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Active multi-scale modeling and gas permeability study of porous metal fiber sintered felt for proton exchange membrane fuel cells

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ABSTRACT

Porous metal fiber sintered felt (PMFSF) is a promising critical component in proton exchange membrane fuel cells, having the ability of simultaneously acting as the flow field plate, gas diffusion layers and also the catalyst layers support, and owing the property of multi-scale surface morphology. A simple multi-scale mathematical method was proposed to actively construct three dimensional models of PMFSF's microstructure by synthesizing the implicit periodic surface (PS) model and the Weierstrass-Mandelbrot (W-M) fractal geometry. In this method, the PS model described the macro overall fiber shape, and the W-M fractal geometry modeled the micro fractal roughness topography attached. Based on the method, multi-scale fractal PMFSF models were reconstructed according to morphology parameters of physical PMFSFs, and were discretized in ANSYS/ICEM to generate refined mesh for computational fluid dynamics analysis. To verify the validity of the proposed modeling approach, PMFSFs with different porosity and fiber orientation are generated, and then the effects of the fractal surface topography and the fractal parameters such as fractal dimension and height scaling parameter on the gas permeability of PMFSF were investigated. The numeric simulation results show that the influence of the fractal topography on the in-plane and through-plane permeability of PMFSF cannot be ignored, and the permeability of fractal PMFSF models agrees with experimental measurements better. Especially, the results imply that the fractal morphology may have the potential to adjust the anisotropic properties of PMFSFs' permeability. It is further found that the larger the fractal dimension is and the lower the height scaling parameter is, the better the permeability of PMFSF will be. The synthesis approach and numerical simulation method may facilitate the development of active functional design mode to predict and optimize key characteristics of PMFSF ahead of manufacture.

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Nomenclature

A_k	magnitude factor of periodic surface
a_p	cutting depth
B	magnitude factor of fractal height
C	constant value of a periodic surface
CAD	computer aided design
CFD	computational fluid dynamics
CL	catalyst layers
CT	computed microtomography
D	fractal dimension of a curve in 2-dimensional space
D_s	fractal dimension of a surface in 3-dimendional space
E	porosity of porous metal fiber sintered felt
F-fiber	single fiber with fractal geometry
F-PMFSF	porous metal fiber sintered felt with fractal surface topography
G	height scaling parameter
GC	gas channel
GDL	gas diffusion layers
$\mathbf{h}_k$	k^{th} lattice vector in reciprocal space
K	permeability
K_{xx}	in-plane permeability along x axis
K_{yy}	in-plane permeability along y axis
K_{zz}	through-plane permeability
L_c	Brinkman screening length criteria
L_s	sample length of scan instrument
M	number of superposed ridges
M_p	mass of porous metal fiber sintered felt
$n_{\max}$	number of cosine shapes added
P	pressure field
∇P	pressure drop per unit length
PEMFC	proton exchange membrane fuel cell
PMFSF	porous metal fiber sintered felt
p_k	phase shift
PS	periodic surface
R	fractal height
$\mathbf{r}$	location vector in Euclidean space
SEM	scan electron macroscopy
Syn	synthesis function of periodic surface and W–M fractal function
2/3D	2/3 dimensional
$\mathbf{u}$	velocity of the fluid
$\mathbf{V}$	superficial velocity
V_p	volume of porous metal fiber sintered felt
W–M	Weierstrass–Mandelbrot
Γ	periodic surface
Γ_R	rod periodic surface
δ	resolution of scan instrument
$\phi_{m,n}$	random phase
γ	scaling parameter to determine the spectral density and self-property
φ	in-plane angle
λ_k	wavelength of periods
μ	fluid viscosity
θ	side angle
ρ	density of the fluid
ρ_c	density of red copper
ω_l	low cut-off frequency
ω_h	high cut-off frequency

Introduction

By virtue of their high-energy efficiency, low operating temperature, pollution-free characteristics, relatively quick start-up and rapid response to varying loads, proton exchange membrane fuel cells (PEMFCs) are widely studied in many fields including vehicle power supply, distributed power station, and are considered as one of the most efficient energy conversion devices in the foreseeable future [1–3]. A typical PEMFC consists of the following components: bipolar plate, gas channel (GC) curved in bipolar plates, gas diffusion layers (GDL) made from woven or non-woven carbon papers or cloth, catalyst layers (CL) and proton exchange membrane sandwiched between anode and cathode [4,5]. However, with the advance of porous metal fiber sintered felt (PMFSF, consisting of e.g. stainless steel, nickel, or copper fibers) [4,6–8], the conventional configuration of PEMFC can be greatly simplified: thanks to the properties of good mechanical properties, high thermal conductivities, corrosion resistance and easy molding, PMFSF has the ability of simultaneously acting as the flow field plate (i.e. GC) [8], GDL [9] and also the CL support [4,10], thus can effectively reduce the cost for producing the traditional components, and is becoming a novel promising component in PEMFCs. This makes the PEMFC be more likely to be commercialized in large scale. Namely, a PMFSF can integrate the structural features, material properties, functional performances and also economic efficiency [8].

Compared with traditional components in PEMFC, two structural characteristics are prominent in PMFSF. Firstly, its length scale is relatively larger: its thickness is usually about 2 mm [11], while the thickness of other components is usually no more than 0.1 mm. The larger length scale can provide enough space for PMFSF to simultaneously act as GC, GDL and CL support. Secondly, there is an obvious multi-scale morphology in its microstructure, especially when it is produced through cutting method (e.g. Ref. [12]). For example, from the SEM (scanning electron microscopy) image of a PMFSF produced by cutting method shown in Fig. 1, it is obviously observed that at pore-size (micro) scale the morphology of the PMFSF at least consists of two different scale parts: one is the macro overall shape of fibers and the other is the micro surface roughness, as well as bending and tortuosity attached to the overall fiber shape. The measurements for Fig. 1 further implies that the magnitude of the surface roughness (R_a is 5–20 μm, R_y 15–60 μm) is comparable to the pore size (averaged 100–300 μm [12]) of PMFSF. It is recognized that there exists multi-scale phenomenon between traditional components in PEMFC [5]. Considering the multi-scale morphology, this phenomenon may equivalently happen in the single PMFSF component of PEMFC. This is a functional basis for PMFSF to simultaneously act as GC, GDL and CL support.