Observing liquid water build-up in proton exchange membrane fuel cells using terahertz imaging and high-resolution optical gauging

Décio F. Alves-Lima[1], Harald Schlegl[1], Bryan M. Williams[2], Rosa Letizia[1], Richard Dawson[1], Hungyen Lin[1]
[1]Department of Engineering, Lancaster University, Lancaster LA1 4YW, United Kingdom
[2]Department of Computing and Communications, Lancaster University, Lancaster LA1 4WA, United Kingdom

***Abstract* – The performance and durability of proton exchange membrane fuel cells are closely linked to effective water management strategies. Inadequate water balance results in polymer electrolyte membrane (PEM) dehydration or water flooding, both leading to performance loss and possible cell failure. Exploiting the contrast from liquid water absorption and transparency of dielectric materials, such as polymers, at terahertz (THz) frequencies, we apply a simple, compact THz imaging system to image water build-up in the flow channels of a THz-transparent fuel cell supported by high resolution optical gauging.**

I. INTRODUCTION

Proton exchange membrane fuel cells (PEMFCs) are electrochemical devices for clean hydrogen energy production. Successful water management in PEMFC is critical for the cell's performance and long-term durability. To better understand liquid water accumulation and transport dynamics, several visualisation techniques have been used, such as magnetic resonance imaging (MRI), neutron imaging, x-ray radiography and microtomography, infrared imaging and optical imaging [1]. In general, MRI, neutron and x-ray techniques can yield valuable information on liquid water transport inside optically opaque PEMFC parts, but suffer from low frame-rate, limited availability and a relatively high cost. Infrared and optical imaging often use compact and video-rate devices with high-spatial resolution and frame-rates but require parts of the cell to be fitted with optically transparent windows with limited penetration depth and contrast.

Terahertz (THz) radiation has been growing in popularity for contactless and non-destructive testing across various industrial sectors [2-7]. The ability of THz to penetrate through non-polar polymers and strong attenuation by liquid water [8] provides the necessary contrast to non-invasively inspect liquid water build-up inside an operating PEMFC. In this work, we develop a simple THz imaging system in transmission geometry based on a low-cost THz focal-planar array camera. Such an imaging system was used to quantitatively image liquid water across Nafion PEMs previously [9]. Here, we apply the same imaging system to observe water build-up in an operating PEMFC fitted with THz transparent windows, supported by simultaneous high-resolution optical gauging analysis.

II. METHODOLOGY

A 100 cm^2 active area THz-transparent PEMFC was designed and assembled for this investigation. In particular, the PEMFC featured a 0.05 mm-thick Nafion NRE-212 PEM, Toray carbon paper gas diffusion layers (Fuel Cell Store, TX, USA), 0.5 mm-thick stainless steel current collectors, 4 mm-thick acrylic flow field plates and 10 mm-thick aluminium compression endplates. To allow for THz beam penetration, all of the components (except the acrylic plates and PEM) have a 3.5x3.5 cm^2 opening (Figure 1a) at a spatial position susceptible to water accumulation [10]. The THz imaging system is based on a 0.1 THz IMPATT diode source and a THz camera with an array of 16x16 GaAs-based semiconductor detectors (Terasense Inc., CA, USA). Simultaneously, we imaged the same area using a high-resolution optical gauging system based on an IMT-CAM-028 high-resolution optical camera with a 2452x2056 pixel array (Imetrum, UK). A photograph of the complete setup is shown in Figure 1b.

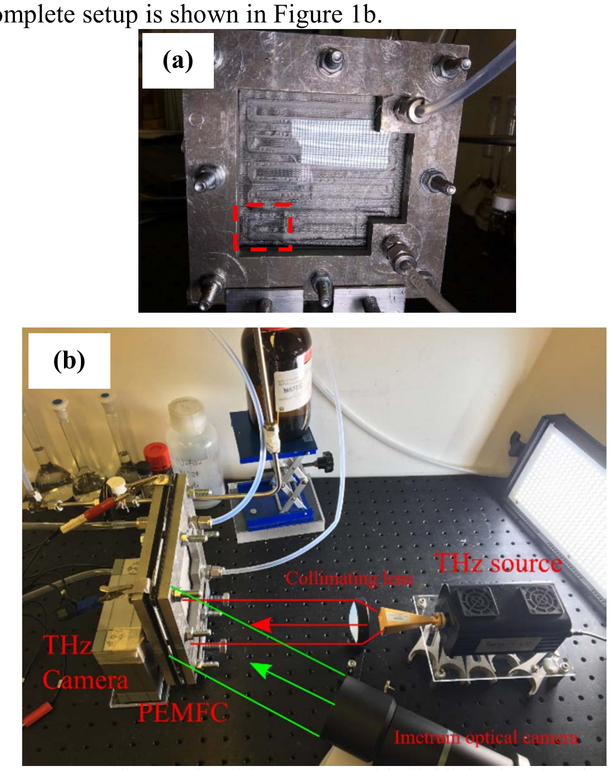

Figure 1. (a) Photograph of the PEMFC with highlighted region for THz imaging. (b) Photograph of the complete setup including the PEMFC, THz and optical imaging systems. Red and green lines and arrows represent the width and direction of the THz and optical light, respectively.

III. RESULTS

Preliminary results with only THz measurements showed signs of substantial flooding after several hours of operation, evidenced by a 72% reduction in average THz intensity. By further increasing the reactant gases' flowrate, accumulated water was gradually removed from the cell, resulting in the return of THz intensity values to the initial levels.

We performed analysis on the lower half of the measurement window which corresponds to the bottom channel. Water presence seen in the optical images is analysed by image processing methods. The images were first pre-processed automatically to correct for changes in illumination and light reflections of the water. A saturation probability map is created by examining change in each frame; this is used to measure the collected water by finding the boundaries in a fast, unsupervised approach, and to calculate the regional saturation. As the camera does not move during the recording, the model runs fully automatically for each frame without user intervention.

Figure 2 compares the optical and THz images at the beginning (Figure 2a) and end (Figure 2b) of the PEMFC operation, where the transition from a fully dry channel to a flooded state can be observed. This pattern is consistent with two phase flow and droplet dynamics previously reported in PEMFCs [11]. The THz images also display a similar behaviour, as shown by the predominance of ‘darker’ pixels (low intensity), which are caused by liquid water presence, at the end of operation [9].

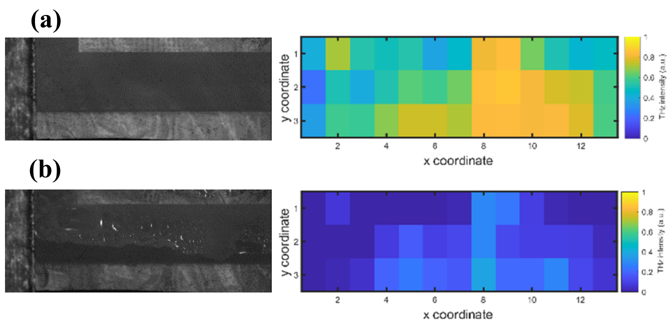

Figure 2. Comparison between high-resolution optical (left) and THz (right) images at (a) 1 minute and (b) 330 minutes of PEMFC operation.

Figure 3 compares the average THz intensity against optical images throughout water accumulation in the regions of interest. For the sake of clarity, the THz intensity values have been inversed for comparison against the optical measurement. Though subject to slight discrepancies, it can be seen that the two independent measurements are generally in good agreement in terms of the slope of the data. Examples of the discrepancies include a sharp increase in the optical density in the first 100 minutes followed by a plateau, while the THz intensity grows steadily at a lower rate. There is also discrepancy between the acquired values, which is possibly due to an imperfect mapping between THz intensity and the saturation measurable in optical images. In spite of these imperfections for our preliminary measurement, the results are promising and highlight the potential use of the THz imaging for inspecting water build-up in the flow channels of PEMFCs.

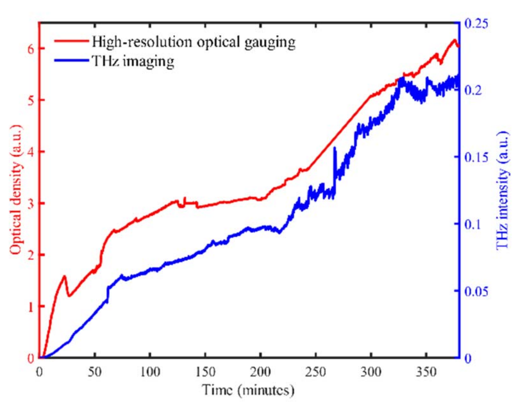

Figure 3. Water accumulation in the PEMFC measured by high-resolution optical gauging (red) and THz imaging (blue).

IV. CONCLUSIONS

In this study, we have explored the potential of a compact THz transmission imaging system to observe water accumulation in a section of a PEMFC during operation. We have compared the measurements against high resolution optical gauging. Analysis of the data shows agreement between these two measurement techniques.

ACKNOWLEDGEMENTS

The authors acknowledge the EPSRC Impact Acceleration Account EP/R511560/1. HL also acknowledges the financial support from the EPSRC Research Grant EP/R019460/1. The authors also acknowledge Mr Karl Cooper and Mr David Dare for assistance in the electrochemical characterisation of the PEMFC.

REFERENCES

[1] J. St-Pierre, “PEMFC In Situ Liquid-Water-Content Monitoring Status”, *J. Electrochem.. Soc.*, 154(7), B724-B731, 2007.

[2] A.K. Vynckier, et al., “Calendering as a direct shaping tool for the continuous production of fixed-dose combination products via co-extrusion”, *Eur. J. Pharm. Biopharm.*, 96, 125-131, 2015.

[3] D.F. Alves-Lima, et al., “Review of Terahertz Pulsed Imaging for Pharmaceutical Film Coating Analysis”, *Sensors*, 20(5), 1441, 2020.

[4] H. Lin, et al., “Review of THz near-field methods”, *In Proceedings of the Smart Structures, Devices, and Systems III*, Adelaide, Australia, 10-13 December 2006; SPIE: Bellingham, WA, USA, 2006.

[5] D.Y.S. Chau, et al., “Determination of Water Content in Dehydrated Mammalian Cells Using Terahertz Pulsed Imaging: A Feasibility Study”, *Curr. Pharm. Biotechnol.*, 17(2), 200-207, 2015.

[6] H. Lin, et al., “Through-substrate terahertz time-domain reflection spectroscopy for environmental graphene conductivity mapping”, *Appl. Phys. Lett.*, 116, 021105, 2020.

[7] H. Lin, et al., “Gas recognition with terahertz time-domain spectroscopy and spectral catalog: A preliminary study”, *In Proc. SPIE Terahertz Photonics*, 6840, 68400X, 2008.

[8] J.F. Federici, “Review of Moisture and Liquid Detection and Mapping using Terahertz Imaging”, *J. Infrared Millim. Terahertz Waves*, 33, 97-126, 2012.

[9] D.F. Alves-Lima, et al., “Quantitative video-rate hydration imaging of Nafion proton exchange membranes with terahertz radiation”, *J. Power Sources*, 450, 227665, 2020.

[10] J. Wang, “Theory and practice of flow field designs for fuel cell scaling-up: A critical review”, *Appl. Energy*, 157, 640-663, 2015.

[11] I.S. Hussaini, C.Y. Wang, “Visualization and quantification of cathode channel flooding in PEM fuel cells”, *J. Power Sources*, 187(2), 444-451, 2009.