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The experimental study of water management in the cathode channel of single-serpentine transparent proton exchange membrane fuel cell by direct visualization

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ABSTRACT

The water existence is essential to preserve membrane of PEMFC well-hydrated but accumulation of excessive water in channel leads to flooding and performance loss. In current research, the water management in cathode channel of a single-serpentine transparent PEMFC is studied for different stoichiometry, RH and temperature using direct visualization and image processing. An algorithm is introduced to quantify and classify the water and flow patterns in the cathode channel. The water coverage ratio is defined as measurement of liquid water accumulation in the total and local areas of channel. It is found that accumulation of water in the elbows is significant. Most of liquid water accumulates in latter channel rows near to gas outlet. The cathode stoichiometry has more effect on water management and cell performance than anode's. The effect of water coverage on cell performance is investigated. The time durations for first formation of important two-phase flow patterns in cell water management as fog/mist, slug and plug are calculated to obtain the time-scale of two-phase flow and water management. The superficial velocities of moving slugs and plugs are studied.

Introduction

Proton Exchange Membrane Fuel Cell (PEMFC) has received considerable attention from researchers in the recent decades as a source of clean energy and alternative to conventional internal-combustion engines in automobile and transportation applications due to its high power density, high efficiency, low pollution, low or zero emissions, fast startup, nonmoving parts and silent operation [1–6]. As an advantage of the PEMFC, the redox reaction of oxygen and hydrogen produces electrical power with heat and water as only byproducts [7]. So the PEMFC is an environmentally friend source of energy with high power density and high efficiency.

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However, some technical issues lie toward the PEMFC application and commercialization. One of the key issues attracted much attention is appropriate water management in the PEMFC [1,8]. Water management is a very important subject due to the two-sided impact of water on cell performance. Water makes the membrane hydrated and increases its ionic conductivity while too much liquid water causes flooding, which reduces reaction sites, reactant starvation and gases maldistribution and consequently leads to a drop in the cell performance [1,4,9]. Flooding is the phenomenon of excessive liquid water accumulation in the GDL or gas channels and leads to reduction or blockage of reaction sites [9]. Flooding has two effects on cell performance: reduction of cell voltage and increase pumping power to decrease pressure drop effect and both lead to significant cell power loss [10]. Proper water management depends on characterization and study two-phase flow phenomena of PEMFC as flooding [1,11,12].

In a general classification, flooding studies are classified in two main groups: direct and indirect methods [10]. Direct methods use in situ visualization such as direct visualization of a transparent cell [10,13–26], neutron radiography [16,27–30], X-ray radiography [31–33] and NMR (Nuclear Magnetic Resonance) [34–36] to calculate the accumulation of liquid water and purging. Indirect methods include experiments of studying externally measurable parameters such as the pressure drop [10,37], HFR (High-Frequency Frequency Resistance) [14] and resident time [37] to survey the two-phase flow of water. Among various visualization techniques, optical visualization has the benefit of simultaneous high local and temporal resolution [14,38].

Some researchers studied water management of cathode channel while their visualizations lead to the qualitative characterization of two-phase flow in PEMFCs without any quantitative results. Quantitative data is more worthwhile for stack design and validation of numerical models [10]. The subject almost disregarded in literature is deriving quantitative data related to liquid water by take the advantage of visualizations without manual detection of the regions with the two-phase flow while manual detection has much intrinsic error [10,14,39], and the researches mainly have focused on PEM fuel cells with parallel or other non-serpentine flow fields while serpentine channels were nearly disregarded.

Authors of Refs. [10,39,40] used manual selection of channel regions included water by optical visualization of a PEMFC. Hussaini et al. [10] studied a straight-channel PEM fuel cell with an effective membrane area of 14 cm^2 for direct optical visualization and quantification of water accumulation in cathode channel while an isothermal environment within the cell was established. The visualization setup mainly consisted of a high resolution Olympus video microscope, and for purpose of conciseness, a limited set of steady state images was shown. Tests were conducted at temperature of 80 °C and various gas relative humidity, stoichiometry ratio and current density. They introduced the parameter "wetted area ratio" for quantifying the liquid water within the channels. It was defined as fraction of the total channel surface area covered by liquid water. The incidental and short-lived droplets was not considered in their calculations. In order to tests repeatability, a subset of tests were repeated and the wetted area ratio was recalculated and proved to be repeatable within 5% of its value. Physical distribution of liquid water across channels tended to be random in nature and may not be identical for any two experiments conducted under same test conditions. Yamauchi et al. [39] used a triple-serpentine PEM fuel cell with an active area of 25 cm^2. They utilized a high spatial resolution video camera for direct visualization of both anode and cathode side channel. The temperature of the PEFC was maintained at 80 °C, and the cell was tested at a constant current density. They aimed to explain the water transport through the membrane by two-side (anode and cathode) simultaneous image measurement, and to propose an optimum water management method. The influence of humidity and each gas channel arrangement on flooding and plugging in channels were surveyed by means of study on cell performance and also water condensation in channels. The water coverage of channels was calculated manually and introduced by parameter "condensation rate" and defined by dividing the area where the condensate forms by the entire area of channel. Sugiura et al. [40] studied cathode channel of PEMFCs with single-serpentine and parallel configurations by direct visualization with a high speed camera to study the effect of water absorption layer on water accumulation in channel and flooding. They quantified the water within channel by manual water detection while flooding was occurred and introduced it by parameter "Flooding Water Volume" which was calculated from the channel size and the channel length blocked by the flooding water. The authors of Refs. [10,39,40] used manual delimitation of water accumulation areas which involved an inherent error and uncertainty, and also this method was time-intensive, hence they proposed use of software-based image processing to improve accuracy of water quantification.

Some other authors took the advantages of digital image processing to improve the accuracy of their results for water quantification in PEMFC channels. Nirunsin et al. [41] used digital camera for direct optical visualization to quantify the water in the single-serpentine cathode channel of a PEMFC with active area of 25 cm^2. They studied the change in water coverage of channel area with temperature and stoichiometry by using image processing technique with subtraction image between the reaction's state and dry state images and counting the water pixels in histogram of processed image without any morphological or refining process on images. The accumulated water was defined by parameter "water coverage area" which was the area of channel covered by liquid water. Ous et al. [42] studied the accumulation of water in the anode/cathode serpentine flow channels of a transparent PEMFC by direct visualization for various operating conditions as anode and cathode stoichiometry, cell temperature and current density. They used two CCD cameras (Sensi-Cam) to study the cell from two directions to obtain the contact angle and diameter of droplets by image processing. Using these parameters and further calculation by utilization of Young's equation, the parameter "Water Volume" in the channel was calculated which defines the volume of accumulated water in the channel. Sergi et al. [14] utilized two Photron high speed cameras for direct optical visualization. They developed an image processing technique for simultaneous quantification and characterization of both static and dynamic water droplets in anode and cathode parallel channels of a PEMFC with active area of 50 cm^2. This technique was employed to