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Effects of structural parameters on the performance of a micro-reactor with micro-pin-fin arrays (MPFAR) for hydrogen production

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ABSTRACT

To enhance the energy conversion efficiency of the micro-reactor with micro-pin-fin arrays (MPFAR) for hydrogen production, the effect of structural parameters (the height of the micro-pin-fin, the transverse and longitudinal center distance between two adjacent micro-pin-fins) on the performance of the MPFAR for hydrogen production is investigated. Based on the geometrical parameters, a theoretical model of material balance for hydrogen production in the MPFAR is established. The calculated results show that with the increase of the micro-pin-fin height or the decrease of the distance between two adjacent micro-pin-fins, the methanol conversion rate and the CO molar fraction increase. The methanol conversion rate increases by about 10% when the height of micro-pin-fin increases from 0.2 to 1 mm or the center distance between the two adjacent micro-pin-fins increases from 1.2 to 2.6 mm. The comparisons between the experimental and calculated results validate the theoretical model of material balance utilized in this study. Finally, a better geometrical structure of micro-pin-fin arrays is obtained, in which the height of the micro-pin-fin, the transverse and longitudinal center distances between two adjacent micro-pin-fins are 1.0 mm, 1.2 mm and 1.2 mm, respectively. The hydrogen yield in the MPFAR can reach about 8.3 ml/min under the condition that the methanol conversion rate is above 90%.

1. Introduction

Fuel cell vehicles are a better alternative in comparison to internal combustion engine vehicles, in the context of energy sustainability and environmental impacts. This is due to the increase in efficiency and reduction in CO_2 emissions associated with the fuel cell vehicles [1]. Furthermore, micro-reformers fueled by liquid fuels such as methanol have received increasing interest to produce hydrogen for proton exchange membrane fuel cell (PEMFC) vehicles. This is attributed to the increased safety and volume efficiency relative to fuel cell vehicles fueled by high-pressure hydrogen [2]. It is widely accepted that the design of the fuel processor for hydrogen production can allow for small volume, small weight, low cost, long lifetime, low byproduct (carbon monoxide), ease of manufacture, low flow resistance and

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Nomenclature

A	section area along the flow direction (m^2)
A_0	section area of the reaction channel at the entrance (m^2)
A_R, B_R	pre-exponential factors for methanol reforming reaction ($m^3\,kg^{-1}\,s^{-1}$)
A_D	pre-exponential factor for methanol decomposition reaction ($mol\,kg^{-1}\,s^{-1}$)
C_1	molar concentration of the gaseous methanol ($mol\,m^{-3}$)
C_{10}	molar concentration of methanol at the surface of catalyst layer ($mol\,m^{-3}$)
C_i	molar concentration of species i ($mol\,m^{-3}$)
d	diameter of the micro-pin-fin (m)
E_{a1}	activation energy of methanol reforming reaction ($J\,mol^{-1}$)
E_{a2}	activation energy of methanol decomposition reaction ($J\,mol^{-1}$)
F_{M0}	methanol molar flow rate at the entrance of the reaction channel ($mol\,s^{-1}$)
h	height of the micro-pin-fin (m)
H	height of the reaction channel (m)
j	natural number sequence
k_D	reaction constant of methanol deformation reaction ($mol\,kg^{-1}\,s^{-1}$)
k_R	volumetric reaction constant of methanol reforming reaction ($m^3\,kg^{-1}\,s^{-1}$)
L_0	distance between two adjacent micro-pin-fins (m)
n_L	column number of micro-pin-fin arrays in the reaction channel
n_T	row number of micro-pin-fin arrays in the reaction channel
r_D	reaction rates of methanol decomposition reaction ($mol\,m^{-3}\,s^{-1}$)
r_i	chemical reaction rate of species i ($mol\,m^{-3}\,s^{-1}$)
r_R	reaction rates of methanol steam reforming reaction ($mol\,m^{-3}\,s^{-1}$)
R	universal gas constant ($J\,mol^{-1}\,K^{-1}$)
S/C	steam to methanol
SMR	molar ratio of steam and methanol
T	reaction temperature of the MPFAR (K)
u_0	mean velocity at the entrance ($m\,s^{-1}$)
$\dot{V}$	volumetric flow rate of the dry reformed gas at standard conditions ($m^3\,s^{-1}$)
V_m	molar volume ($m^3\,mol^{-1}$)
W	width of the catalyst support (m)
X_m	volumetric expansion coefficient produced by methanol steam reforming reaction
Y_C	carbon volumetric fraction in the dry reformed gas

Greek symbols

δ	thickness of the catalyst layer (m)
ε	void of catalyst
η_m	methanol conversion rate for the methanol steam reforming process
ρ_s	catalyst density ($kg\,m^{-3}$)

short start-up time [3]. These demands can be met by enhancing the heat and mass transfer of the fuel processor. As a result, the catalyst support with microstructure has been widely utilized in the reactor for hydrogen production due to its great heat and mass transfer characteristics. There are two types of typical reactors for the intensification of heat and mass transfer: the tubular reactor with micro-tube as the catalyst support and the micro-channel reactor. The tubular reactor with micro-tube as a microstructure used for fuel process has been found to be able to enhance the heat and mass transfer [4]. However, there are still some crucial obstacles for the tubular reactor to be applied in fuel cell vehicles considering the scale up and the coating of the reforming catalyst [5]. The micro-channel reactor is a better alternative as a fuel processor due to the relative ease of scale increase; and the study of the micro-channel reactors has also demonstrated the enhancement of mass and heat transfer in comparison with the traditional reactor for hydrogen production [6,7]. For a micro-channel reactor, the catalyst support is usually a metal sheet such as the stainless steel sheet with straight micro-channels [8], or the porous sintered felts such as copper fiber sintered felts [9–11]. It has been known that the ratio of surface area to volume is large for the micro-channel reactor with multi-micro-channels, but it can be much larger when changing the structure of catalyst support from ‘straight channels’ to the ‘micro-pin-fin arrays’ as shown in Fig. 1. Therefore, a novel micro-reactor with micro-pin-fin arrays (MPFAR) for fuel processing has been developed in our previous study, and some results have shown advantages of the MPFAR for hydrogen production [12].

Due to the importance of structural effects of the catalyst support on the reactor performance of hydrogen production, it is crucial to establish a theoretical model to study the process of hydrogen production in the micro-reactor with various

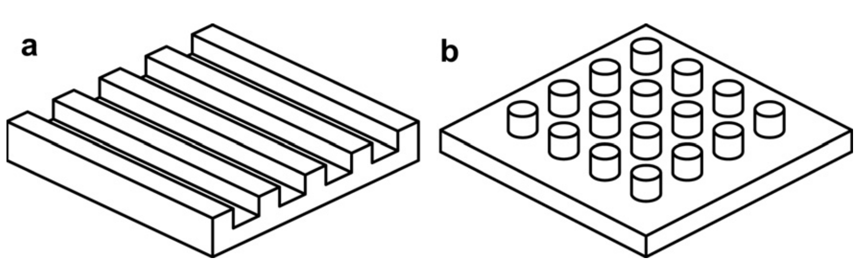

Fig. 1 – Configuration of the catalyst support: (a) straight channels, and (b) micro-pin-fin arrays.