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Measurement Systems for In-Situ Monitoring of Fuel Cell Systems Using Fiber Optical Sensors and Colorimetric Fluorescence Technology

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Summary:
Fuel cells (FC) are crucial in advancing sustainable transportation and energy production, though their industrial and automotive deployment remains limited. This research focuses on in-situ measurement solutions to enhance fuel cell performance, safety, and durability. Two instruments are being implemented: multiparameter fiber-optic (FO) sensors embedded in an additively manufactured bipolar plate (BP) for minimal invasive in-cell measurements and an online water analysis device for detecting degradation in FC wastewater. These solutions enable enhanced in-situ chemical and physical FC measurements.

Keywords: fuel cells, in-situ degradation monitoring, laser powder bed fusion, embedded fiber optical sensor, fluorescence sensor

Introduction

Innovative FC sensor solutions are essential for enhancing the development of proton exchange membrane (PEM) FCs, making them more affordable and durable. Real-time, in-situ measurements and characterization of inappropriate operating conditions is essential for better FC development and lifetime prediction. Dangerous conditions, such as an uneven humidity distribution or degradation of the perfluoro sulfonic acid (PFSA) Nafion® membrane material lead to membrane shrinkage and can cause irreversible damage to the FC. Monitoring spatially resolved membrane humidification and fluoride emission rates could be crucial for a more accurate FC system performance assessment. Additional in-situ data supports the development of simulation models and enhances their accuracy [1][2].

Methodology

A novel sensor solution for in-cell spatially resolved multiparameter monitoring is presented based on FO sensors embedded into an Additive Manufactured (AM) "smart" BP. The invention enables a minimally invasive multi-parameter measurement close to the chemical reaction of the FC. A Fiber Bragg Grating (FBG) technology is used for temperature and strain sensing, while tapered and laser-cut single-mode fibers are employed for humidity sensing [3].

Using the Laser Powder Bed Fusion (LPBF) process, a stainless-steel BP is 3D printed, embedding the fibers during process interruptions. However, this printing method encounters challenges, such as obtaining hydrogen gas tightness and ensuring that the BP's thermal, electrical, and fluid dynamical properties match those of standard BPs.

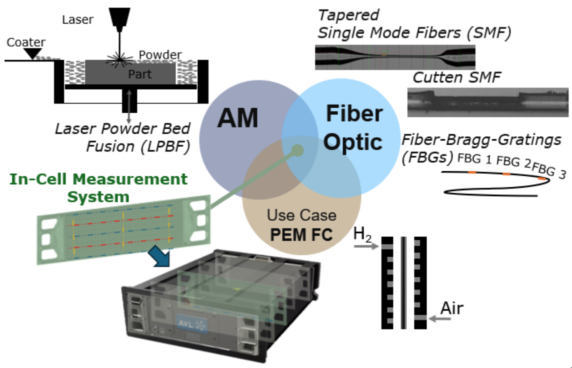


Fig. 1. Fusion of Additive Manufacturing and fiber optic sensors creates a "smart" bipolar plate for minimally invasive fuel cell application

Additionally, a real-time water analysis system for monitoring membrane degradation caused by free hydrogen radicals measures fluoride emissions in a time-resolved manner. This system uses a colorimetric fluorescent reagent with high selectivity for fluoride [4], laser excitation, and a microfluidic cuvette to detect fluorescence, providing early indications of FC degradation. An integrated optical, microfluidic setup realized with an online sampling concept in the FC environment enables time-resolved measurement.

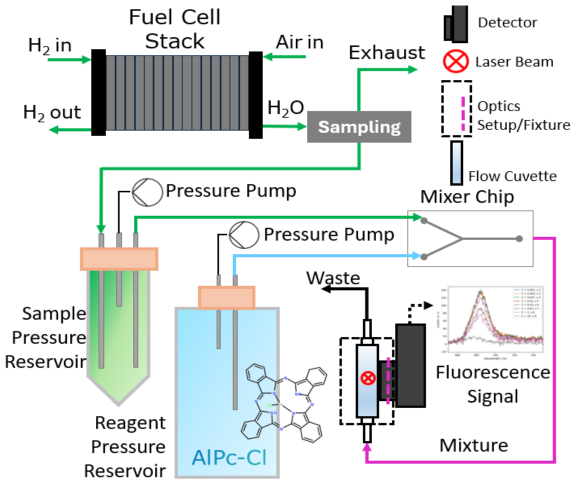
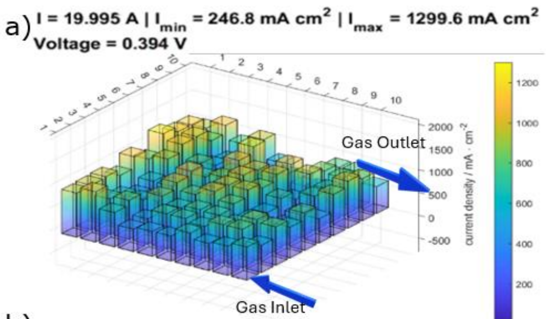


Fig. 2. Scheme of sensor concept for real-time fluoride measurement in PEM FC systems

Results and Discussion

The initial 3D printed BP was realized using 316L stainless steel, with the embedding OF for temperature and strain sensing based on FBG technology. AM prototypes successfully demonstrated H_2 gas tightness for FC applications. The first single-cell FC test bed application of a smart BP with embedded temperature OFs showed a good measurement correlation between detected hot spots and current density peaks measured with a shunt resistor current mapping board.



b)

	FBG 5	FBG 4	FBG 3	FBG 2	FBG 1
Fiber 1	53,8 °C	53,8 °C	53,8 °C	54,1 °C	53,9 °C
Fiber 2	55,4 °C	55,6 °C	55,7 °C	55,5 °C	55,2 °C
Fiber 3	56,0 °C	56,0 °C	56,3 °C	56,0 °C	55,7 °C
Fiber 4	55,7 °C	55,6 °C	55,4 °C	55,5 °C	55,7 °C
T-Difference (Max-Min):					2,5 °C

Gas Inlet

Gas Outlet

Fig. 3. a) Current density distribution in a 5x5 cm single-cell FC test bed (cathode side). b) Temperature distribution in the smart bipolar plate (anode side)

Further enhancements aim to include humidity sensing using tapered or laser-cut single-mode fibers. Laser-cut fiber sensors demonstrated promising humidity correlation between 20%rH and 80%rH with ~1% accuracy. Improvements in fiber processing, such as debris cleaning and round edges design, enhance robustness in the embedding process and against rough environmental conditions in the FC.

A first research prototype for online sampling and time-resolved fluoride concentration measurements showed a detection limit below 10 ppb. The microfluidic system achieved accurate and bubble-free control of water analyte mixing with a constant flow rate of 15 µl/min and 10% water concentration. To achieve a faster aggregation of the F- with the reagent of approx. 6 minutes, the mixture was heated to 45°C, significantly improving PEM FC water quality assessment and membrane degradation detection.

Conclusion

Initial studies and implementations of the AM BP and the presented online product water analyzer show the potential of innovative sensor systems to identify and characterize unfavorable FC conditions. Preliminary lab and test bed applications demonstrated the potential for obtaining critical in-situ parameters and improving the identification of membrane degradation indicators, thus enhancing FC performance, lifetime, and safety.

Acknowledgment

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