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Convective drying in thin hydrophobic porous media

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ABSTRACT

A pore network (PN) model is developed to explore drying of a thin hydrophobic porous medium bounded with a gas purge channel. The PN is composed of cubic pore bodies connected by cylindrical pore throats. At the interface between a pore throat and body, a sudden geometrical expansion exists. When a meniscus advances to this interface, it will be pinned first until the pressure across the meniscus increases to a critical value. This phenomenon is called the capillary valve effect. Because of this effect, two types of invasion into pore bodies are discerned, i.e. bursting and merging invasion. The developed PN model with the capillary valve effect is validated against the experimental results. For the drying case of dominant merging invasion, a drying front of finite width is stably receded. But when bursting invasion dominates, gas invasion is a random process; the drying process can be characterized by three regimes: a surface evaporation period, a constant rate period, and a falling rate period. The total liquid saturation for transition from the constant to falling rate period is close to that at which the total area for vapor transport is maximal between the partially filled pores and their neighboring empty pores.

1. Introduction

Drying of porous media is of great interest not only for scientific research, but also for industrial applications. Pertinent examples include recovery of volatile hydrocarbons from underground oil reservoirs, remediation of contaminated soils by vapor extraction, and water management of proton exchange membrane fuel cells (PEMFCs). During running of a PEMFC, water is continuously produced at the cathode catalyst layer, which then condenses in the cathode gas diffusion layer (GDL), Fig. 1. The GDLs are thin porous materials. Liquid water in GDLs can result in degradation and durability issues. Especially at subzero environment, liquid water in GDLs freezes and forms ice after cell shutdown. Ice in GDLs impedes the reactant transport to the reaction sites, which is disadvantage to the rapid cell start; on the other hand, during cell running, ice melts. This freeze and thaw cycle causes severe damage on GDLs. Hence, residual liquid water in GDLs must be removed after the cell shutdown.

Dry gas is usually pumped into the gas channel (GC) so as to remove liquid water in the GDL through the evaporation process. This gas purge technology consumes pump power. To reduce such parasitic loss and increase system efficiency, it is necessary to understand in detail the evaporative liquid removal from the GDL so as to optimize the gas purge protocol.

GDLs have a thickness of several hundred micro meters, and the sizes of pores in GDLs are of about several dozens of micro meters. For two-phase transport in such thin porous media with relatively small pore sizes, the capillary forces play an important role. The capillary forces depend on both the size and wettability of pores in porous media. The pores in a porous material have different sizes, and sudden geometrical expansions exist at the interfaces between small and larger pores. Such a sudden abrupt geometrical change increases the resistance to movement of menisci during the two-phase flow in porous media, which is called the capillary valve effect [1,2]. Because of the capillary valve effect, two types of pore invasion can be discerned: bursting and merging invasion. The capillary force dominated two-phase flow in a porous material is a random process when pore invasion is controlled by bursting invasion, whereas it is a stable process when merging invasion dominates [1].

In PEMFC applications, the cathode GDLs exhibit hydrophobic characteristics, since they are treated with the hydrophobic agent PTFE (polytetrafluoroethylene) so as to increase cell performance. Up to now, most of studies in the field of drying focus on the hydrophilic porous media. The characteristics of drying of hydrophobic porous media are still unclear, and different findings

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Nomenclature

a	distance between two neighboring pore bodies (m)
A_C	cross sectional area of gas channel (m^2)
A_m	surface area of meniscus (m^2)
A_{vt}	total area for vapor transport from partially filled pores (m^2)
C	vapor concentration (mol/m^3)
D	vapor diffusivity (m^2/s)
D_C	hydraulic diameter of gas channel (m)
E_d	total drying rate (m^3/s)
H	height of GDL or gas channel (m)
l	length of pores in PN (m)
L	length of GDL or gas channel (m)
M_l	molecular weight of liquid (kg/mol)
P	pressure (Pa)
P_{th}	threshold pressure (Pa)
Q_C	gas flow rate in gas channel (m^3/s)
Q_d	vapor diffusion rate between two pores in PN (mol/s)
Q_f	liquid flow rate between two pores in PN (mol/s)
r	radius of pores in PN (m)
t^*	normalized drying time
u	gas velocity (m/s)
V	volume (m^3)
W_C	width of GDL or gas channel (m)
W_m	Work done to meniscus (J)

Greek symbols

θ	contact angle
θ_m	moving contact angle
μ	dynamic viscosity (Pa s)
ρ	density (kg/m^3)
σ	surface tension (N/m)

Subscripts

C	gas channel
D	displaced fluid
l	liquid
g	gas
G	GDL
i, j	pores indices
I	invading fluid
t	pore throat
p	pore body

Abbreviations

CBLT	concentration boundary layer thickness
GC	gas channel
GDL	gas diffusion layer
PDMS	polydimethylsiloxane
PN	pore network
PTFE	Polytetrafluoroethylene

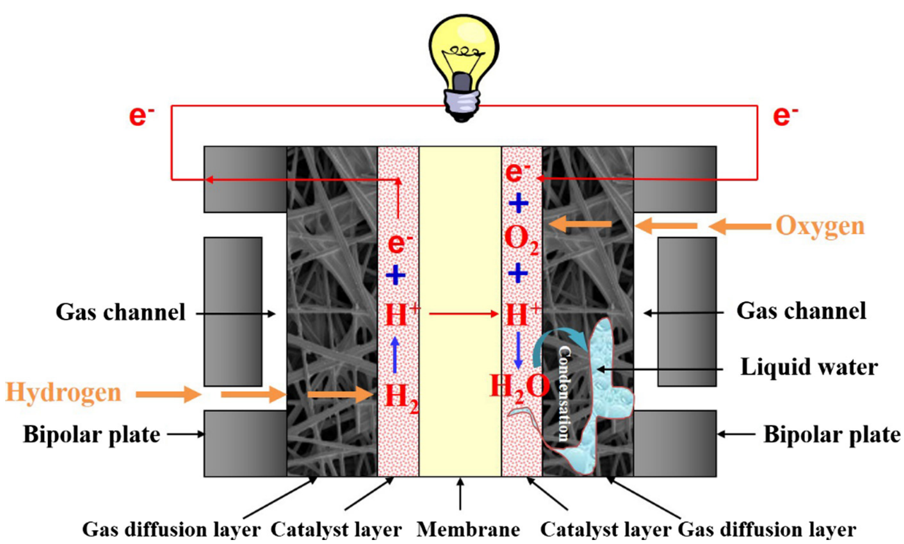

Fig. 1. Schematic of a proton exchange membrane fuel cell.

were reported in literatures [3–7]. For drying of model porous media composed of hydrophobic beads or sands [3,4], the drying front recedes stably, and the curve of drying rate versus time is completely different from that in the hydrophilic case. The slow drying process in a hydrophilic porous material can be characterized by an initial drying period, a constant rate period, a falling rate period, and a receding front period [8,9]. Similar drying regimes have also been observed in drying of GDLs [5–7].

The difference between drying of PTFE treated GDLs and model porous media composed of hydrophobic beads or sands could be attributed to the different pore invasion patterns mentioned above. To reveal how the pore invasion pattern influences the drying process in a porous material, a pore scale investigation is needed. Nevertheless, it is a nontrivial task to experimentally capture the pore scale events during drying in thin porous media (e.g., GDLs) since they are not only opaque but also have complex pore structures of small sizes. An alternative is to use the pore network (PN) modeling approach. This method has been widely used as an effective tool to disclose the pore-scale transport phenomena in porous media during drying. The basis of this method is first to approximate the void space of a porous material into a PN composed of regular pores of various sizes; then in these pores the