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Two-phase flow pressure drop in flow channels of proton exchange membrane fuel cells: Review of experimental approaches

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ABSTRACT

Water management in proton exchange membrane (PEM) fuel cells has stimulated an extensive research on different aspects of water transport phenomena. As a PEM fuel cell operates, power is produced with water and heat as inevitable byproducts. The water produced during the operation of a PEM fuel cell results in a liquid–gas two-phase flow in flow channels. A successful PEM fuel cell design requires a comprehensive knowledge about different properties of liquid–gas two-phase flow. One such property, that has a dominant impact on the performance of a PEM fuel cell, is the two-phase flow pressure drop within the flow channels. This paper reviews the two-phase flow pressure drop correlations that have been developed for the application of PEM fuel cell. It also reviews the effect of different working conditions on the two-phase flow pressure drop in PEM fuel cell flow channels.

Contents

1. Introduction

A proton exchange membrane (PEM) fuel cell is considered to be an efficient and pollutant free energy system that can generate

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Nomenclature

$[Bo]$	Bond number
$[Bo^{\star}]$	modified Bond number
$[C]$	parameter in Lockhart–Martinelli correlation
$[D]$	channel diameter
$[D_{\mathrm{h}}]$	hydraulic diameter
$[Fr]$	Froude number
$[f]$	Fanning friction factor
$[g]$	gravitational acceleration
$[G]$	mass flux (kg/m^2 s)
$[j_{\mathrm{f}}]$	superficial liquid velocity
$[j_{\mathrm{g}}]$	superficial gas velocity
$[N_{\mathrm{conf}}]$	confinement number
$[P]$	pressure
$[P_{\mathrm{c}}]$	critical pressure
$[Re]$	Reynolds number
$[Re_{\mathrm{f}}]$	Reynolds number based on superficial liquid velocity, $Re_{\mathrm{f}} = G(1-x)D_{\mathrm{h}}/\mu_{\mathrm{f}}$
$[v]$	specific volume
$[We]$	Weber number
$[x]$	mass flow quality, coordinate
$[X]$	Lockhart–Martinelli parameter

Greek symbols

$[\Delta]$	difference
$[\alpha]$	void fraction
$[\rho]$	density
$[\beta]$	channel aspect ratio ($\beta < 1$)
$[\sigma]$	surface tension
$[\phi]$	two-phase flow frictional multiplier, channel inclination angle
$[\mu]$	dynamic viscosity

Subscript

[A]	acceleration
[F]	frictional
[G]	gravitational
[TP]	two-phase
[f]	saturated liquid
[g]	saturated vapor
[z]	stream wise coordinate
[fg]	difference between saturated vapor and saturated liquid
[fo]	liquid only
[go]	vapor only
[tt]	turbulent liquid–turbulent vapor
[tv]	turbulent liquid–laminar vapor
[vt]	laminar liquid–turbulent vapor
[vv]	laminar liquid–laminar vapor

power for various applications [1,2]. The electrochemical reactions within the electrodes utilize hydrogen and oxygen to generate electricity with heat and water as the byproducts. Reliable fuel cell performance, however, hinges upon a uniform and continuous supply of reactants across the electrodes. The water produced during the operation of the cell can fill open pores of the gas diffusion layer (GDL) and block the transport of the reactants to the catalyst layers. This phenomenon is referred to as GDL flooding and has been reported to extensively deteriorate the performance of the cell [3–5]. Accumulated liquid water within the GDL emerges from its surface at some preferential locations [6]. The liquid water that emerged from the surface of the GDL can be removed by different mechanisms, depending on the gas flow rate and water production rate [7]. When the water removal rate is less than the water production rate, a water lens may form within the gas channel. The growth of this lens can ultimately clog the gas channel and block the transport of the reactants to the catalyst layer. This phenomenon is referred to as channel flooding and similar to GDL flooding, it can lower the overall performance of the cell [8–10]. A uniform and continuous supply of reactants across the electrodes can be achieved by acquiring an accurate understanding about the liquid water behavior within the GDL and gas channel.

The accumulation of liquid water within the gas channel follows with the formation of a two-phase flow during the operation of the cell. Channel flooding becomes even more discernible at low temperatures and/or high current densities in which water accumulation increases because of water condensation and water production, respectively.

The transport of an elongated water slug within the gas channel may be influenced by three forces of gravity, surface tension, and shear force of the core gas flow. Bond number, $Bo = (\rho_{\mathrm{f}} - \rho_{\mathrm{g}})gD^2/\sigma$, describes the ratio of the gravity force to the surface tension effect. The small characteristic length scale associated with the PEM fuel cell suggests that gravity's impact on the two-phase flow is insignificant while surface tension has a dominant impact. Moreover, the small characteristic length scales suggest that capillary forces are important to the behavior of liquid surfaces.

Different methods of studying the two-phase flow in gas channels can be categorized as direct and indirect techniques. Direct techniques include monitoring the liquid–gas flow within the gas channel either through a transparent cell [7,10–15], neutron imaging [16,17], X-ray microtomography [18,19], or gas chromatography [20,21]. Bazylak comprehensively reviewed different methods of visualizing liquid water in PEM fuel cell flow fields [22].

The indirect study of the liquid–gas two phase flow in PEM fuel cells can be accomplished by measuring the parameters that are the immediate result of the liquid water accumulation. One such parameter can be the two-phase flow pressure drop along the gas channel as the accumulated water resists the gas flow and causes an increase in the pressure drop. Thus, the two-phase flow pressure drop can be considered as an in situ diagnostic tool that can reveal information about the amount of liquid water accumulated within the gas channel. While a low pressure drop along the flow channel is desired because of the lower compressor power to supply reactant gases, a minimum pressure drop along the gas channel should be maintained to ensure condensate removal from the flow channels. Different aspects of liquid–gas two-phase flow in gas flow channels of PEM fuel cells have been reviewed by Anderson et al. [23].

In this paper, the two-phase flow pressure drop in the PEM fuel cell flow channels is reviewed. This is achieved first by reviewing the two-phase flow patterns and two-phase flow pressure drop models proposed for general applications. The study is then followed by focusing on the two-phase flow pressure drop with the application of PEM fuel cells. In Section 2, different patterns of two phase flows are introduced. The models developed to predict the two-phase flow pressure drop are presented in Section 3. Section 4 focuses on the two-phase flow pressure drop in PEM fuel