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Novel approach to determine cathode two-phase-flow pressure drop of proton exchange membrane fuel cell and its application on water management

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HIGHLIGHTS

- Originally find two jumps in cathode pressure drop when rising through two levels.
- Discover a steady pressure drop due to constant average water film in channels.
- Originally quantify this pressure drop online in all operating conditions.
- Propose efficient online water management strategy based on pressure drop.
- The strategy helps avoid flooding, extend life and cut parasitic power consumption.

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ABSTRACT

In proton exchange membrane fuel cell (PEMFC), pressure drop at cathode can be used in water management. However, the equation to determine the cathode two-phase-flow pressure drop online and in real time has not been reported. This paper aims to develop a novel approach to calculate this pressure drop. The originalities are the fact that cathodic pressure drop actually experiences two jumps as it rises through two levels during flooding process and the proposal of spatial average water film to determine the pressure drop online. Firstly, the equation to calculate the pressure drop of cathode single-phase-flow, covering all operating conditions, is proposed and is verified at a 10 kW fuel cell stack. Secondly, we find that there exists a steady two-phase-flow pressure drop linked to an equivalent film flow in unit channel and put forward a novel approach to determine this pressure drop. Finally, water management strategy based on pressure drop is applied to a 34 cm^2 fuel cell and the voltage drop rate decreases by 35%, from 72 mV/h down to 47 mV/h, at a low cathode stoichiometric ratio 2.0 in long time operation, and the parasitic consumption is reduced by up to 50%. Hence, this strategy is shown to be effective in avoiding flooding, reducing air compressor consumption and extending the running time of single operation and the lifetime of fuel cell. This paper will contribute to the commercialization of fuel cells.

1. Introduction

Appropriate water amount in membrane electrode is necessary to maintain the normal operation of proton exchange membrane fuel cell (PEMFC) [1–3]. Of many researches on PEMFC, water management is a very important area. Technically speaking, it is necessary to find a quantitative criterion that can indicate the best water amount in fuel cell in solving the above problems.

To some extent, the water amount in the channel is reflected by pressure drop between PEMFC inlet and outlet [4–7], and increasing attention has been paid to this phenomenon. Unlike the water management based on voltage [8] or impedance [9,10], water management based on pressure drop can distinguish water-related fault in advance, that is, before the performance declines significantly [7] because the pressure drop can serves as a benchmark [11].

Most of the time, cathode channels are operating in two-phase flow. Hence, the model of pressure drop of two phase flow is investigated so as to give a quantitative criterion to conduct water

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Nomenclature

φ	two-phase multiplier
p	pressure (Pa)
Δp	pressure drop (Pa)
Q	flow rate
Q_m	mass flow rate (kg/s)
Q_v	volume flow rate (SLPM or SLM)
k_1	monomial coefficient
k_2	quadratic coefficient
μ	dynamic viscosity (Pa·s)
T	temperature (K)
R_m	gas constant (8314 J/(kmol·K))
L	channel length (m)
n	channel number
A	cross-sectional area of a channel (m^2)
D_h	hydraulic diameter of a channel (m)
M	molar mass (kg/mol)
V_m	velocity (m/s)
RH	relative humidity of inlet air
Z	compressibility factor
x	molar fraction

Subscript

l	liquid phase
g	gas phase
f	pressure drop along the path
j	discrete pressure drop
a	dry air
w	vapor
stoi	stoichiometric ratio
mix	gas mixture
in	inlet
out	outlet
sat	saturated state
x	x meters away from inlet
ideal	ideal gas

management. Anderson et al. [12] used the parameter φ^2, which is the ratio of two-phase-flow pressure drop to that of gas single-phase flow, to determine the two-phase-flow pressure drop. φ^2 is usually determined by LM method [13,14]. The LM method makes the calculation easier by reducing two-phase-flow pressure drop into a single-phase-flow pressure drop [14]. The logic is: (a) obtain the single-phase-flow pressure drop Δp_l and Δp_g by experiments; (b) calculate parameter χ^2: $\chi^2 = \Delta p_l/\Delta p_g$; (c) use $\varphi^2 = 1 + C\chi + \chi^2$ to obtain parameter φ^2; (d) use the definition formula $\varphi^2 = \Delta p_{gl}/\Delta p_g$ to calculate the two-phase-flow pressure drop Δp_{gl}. The classical LM method is based on three assumptions: homogenous gas-liquid mixture, consistent flow and zero water production. This method needs experimental data of Δp_l and Δp_g, and relies on empirical coefficient C, which is related to flow patterns and must be determined in different situations [15–18]. Zhang et al. [19] adopted this method to determine the pressure drop in the condition of non-uniform water injection. They assume that water is injected into the channels continuously and the injection rate is proportional to the differential pressure between the two sides of GDL according to Darcy's law [20] in the porous media. This assumption pushes pressure drop even closer to practical applications. Rupak et al. [21] calculated the two-phase-flow pressure drop and used the pressure drop multiplier successfully to conduct water fault diagnosis. The ranges of multipliers in three states, namely, normal, flooding and drying out, were given.

To some extent, the above investigations in determining two-phase-flow pressure drop is still of ex-situ nature. Researchers need to get C and χ^2 through large amount of experimental data, which limits the online application of pressure drop. However, in water management or diagnosis, it is necessary to obtain the pressure drop online and in real time even as at different operating conditions. Hence, a more efficient way to comprehensively calculate this pressure drop needs to be proposed.

Pei et al. [11] proposed a method to determine pressure drop online. However, it is for single phase flow and conducted at anode. The equation or method cannot be used to determine the pressure drop of cathode because its state is quite different from that at anode. Firstly, the air flow rate is much higher than the hydrogen flow rate, so the discrete pressure loss cannot be ignored. Secondly, unlike anode, the inlet of air at cathode is usually humidified. Therefore it is better to calculate the cathode pressure drop covering all possible inlet relative humidities. Finally, the pressure and density of moist air keep changing along the channel and this condition must be taken into account. Only when cathodic pressure drop is determined can water management based on pressure drop be proposed and verified. Song et al. [22] proposed an approach to conduct water management using anodic pressure drop. They gave the flooding extent by comparing the real-time pressure drop with the single-phase-flow pressure drop. However, flooding does not always occur at the anode side.

Monitoring only the pressure drop at anode is not enough. Hence, in real fuel cell operation, cathode pressure drop also needs to be monitored so as to find a way to conduct water management or carry out water fault diagnosis. Of cause, it would be better if pressure drop at both anode and cathode were monitored and corresponding water management strategy based on their pressure drops were developed. But they all need the quantification of cathodic pressure drop, which, applicable to different fuel cells and operating conditions, is rarely reported, even in the case of single-phase flow.

Furthermore, the pressure drop can be determined by simulation model [23]. Most of these simulations are based on droplet dynamics and use the VOF method [7]. They usually focus on the formation, deformation and detachment of the droplets and calculate the liquid water saturation to illustrate the flooding condition [23–25]. However, considering the CFD simulation usually takes a long time, pressure drop calculation based on simulation is seldom used in online water management.

In addition to water management, calculation of cathodic pressure drop can also help to design the flow field [26–30]. According to Li et al. [31], in a given condition, the pressure drop of cathode flow field is known in advance if the moist air at the exit of cathode is maintained saturated, which is also beneficial to in keeping the PEMFC in non-flooding nor non-dehydrated state. Therefore, the cathode flow field can be modified by comparing the calculated pressure drop with the pressure drop already known.

Finally, there are some other ways to conduct water management. For example, visualization [32] coupled with pressure drop. Murakava et al. [33,34] investigated the effect of water distribution on performance of serpentine channel PEMFC by means of neutron radiography. They qualitatively demonstrated the changes of pressure drop and water thickness in time domain and found that pressure drop increases with water thickness. Klaus et al. [35] investigated water buildup in a dual-parallel straight channel