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Heat and mass transfer characterization of porous copper fiber sintered felt as catalyst support for methanol steam reforming

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HIGHLIGHTS

- A porous copper fiber sintered felt (PCFSF) as catalyst support is fabricated.
- The PCFSF with different porosities exhibits good uniform heat transfer.
- Larger pressure drop is produced with higher nitrogen gas feed rates.
- Resident time is gradually decreased with increasing porosity in the range of 70–90%.
- The PCFSF with 80% porosity presents better reaction performance.

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ABSTRACT

A novel porous copper fiber sintered felt (PCFSF) as catalyst support is fabricated to construct the methanol steam reforming microreactor for hydrogen production. In this study, the heat and mass transfer properties of PCFSF with different porosities is experimentally investigated. The results show that the PCFSF with different porosities exhibits good uniform heat transfer. The thermal conductivity is decreased with increasing porosity in the porosity range of 70–90%. With lower gas feed rate, no great change of the pressure drop is observed. However, larger pressure drop is produced with the higher gas feed rates. Moreover, we found that the resident time in the PCFSF is gradually decreased with increasing porosity. Much longer resident time is obtained when the lower gas feed rate is selected. The PCFSF with 80% porosity as catalyst support presents better reaction performance because of the enhancement of heat and mass transfer resulting from the unique porous structure.

1. Introduction

Hydrogen, a clean and safe energy carrier with the higher specific energy density, is widely used for transportation and stationary power generation because of its outstanding advantages of energy and environmental sustainability. Hydrogen generation can be achieved with a number of different chemical processes. Nowadays, hydrogen can be produced from many kinds of energy fuels such as coal, and oil and natural gas, [1–3]. Currently, hydrogen has been considered as a significant clean fuel in the near future. Especially, the polymer electrolyte membrane fuel cell (PEMFC) with the hydrogen or hydrogen-rich gas as fuel appears to be the preferred fuel cell, which providing high energy efficiency, relatively low operating temperature, rapid start up as well as reduced environmental impact [4,5]. Therefore, the developed PEMFC exhibits increasing potential applications in mobile and stationary device.

Microreactors are considered as novel miniaturized chemical reaction systems, which can be used to convert liquid or gaseous fuels such as gasoline, and methanol, ethanol, ammonia and methane to a hydrogen-rich gas [6–8]. Among these considered fuels, methanol is an attractive and competitive fuel because of its high hydrogen–carbon ratio, high energy density, low boiling point and good miscibility with water. Moreover, methanol is sulfur free and can be reformed easily at low temperature [9,10]. Thus methanol steam reforming technology has been considered a promising approach to supply the hydrogen source for the miniature fuel cell to produce the electricity. Up to now, the typical microreactors

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usually contain reaction channels with a diameter range of 10–500 μm or porous support with three-dimensional pore structure as catalyst support. These microreactors offer particular advantages in the fuel processing due to the enhanced heat and mass transfer resulting from the small channel dimensions of the integrated system.

As we know, the fabrication of microchannels is a key step for the development of microchannel reactor. Several methods such as chemical etching, and electrical discharge machining and laser milling technology have been explored to fabricate the microchannel using different materials including metal, ceramic, silicon and so on [11–14]. However, their high production cost and low machining efficiency for microchannels become a major obstacle for the commercialization application. Fortunately, porous metal material as catalyst support is attracting the world-wide attention because of outstanding porous structure and manufacturing cost saving. In general, the porous metal material can be classified into foam metal and fiber porous metal. Foam metal can be fabricated using liquid state or solid state processing technology such as direct foaming, casting method, and foaming of slurries [15,16]. For the fiber porous metal, both the sintering method and papermaking technique have been developed to satisfy with different applications [17–20].

In recent years, a number of studies about transport phenomena and performance of microreactor have been carried out. Suh et al. [21] studied the effect of internal heating on the transport phenomena and conversion characteristics of steam reforming of methanol in a microreactor tube packed with a commercial catalyst. Hsueh et al. [22] developed a numerical model to study the methanol conversion and local heat and mass transfer in the channel of a micro-reformer. The geometric and thermo-fluid parameters were optimized to improve the performance of plate methanol steam reformer. Mei et al. [23] investigated the effect of tip clearance on the performance of heat transfer and pressure drop at low Reynolds number. The thermal and hydrodynamic performance of microreactors with micro-pin–fin was improved. Lee et al. [24] studied the microreformers with wall-coated or suspended catalytic layer configurations due to their lower transport resistance compared to packed-bed microreformers. The effect of the catalyst layer thickness, wall temperature and the flow velocity of the reactants for wall-coated reformers were reported. Thus we can easily conclude that the previous research works focus on the transport phenomena of microchannel in chemical reaction process.

Meanwhile, many studies on the heat and mass transfer properties of foam metal have been experimentally and numerically investigated for different applications [25]. Giani et al. [26–27] characterized the gas–solid heat and mass transfer of open-celled metal foams as supports for structured catalysts, considering their utilization in gas–solid catalytic processes with short contact times and high reaction rates. Li et al. [28] investigated the flow boiling characteristics of water and FC-72 in aluminum foams. Numerical simulations were performed for both single and two-phase heat transfer for water flow through aluminum foam. Reasonable agreements were obtained between the numerical and experimental results. Tadrist et al. [29] compared transport properties and heat transfer characterization of the randomly stacked fibers and metallic foams that were used in industrial systems, and then discussed several aspect of the two-phase flow in heat exchangers. Topin et al. [30] developed an experimental methodology to analyze the biphasic flow and heat transfer phenomena in metallic foam. The results showed that both single-phase and biphasic heat transfer were improved by the use of metal foam.

In spite of a serious of works about the transport phenomenon of microchannel and foam metal are reported, the study on the heat and mass transfer characterization of fiber porous metal as catalyst support is limited. In the present study, the low temperature solid-phase sintering method is proposed to fabricate a novel PCFSF with different porosities. The heat and mass transfer properties of PCFSF with different porosities is investigated in detail. Finally, the reaction performance of microreactor with PCFSF as catalyst support is analyzed and discussed with different feed rates and reaction temperatures.

2. Experimental procedures and apparatus

2.1. Fabrication process of PCFSF

According to our previously proposed method, the fabrication procedure of PCFSF is divided into the following five steps: chipping fibers, mold pressing, sintering, cooling and testing [17]. To prevent the copper fibers from oxidizing, the solid-phase sintering method was employed to fabricate the PCFSF in a box-type furnace in a gas protection atmosphere. In this study, the sintering temperature and holding time were selected as 800 °C and 30 min, respectively. By adjusting the amount of copper fiber, the PCFSF with different porosities could be obtained. To analyze the heat and mass transfer properties of PCFSF with different porosities, the dimensions of PCFSF were determined as 70 × 40 and 2 mm in thickness. The appearance of PCFSF with different porosities produced by above manufacturing procedure is shown in Fig. 1. Since the obtained PCFSF has a regular geometric shape, the average porosity can be determined by using the quality-volume method given by

$$E(\%) = \left(1 - \frac{M}{\rho V}\right) \times 100 \tag{1}$$

where V is the volume of PCFSF (cm^3), M is the mass of PCFSF (g), and ρ is the density of red copper (g/cm^3).

2.2. Characterization of heat transfer performance

Thermal conductivity is a key parameter to evaluate the heat transfer property of PCFSF. In this study, the thermal conductivity of PCFSF was measured using the thermal constant analyzer (No: Hot Disk TPS 2500, Sweden). The measurement probe was embedded between two PCFSFs to form a stable sandwich structure, as shown in Fig. 2. There was no gap between the probe and testing sample, which could ensure the better heat absorption. Moreover, the smooth flat surface of testing sample was selected to tightly contact with the probe to reduce the contact thermal resistance. In addition, a thermal infrared imager (No: FLIR Therma CAM A20, USA) was used to analyze the temperature distribution in the PCFSF when the heating temperature was increased to 150 °C. A temperature controller was used to provide the stable heating temperature condition.

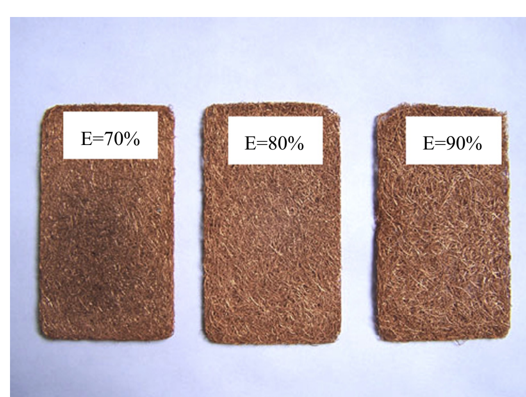

Fig. 1. Appearance of PCFSF with different porosities sintered at 800 °C for 30 min.