q\lambda U_1 + k_Y U_S S\left[\lambda + C_{P,W}(T_S - T_0)\right] + S\left[h(T_S - T_2)\right]\right\}}{\left\{Q\lambda + k_Y S\left[\lambda + C_{P,W}(T_S - T_0)\right]\right\}} \qquad 4$$

RH_2 can be calculated by substituting 1 in 4. The model (4) can be used to implement a control strategy substituting in the model the values of T_1 and RH_1 (obtained by measurement), the set values of Q, and the desired values of T_2 (e.g., 37 °C) and RH_2 (e.g., 95 %). All other values (specific heat of humid inlet gas, $C^U_{P,1}$, specific heat of humid outlet gas, $C^U_{P,2}$, liquid vapor specific heat at constant pressure, $C^U_{P,W}$, convective heat transfer coefficient, h, liquid evaporation latent heat at reference temperature T_0, λ, matter transfer coefficient experimentally calculated, k_Y, gas absolute humidity at saturation, U_S, gas-liquid interface surface, S) are reported in a previous study [9]. Numerical simulations, presented in figure 2, show the combinations of T_W, T_2 and Q values to perform optimal gas humidification (RH_2= 95 %).

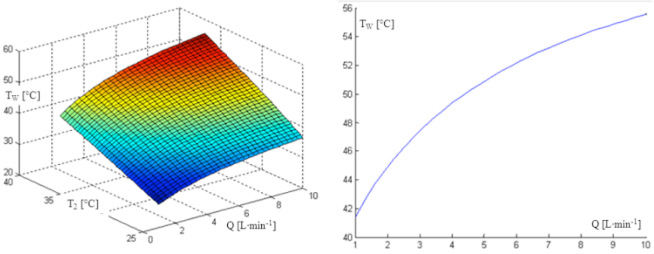

Fig. 2. Left side: iso-surface representing the combinations of T_W, Q and T_2 values to obtain an RH_2 value of 95 % in presence of gas pre-warming treatment; right side: theoretical trend of T_W as a function of Q setting ideal thermo-hygrometric values of gas after humidification treatment (T_2=37 °C and RH_2=95 %).

Simulations show that T_W must be increased, when Q increases, to obtain T_2=37 °C, and RH_2= 95 % (e.g., when Q varies from 1 L·min^{-1} to 10 L·min^{-1}, T_W must be increased from 42 °C to 55 °C).

III. EXPERIMENTAL SETUP

Experimental tests have been carried out to evaluate the conditioning efficacy of a HH (SCH 1000 PLUS, Ginevri srl) with and without gas pre-warming. A picture of the experimental setup is reported in figure 3.

A continuous flow rate (Q) is delivered by a mass flow controller, figure 3.D (Bronkhorst El-Flow, range from 0.05 $L\cdot min^{-1}$ to 10.00 $L\cdot min^{-1}$, accuracy 0.2 % of the set-point value), to generate a controlled Q ranging from 2 $L\cdot min^{-1}$ to 10 $L\cdot min^{-1}$, in steps of 1 $L\cdot min^{-1}$. The air flows from the mass flow controller to the HH through a pipe provided with a heated wire, figure 3.E.

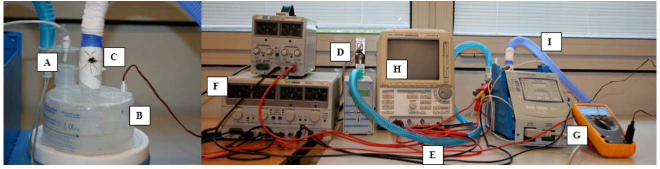

Fig. 3. Experimental setup. Right side. (D) mass flow controller, (E) and (I) breathing circuit, (F) power supplies, (G) Multimeter, (H) oscilloscope; left side. Zoom of the humidification chamber: (A) inlet gas temperature sensor, (B) thermocouple to monitor water temperature, (C) outlet gas temperature and humidity sensors.

A power supply unit (DC ISO-TECH IPS2302A, figure 3.F) is used to power the heated wire that warms up the air. This way, T_2 values in the range 37±1 °C were obtained. Further trials are performed without pre-warming treatment (T_2=26±2 °C). T_2 and RH_2, and RH_1 are measured by two humidity and temperature sensors (HIH 4602A Honeywell, range from 0% to 100% and accuracy ±3.5 % for humidity measurements, and range from -40 °C to +85 °C for temperature measurements, figure 2.C). The resistance of temperature sensor is displayed on a multimeter (179 Fluke, figure 3.G), the output voltage of the RH sensor is displayed on a two channel digital oscilloscope (DL 1520 Yokogawa, figure 3.H). Inlet gas temperature (T_1) is measured through the temperature sensor embedded in the HH (figure 3.A). Water temperature (T_W) is measured by a K-type thermocouple (range from -40 °C to +400 °C, accuracy ±1 °C, figure 3.B). The gas is conveyed from the humidification chamber outlet to the "Y" piece through the inspiratory limb of a standard neonatal breathing circuit (about 130 cm of length), figure 3.I. This tube is provided with a heated wire powered by a power supply unit manually controlled to obtain T_Y≈37 °C (figure 3.H). T_Y and RH_Y values are measured by a HIH 4602A with the output voltage displayed on the two channel digital oscilloscope (figure 3.H).

With pre-warming treatment, the value of supply voltage is set to reach a T_1 value allowing to obtain a T_2 value of 37 °C and non-saturated gas with high relative humidity (RH_2=95 %). T_W is adjusted at a particular value, calculated by the model reported in 4, allowing to obtain RH_2≈95 %. The boundary conditions are: the measured value of RH_1, RH_2= 95 %, T_2= 37 °C, Q equal to the volumetric air flow rate delivered through the mass flow controller, and T_1 equal to the value measured in real time by the temperature sensor. T_2 is utilized as a feedback variable: when the T_2 value is lower than the desired one ($T_2^* \approx 37°C$), the pre-warming is increased and *vice-versa* with the condition of $T_2 > T_2^*$. If the gas presents the thermo-hygrometric conditions above described, it will not be necessary to warm it up along the tract of breathing circuit between the chamber and the "Y" piece.

IV. RESULTS AND DISCUSSION

The experimental results are shown in figure 4. Data have been compared with data obtained without pre-warming and reported in a previous study [9]. Preliminary experimental data show that RH_1 can be considered constant and equal to about 5 %.

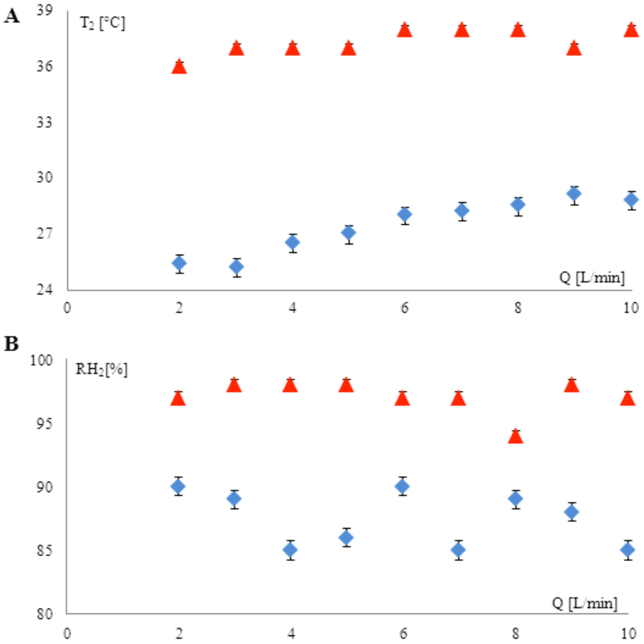

Fig. 4. A) T_2 as a function of Q in the typical range of neonatal ventilation, between 2 $L\cdot min^{-1}$ and 10 $L\cdot min^{-1}$ in presence (triangle dot) and in absence of pre-warming (rhombus dot); B) RH_2 as a function of Q in presence (triangle dot) and in absence of pre-warming (rhombus dot).

The gas pre-warming, as shown in figure 4, allows to obtain T_2 values very close to the recommended ones for gas delivery to ventilated patients: T_2 ranges from 36 °C to 38 °C independently from the flow rate. This approach allows to avoid the gas warming along the breathing circuit path connecting the chamber and the "Y" piece; without pre-warming, the gas must be heated along this path in order to reach T_Y≈37 °C. In this second case, the post-warming causes a decrease of RH, as shown in figure 1, e.g., when air with thermo-hygrometric condition equal to T_2= 27 °C and RH_2= 95% is heated up to 37 °C it is subject to a decrease of RH reaching a very low value of about 50%, caused by the increase of the saturated water vapor pressure [13]. Figure 4 also shows the appreciable performances of the HH using the pre-warming in the whole range of Q: RH_2 values ranging from 90 % to 98 %.

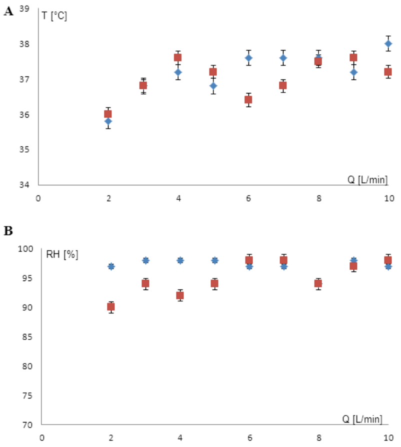

Fig. 5. A) Comparison of T_2 (square dot) and T_Y (rhombus dot) as a function of Q; B) comparison of RH_2 (square dot) and RH_Y (rhombus dot) as a function of Q.

Further trials have been carried out to compare RH_2 and T_2 with RH_Y and T_Y. Figure 5 shows these variable values as a function of Q.

Also the above reported experimental data show that T_2 and RH_2 values are limited in the ranges from 36 °C to 38 °C and from 90 % to 98 % respectively. The temperature is maintained almost constant along the breathing circuit tract between the chamber and the "Y" piece by means of a heated wire; in fact, T_Y ranges from 35 °C to 38 °C. The absence of temperature variations avoids significant RH changes between the exit of the chamber and the "Y" piece: both RH_Y and RH_2 are greater than 90 % in the Q overall range.

T_W value is set to obtain a RH_2 value of 95 % in Q overall range, from 2 $L\cdot min^{-1}$ to 10 $L\cdot min^{-1}$. T_W values must increase with Q as shown in figure 6.

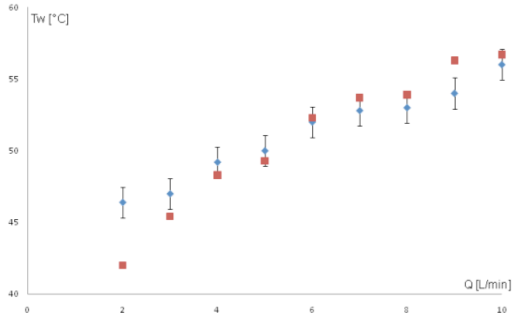

Fig. 6. T_W as a function of Q: experimental values (rhombus dot) and values obtained by the model reported in (4), square dot, setting a theoretical value of RH_2=95 %.

T_W experimental data show a good agreement with the theoretical ones predicted by the model (4) in the whole range of Q, as shown in figure 6 and also confirmed by the low value of MSE (about 3 °C^2).

V. CONCLUSIONS

The introduction of pre-warming combined with a control strategy taking into account the influence of Q, T_1, and T_2 improves the performances of the SCH 1000-PLUS. In fact, this solution allows to avoid vapor condensation at low Q values and decrease of RH_2 if Q increases: RH_Y is close to the ideal value and respects the ISO recommendations (RH>75 %) [14] in overall range of calibration despite of the results obtained without pre-warming (also lower than 30 % [6], [9]).

The approach of maintaining constant the gas temperature between the outlet of the humidification chamber and the "Y" piece also appears a good strategy to avoid changes in thermo-hygrometric gas conditions.

Further research must be performed to evaluate the influence of gas pre-warming on the performances of HHs with different control strategies. As the HH performances depend on inlet gas temperature, a clear advantage associated to the introduction of the pre-warming treatment will be to have inlet gas at constant temperature.

VI. ACKNOWLEDGMENT

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