DOI 10.5162/SMSI2023/P56

2x2 factorial calibration of FBG sensors for simultaneous measurement of temperature and humidity in PEM fuel cells

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Summary:

Fiber Bragg grating (FBG) sensor technology is expected to make an important contribution to extending the lifetime of polymer electrolyte membrane (PEM) fuel cells. It allows accurate measurements of in-situ operating temperature and humidity, which is essential for an accurate control of both. For these applications an accurate and reliable calibration is crucial. This paper demonstrates the successful use of a 2x2 factorial calibration method for calibration of two standard FBGs for application in a PEM fuel cell. The calibrated low-cost FBG sensor allows temperature and humidity measurements with a RMS error (RMSE) of 0.45°C and 4.8 %RH, respectively.

Keywords: factorial design, fiber Bragg grating, calibration, temperature sensing, humidity sensing, PEM fuel cell

FBG sensors in PEM fuel cells

Polymer electrolyte membrane (PEM) fuel cells will contribute significantly to the mobility of the future. For an extension of the service life of the membrane as most critical component, it is necessary to precisely monitor and control the process temperature and humidity within the cell. Electronic sensors are of limited use in this harsh environment, whereas fiber Bragg grating (FBG) sensors are sufficiently small, chemically inert and do not generate an electrical short circuit. Characteristic for FBG sensors is the narrow wavelength band, which is reflected by the inscribed grating. It changes almost linear in response to the parameters to be measured. So far, FBG are mainly used for strain and temperature measurements. However, in [1] it was shown that FBG with polyimide coating can be used as humidity sensors. In [2], an FBG-based temperature and humidity sensor was successfully integrated into a PEM fuel cell. However, it required a complex production process, especially for the humidity measuring sensor requiring etching and coating with a specialty polymer. Therefore, in the present work simple FBG sensors are used for the same measurement task. Each FBG requires an initial calibration. Following [3], a 2x2 factorial design calibration is used. It allows to determine additional cross sensitivities between the quantities to be measured.

FBG sensor calibration by 2x2 factorial design

The used measurement setup is shown in Fig. 1. It relies on ordinary FBG sensors. One of the FBG has an acrylate coating and is therefore mainly sensitive to temperature changes, hereafter referred to as FBG_T. A second FBG with an ORMOCER coating (hereafter $FBG_{T,RH}$) is sensitive to both, temperature and humidity changes.

The FBG are placed in a climatic chamber and fed by a SLED Denselight DL-BP1-1501A broad-band light source, while the reflected signals are detected by an Ibsen I-MON USB 256 spectrometer serving as an interrogator.

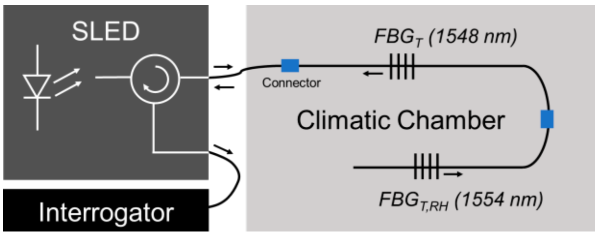

Fig. 1. Measurement setup for FBG sensor calibration.

A 2k factorial design calibration can be used when the parameter range to be covered is sufficiently small. For each calibration parameter *k* a measurement at an upper and a lower limit is to be performed. For two parameters, this results in $2^2=4$ measuring points. A control point in the center is used for verification. Fig. 2 gives an overview of the parameter range used, which is typical for the targeted fuel cell. After successful calibration any combination of temperature and humidity that lies within the modelled square can be measured.

Each of the four measurement points defining the corner of the square forms a row in the equation system in Eq. (1). The reflected wavelength λ_i is

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captured together with the temperature T_j and the relative humidity values RH_j for every point.

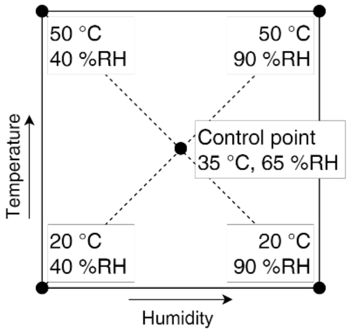

Fig. 2. Measurement square for calibration with 2x2 factorial design.

By solving the linear system of equations in Eq. (1), four calibration parameters are determined for each FBG: the fundamental wavelength λ_0, the temperature coefficient S_T, the humidity coefficient S_H and a mutual coefficient between temperature and humidity S_{TH}.

$$\begin{bmatrix} \lambda_1 \\ \lambda_2 \\ \lambda_3 \\ \lambda_4 \end{bmatrix} = \begin{bmatrix} 1 & \Delta T_{low} & \Delta RH_{low} & \Delta T_{low}\Delta RH_{low} \\ 1 & \Delta T_{low} & \Delta RH_{high} & \Delta T_{low}\Delta RH_{high} \\ 1 & \Delta T_{high} & \Delta RH_{low} & \Delta T_{high}\Delta RH_{low} \\ 1 & \Delta T_{high} & \Delta RH_{high} & \Delta T_{high}\Delta RH_{high} \end{bmatrix} \times \begin{bmatrix} \lambda_0 \\ S_T \\ S_H \\ S_{TH} \end{bmatrix} \quad (1)$$

Tab. 1 shows the determined coefficients for the two FBGs. It shows that FBG_T is as expected almost insensitive to humidity variations. For FBG_{TH} a 1°C temperature change results in a wavelength change that is almost equivalent to an approx. 5% change in relative humidity. In combination, both sensors allow a good temperature and humidity measurement. This is verified by a measurement of the control point showing an accuracy of -0.45 K and +1 %RH.

Tab. 1: Temperature and humidity sensitivities.

	FBG_T	$FBG_{T,RH}$
λ_0 [nm]	1548.815	1554.005
S_T [pm K^{-1}]	9.9	12.8
S_H [pm / %RH]	0.109	2.71
S_{TH} [pm / (K %RH)]	$7.41 \cdot 10^{-3}$	$-1.58 \cdot 10^{-2}$

Results and Conclusion

Since the measurement environment in a PEM fuel cell is varying, a dynamic measurement cycle is used to check the measurement accuracy and precision of temperature and humidity values under close-to-real operating conditions. The internal temperature and humidity sensors of the climate chamber are used as a reference to calculate the RMSE.

As all possible parameter combinations are to be well covered by the model in Fig. 2, the dynamic test uses temperature plateaus in intervals of 10°C within the range between 20°C and 50°C. The humidity is varied linearly from 40 %RH to 90 %RH and back over a period of 4 hours to capture also possible hysteresis effects. Fig. 3 shows the temperature and humidity values as recorded by the climate chamber and the parallel measured Bragg wavelengths for the two FBGs. Since the two FBGs are installed in close proximity, they experience the same climatic conditions. From the Bragg wavelengths the temperature T and humidity RH can be calculated by solving the inverted equation system Eq. (1).

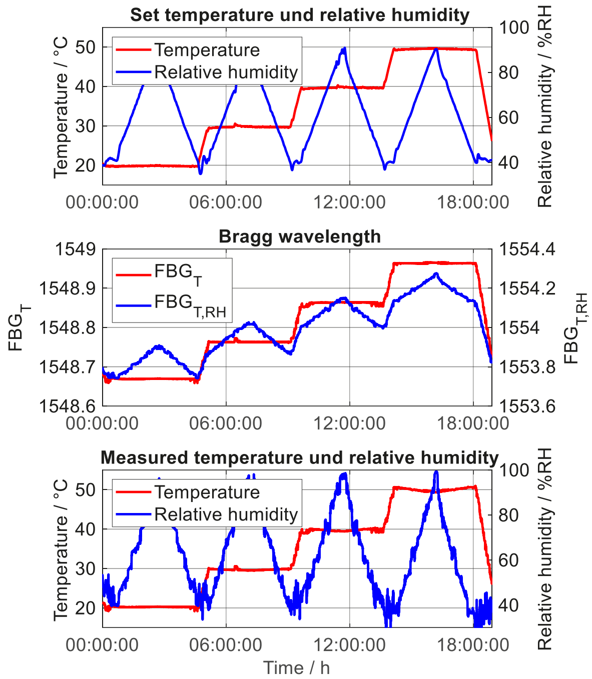

Fig. 3. Dynamic measurement cycle for verification.

With the presented set-up and a 2x2 factorial design calibration the temperature and the humidity can be measured with a RMSE of 0.45 °C and 4.8 %RH, respectively, with the internal climatic chamber sensors as reference. A part of the uncertainty of the RH measurement could be attributed to a limited precision of the climatic chamber, especially at high RH, and the low reflectivity of $FBG_{T,RH}$ of only 2.4 %. Thus, it has been demonstrated in this paper that it is possible to build a two-parameter measurement system for temperature and humidity based on ordinary and 'state of the art' FBG sensors.

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