Simultaneous temperature and humidity measurements in a mechanical ventilator using an optical fibre sensor

F.U. Hernandez[a], R. Correia[a], S.P. Morgan[a], B. Hayes-Gill[a], D. Evans[b], R. Sinha[b], A. Norris[b], D. Harvey[b], J.G. Hardman[b] and S. Korposh[*a]

[a]Advanced Optics Group, Faculty of Engineering, University of Nottingham, Nottinghamshire, NG7 2RD, UK; [b]Department of Anaesthesia, Queen's Medical Centre, Nottingham, NG7 2UH, UK

ABSTRACT

An optical fibre sensor for simultaneous temperature and humidity measurements consisting of one fibre Bragg grating (FBG) to measure temperature and a mesoporous film of bilayers of Poly(allylamine hydrochloride)(PAH) and silica (SiO_2) nanoparticles deposited onto the tip of the same fibre to measure humidity is reported. The hygroscopic film was created using the layer-by-layer (LbL) method and the optical reflection spectra were measured up to a maximum of 23 bilayers. The temperature sensitivity of the FBG was 10 pm/^{0}C while the sensitivity to humidity was (-1.4×10^{-12} W / %RH) using 23 bilayers. The developed sensor was tested in the mechanical ventilator and temperature and humidity of the delivered artificial air was simultaneously measured. Once calibrated, the optical fibre sensor has the potential to control the absolute humidity as an essential part of critical respiratory care.

Keywords: temperature, humidity, fibre Bragg grating (FBG), Fabry-Perot, layer-by-layer (LbL), mechanical ventilator.

1. INTRODUCTION

Reviews and studies on humidification during invasive and non-invasive mechanical ventilation[1,2] provide recommendations about suitable hygroscopic parameters (absolute humidity (AH), relative humidity (RH) and temperature) values when delivery of humidified gas is required in patients. Thus, AH levels between 33 mg H_2O/L and 44 mg H_2O/L, and a gas temperature between 34 ^{0}C and 41 ^{0}C near the upper airways of the patient (100 % RH at the Y-piece of the breathing circuit) are suggested during invasive ventilation[2]. Active humidification (using generally a heated humidifier) is favoured more than passive humidification (using a heat and moisture exchanger, HME) during invasive and non-invasive ventilation, however, other devices and studies have incorporated HME with active heating and water addition as different approach to provide more convenient humidification (~100% RH) and less water consumption[3,4]. Tests using a lung model should regulate temperature in the model itself to maintain 37 ^{0}C and reach 100 %RH, for instance, Larsson et al[4] have reported an absolute humidity of 41 to 44 mg/L in the bench test and 7.5 mg/L in the expiratory ventilator tubing.

Control of humidity and temperature in ventilator care equipment is essential for conditioning delivery of inspired gases during mechanical ventilation, and optical fibre technology could potentially solve the drawbacks of using electrical sensors for this application, for instance, smaller sensors embedded in the breathing elements used with ventilator care equipment and better response time to enable breath to breath humidity and temperature monitoring.

Our previous work aimed to characterise and calibrate an optical fibre humidity sensor probe (based on Fabry-Perot cavity), determining sensitivity to humidity, better response time than a commercially available capacitive sensor and feasibility to resolve individual breaths in a bench lung model using a mechanical ventilator[5]. The primary goal of this work is to present an extension of the optical fibre sensor through including a fibre Bragg grating (FBG) to measure temperature simultaneously and allow us to calculate absolute humidity levels.

Sixth European Workshop on Optical Fibre Sensors, edited by Elfed Lewis, Proc. of SPIE Vol. 9916, 99160C · © 2016 SPIE · CCC code: 0277-786X/16/$18 · doi: 10.1117/12.2236850

2. MATERIALS AND METHODS

The method of deposition of the multilayer film of PAH/SiO_2 follows the steps (Fig. 1a): (i) treatment of the surface-tip of the fibre coupler with 1 wt% ethanolic (H_2O:ethanol (Sigma-Aldrich)=3:2) KOH (Sigma-Aldrich) for 20 min; (ii) wash with deionized water and dry with nitrogen, followed by immersion of the fibre tip in 0.17 wt% of positively charged polymer PAH (M_W: ~58,000, pH=11) for 15 min; (iii) wash and dry, and immerse the fibre tip into a solution containing negatively charged SiO_2 nanoparticles (SNOWTEX 20L, diameter 40 nm to 50 nm, Nissan Chemical, Japan) for 15 min; (iv) after deposition of the SiO_2 nanoparticles, wash and dry and repeat steps (ii) and (iii) until the desirable "X" number of bilayers denoted as $(PAH/SiO_2)_X$ is created.

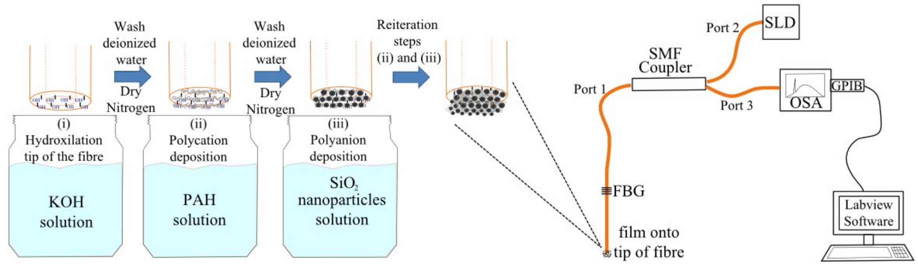


Figure 1. (a) LbL deposition method (bilayers of PAH/SiO_2); (b) optical SMF coupler used to obtain reflection spectra from port 1 containing the film $(PAH/SiO_2)_{23}$ and the FBG. The super-luminescent diode (SLD externally isolated) sends light which is reflected in port 1 and recorded in port 3 through an optical spectrum analyzer (OSA).

Figure 2a presents the experimental set-up for temperature and humidity measurements in a drying and heating chamber (FD23, BINDER). One FBG with reflection (~60%) wavelength of 1551 nm and length of 3 mm was fabricated in the core of a hydrogen-loaded optical fibre (SMF-28e+, Corning) using phase mask technique. This piece of fibre containing the FBG was spliced at port 1 of the SMF coupler (1x2 SMF coupler 50/50, operating wavelength 1310/1550 nm, bandwidth 40 nm). After depositing 23 bilayers on the tip of the fibre as described in Fig. 1a, the sensor probe (port1 containing the film (PAH/SiO_2) and the FBG) was placed inside the climatic chamber along with two type-k thermocouples (USB TC-08 Data Logger, Pico Technology), and a capacitive humidity sensor (iButton hygrochron Logger DS1923, Maxim Integrated). The fibre coupler received light from a super-luminescent diode (SLD-761-HP1, central wavelength 1557.6 nm, spectral width 43.8 nm, SUPERLUM) into port 2; there were two main reflections at port 1, the strongest was due to the Bragg wavelength of the FBG and the other was due to the reflections originating at the $(PAH/SiO_2)_{23}$ film working as a Fabry-Perot cavity[6]. The reflected spectra were collected using an optical spectrum analyzer (OSA MS9710C, Anritsu) which was interrogated using Labview software to display and store data in a personal computer.

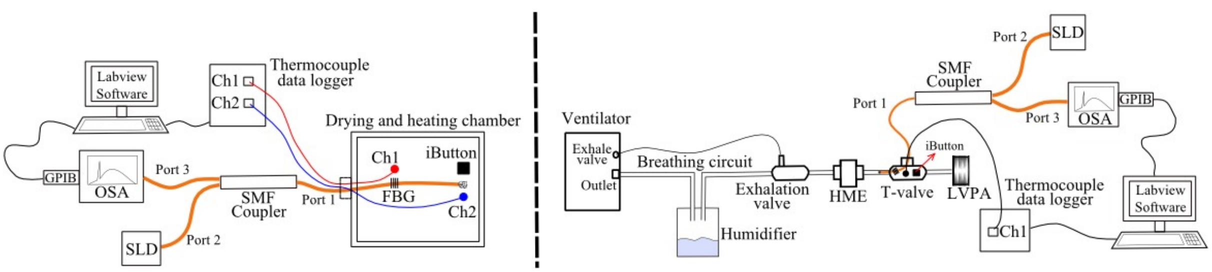
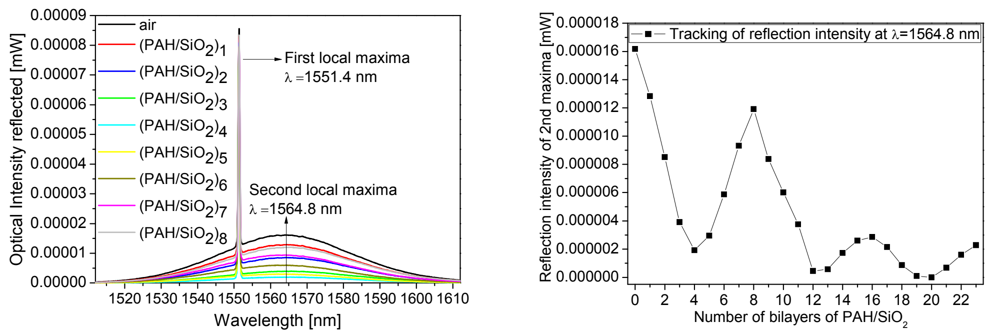


Figure 2. (a) Set-up to test the optical fibre temperature-humidity sensor in a drying and heating chamber. Two thermocouples and the capacitive humidity sensor (iButton) were placed inside the chamber for comparison with the optical sensor; (b) Testing the optical sensor in the breathing circuit connected to a positive pressure ventilator. One thermocouple and the capacitive sensor (iButton) were also inserted in the T-valve in order to corroborate the response of the fibre sensor. The HME was used to reduce moisture that could affect the performance of the humidity sensor probe[5]. All the devices involved in both experiments were synchronized (recording at the same sampling frequency of 1 Hz).

Using the same optical fibre sensor, temperature and humidity measurements were also performed at the patient end of a breathing circuit (Fig. 2b) connected to a model lung ventilator performance analyzer (LVPA, BOC Medishield Ltd); the breathing system was plugged to a non-invasive positive pressure ventilator (model NIPPY3+, B&D Electromedical Ltd) which was used with a pressure of 9 cm H_2O and flow of 80 L/min. Port 1 of the optical fibre sensor, a thermocouple and the capacitive humidity sensor were inserted between the filtered HME (B&D Electromedical Ltd) and the LVPA. Temperature and humidity were estimated after switching on a heated humidifier (MR-850AEK, Fisher & Paykel Healthcare Limited) included in the circuit (Fig. 2b). After connecting all the elements as shown in Fig. 2b, the humidifier was switched on after 200s and was heating water for 1400 s (total duration of the experiment).

3. RESULTS

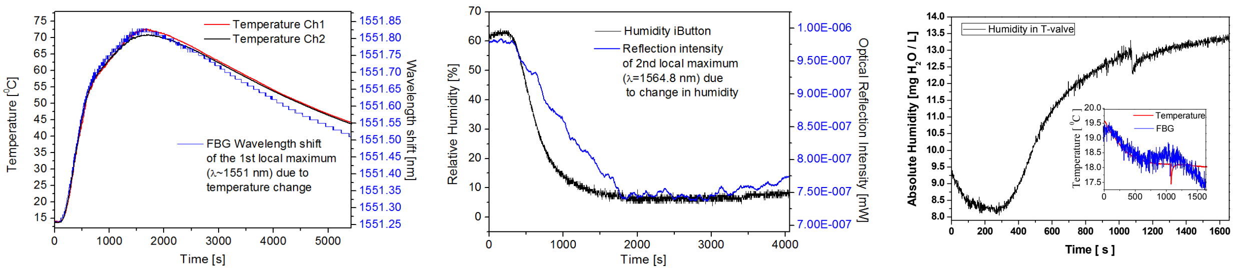
Figure 3a shows the total reflection spectra obtained after depositing the first eight bilayers of PAH/SiO_2. The first local maximum (λ=1551.4 nm) in Fig. 3a are due to the Bragg wavelength reflection from the FBG written in the core of the fibre; the second local maximum was used for tracking the reflections due to the Fabry-Perot cavity formed by the film onto the tip of the fibre. Figure 3b plots the change in reflection intensity of the second local maximum (λ=1564.8 nm) after depositing each of 23 bilayers of PAH/SiO_2. It is anticipated from Figure 3b that highest sensitivity to humidity would be observed in the region of thicknesses between 7 and 10 layers where the slope of the reflection change is highest [5].



(a) (b)

Figure 3. (a) Total reflection spectra measured using the set-up shown in Fig. 1b after deposition of bilayers of PAH/SiO_2 onto the tip of the fibre; (b) Tracking of the optical reflection intensity (measured through port 3 of the set-up depicted in Fig. 1b) at the second local maxima (λ=1564.8 nm) after depositing each of 23 bilayers of PAH/SiO_2 on the tip of the fibre[6].

Figure 4a compares the wavelength shift of the FBG (~1551 nm) written in the port1 of the fibre coupler and the readings from two thermocouples placed in the drying and heating chamber used for calibration (Fig. 2a); the Bragg wavelength shift sensitivity was linear 9.9 pm/^{0}C (R^2=0.9993) when increasing temperature and 10.7 pm/^{0}C (R^2=0.9983) decreasing temperature. Figure 4b contrasts the change in optical reflection of the 2nd local maxima (1564.8 nm, described in Fig. 3) and the humidity capacitive sensor (iButton), both placed in the climatic chamber for calibration (Fig. 2a). Figure 4c shows the change in absolute humidity in the T-valve (Fig. 2b) which was calculated based on the change of temperature (from 19.5 ^{0}C to 18.0 ^{0}C) and relative humidity[1] (50 to 85 %). The graphic inset in Fig. 4c corroborates the same typical sensitivity (10 pm/^{0}C) and correlation between the Bragg wavelength shift at 1551 nm and temperature measured by thermocouple (both located in the T-valve, Fig. 2b).



(a) (b) (c)

Figure 4. (a) Bragg wavelength shift of the first local maximum from the spectra measured when port 1 of the fibre coupler was placed with two thermocouples inside a drying and heating chamber (Fig. 2a); (b) tracking of the optical reflection intensity from 2^{nd} local maximum when synchronized and compared with the relative humidity measurements from the capacitive sensor used; (c) Absolute humidity measured when the temperature decreased from 19.5^0C to 18 ^{0}C.

4. CONCLUSIONS AND FUTURE WORK

Using the optical fibre sensor described, the results in Fig. 4c confirm the feasibility to measure simultaneously temperature and humidity in ventilator care equipment. Results of Figs. 4b and 4c support the hygroscopic properties of the film based on bilayers of PAH/SiO_2 which changes its optical thickness when water vapour molecules are absorbed due to humidity changes. Based on the results of Fig. 4c, the absolute humidity changed from 8.2 to 13.5 mg H_2O/L when the temperature decreased 1^0C during experiment described in Fig. 2b; this gradient of absolute humidity was generated by the use of the HME and corresponds to the absolute humidity values obtained with the LVPA model (without warming at 37^0 C). In addition, it was possible to show how the total reflection intensity changed due to the number of bilayers deposited (Fig. 3), verifying the theory related to the thickness of the Fabry-Perot cavity formed at the surface-tip of the fibre. The calibration and testing results presented in Fig. 4 are based on a film $(PAH/SiO_2)_{23}$ which demonstrated there is still small sensitivity to humidity (-1.4×10^{-12} W / %RH) and the Bragg wavelength shift stands in a typical standard sensitivity of 10 pm/^{0}C. Future work aims to demonstrate higher sensitivity to humidity for the range of interest between 7^{th} and 10^{th} bilayers of PAH/SiO_2 (Fig. 3b); full calibration of the optical sensor; and its application to measure absolute humidity in intensive care equipment.

ACKNOWLEDGMENTS

The authors want to thank the National Institute for Health Research Invention for Innovation (NIHR i4i) Programme (Grant Reference Number: II-LA-0813-20008) for funding. The views expressed are those of the authors and not necessarily those of the NHS, the NIHR or the Department of Health. FUH acknowledges the support of the National Council of Science and Technology of Mexico (CONACyT) for a scholarship.

REFERENCES

[1] Jackson, C. and Webb, A.R., “An evaluation of the heat and moisture exchange performance of four ventilator circuit filters,” Intensive Care Med 18, 264-268 (1992).
[2] Restrepo, R. D. and Walsh, B. K., "Humidification during invasive and noninvasive mechanical ventilation: 2012,” Respir Care 57(5), 782-788 (2012).
[3] Kapadia, F., et al., "An active heat and moisture exchanger,” Br J Anaesth 69, 640-642 (1992).
[4] Larsson, A., Gustafsson, A., and Svanborg, L., "A new device for 100 per cent humidification of inspired air,” Crit Care 4(1), 54-60 (2000).
[5] Hernandez, F.U., et al., “Characterisation and use of a fibre optic sensor based on PAH/SiO_2 film for humidity sensing in ventilator care equipment,” IEEE Trans Biomed Eng, in press (Feb. 2016).
[6] Arregui, F.J., et al., “Optical fiber nanometer-scale Fabry-Perot interferometer formed by the ionic self-assembly monolayer process,” Opt Lett 24(9), 596-598 (1999).