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Numerical study of flow distribution uniformity for the optimization of gradient porosity configuration of porous copper fiber sintered felt for hydrogen production through methanol steam reforming micro-reactor

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ABSTRACT

A macroscopic numerical method is proposed to study the flow distribution uniformity of a novel porous copper fiber sintered felt (PCFSF), which has gradient porosities and was developed as the methanol steam reforming micro-reactor catalyst support for hydrogen production for fuel cell applications. The macroscopic porous media developed by the ANSYS/FLUENT software is used to represent the PCFSF. Our results indicate that the gradient porosity can reshape the flow distribution of PCFSFs greatly, thus producing significant influence on their performance. It is further revealed that, for a PCFSF with a determined gradient porosity configuration but different reactant feed directions, the velocity uniformity can be used as a quantitative criterion to evaluate the performance of hydrogen production. Furthermore, new gradient PCFSFs are produced according to the flow distribution of original gradient PCFSFs. The preliminary experimental results of the new gradient PCFSFs of 0.8-0.9-0.7 and 0.7-0.9-0.8 exhibit better methanol conversion and H_2 flow rate. This indicates that the numerical method can be used for the optimization of PCFSFs' gradient porosity configuration, which consists of the shape and position of the interfaces between different porosity portions, the number of interfaces and the porosity distribution in different portions.

Introduction

With the increasing concern of environmental pollution and fossil fuel shortage, hydrogen has been regarded as a clean energy [1–3], which was efficiently applied for environment-friendly fuel cell [4,5]. Proton exchange membrane fuel cell (PEMFC) is one of the most promising fuel cells, due to its high power density, high efficiency, low operating temperature and no pollutant emissions [6–8]. However, the hydrogen supply is still one of the main restraints limiting PEMFC's further development [6]. Because of the readily available, high H/C

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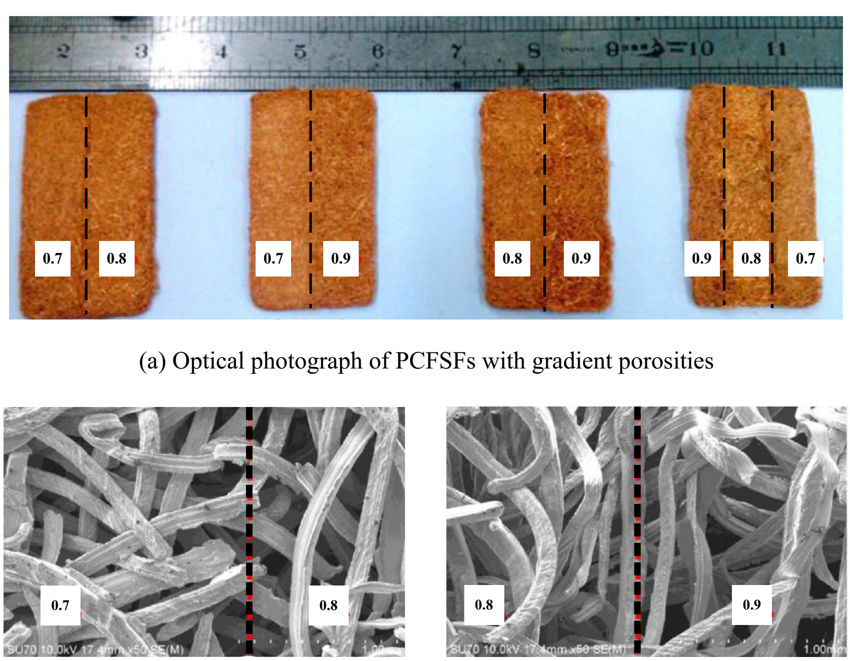
ratio, low cracking and boiling temperatures, and low reaction temperature for hydrogen production (range 200–400 °C), etc., methanol is considered as one of the most reliable fuel candidates [4,9], and steam reforming of methanol on site, via micro-reactors with high heat and mass transfer capability, shows more advantages to supply hydrogen [10].

Many kinds of micro-reactors have been fabricated along with the development of fabrication technology in the past decades [11–14]. In a micro-reactor, the catalyst support is one of the key components. Typical catalyst supports are composed of micro-tubes or micro-channels with an equivalent diameter in the range of 10–500 μm [15–17]. In recent years, more attentions were transferred to develop new catalyst support structure to improve the reaction performance of hydrogen production, including, for example, foam metal materials [14], micro-pin-fin arrays [10,18], metal fiber sintered felts [19,20]. Among them, porous copper fiber sintered felts (PCFSFs) have the properties of good mechanical properties, high thermal conductivities, corrosion resistance and easy molding. In addition, producing by cutting method and solid sintered process [21], a PCFSF possesses a multi-scale morphology (Fig. 1). In the macro structure of a PCFSF (with dimension of 70 mm × 40 mm × 2 mm [22]), the mesoscopic pores (averaged 100–250 μm [21]) are formed based on the randomly distributed fibers, with averaged diameter within 100 μm (even 50 μm) [20] and micro surface roughness (R_a is 5–20 μm, R_y 15–60 μm [23]). All these factors endow a PCFSF the potential to simultaneously act as different conventional components of a PEMFC, such as catalyst support, flow field plate (gas channel), gas diffusion layer, etc. [23,24]. This will greatly simplify the PEMFC's structure and thereby effectively reduce the cost, thus making the PEMFC be more likely to be commercialized in large scale [24].

More importantly, inspired by the concept of gradient porosity in porous metal materials [25–27], recently a novel PCFSF with different gradient porosities (termed as "gradient PCFSF" for short) had been developed as the catalyst support to construct laminated-sheet micro-reactor for hydrogen production through steam reforming of methanol [7]. As is shown in Fig. 1 (a), a gradient PCFSF is partitioned into two or three evenly distributed rectangular portions, which are of the same size and have different porosities. Experimental results further indicated that some of the gradient PCFSFs could produce better methanol conversion and H_2 flow rate [7]. Actually, this kind of strategy had already been developed for the conventional PEMFC component of gas diffusion layers (GDLs), whose structures are also consisted of fibers (e.g., carbon fibers). For example, Huang et al. [28] explored the effects of porosity gradient in GDLs on performance of PEMFCs, and predicted the enhancement of the water transport for linear porosity gradient in the cathode GDL of a PEMFC. Chun et al. [29] prepared a porosity-graded micro porous layer using the double coating method to enhance the water removal ability of the GDL for PEMFCs. Oh et al. [30] introduced a pore size gradient structure in the substrate of a GDL to control the local capillary pressure gradients, and found that the pore size gradient structure could improve the cell performance regardless of the relative humidity conditions used (50% and 100%). Park et al. [31] further investigated the effects of pore size variation in the substrate of the GDL on water management and cell performance, to obtain the optimal structural characteristics of the GDL. Zhang et al. [32] explored the use of functionally graded porosity in the GDLs along the flow direction to minimize the variation in local current density and improve fuel cell reliability. In this method, a computational model was used together with a numerical optimization



(a) Optical photograph of PCFSFs with gradient porosities

(b) SEM image of 0.7-0.8 porosity

(c) SEM image of 0.8-0.9 porosity

Fig. 1 – Appearance of PCFSF with gradient porosity [7]. SEM: scanning electron microscope.

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