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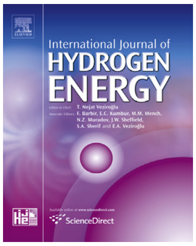

Modeling and analysis of flow distribution in an A-type microchannel reactor

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ABSTRACT

Flow distribution among microchannels is a fatal factor affecting the performance of laminated microchannel reactors for hydrogen production. Homogeneous flow strongly depends on the structural design of the microchannel reactor. The present work concentrates on improving the flow distribution in microchannel reactors for hydrogen production by optimization of the structural design. An innovative A-type microchannel reactor for hydrogen production with one inlet/two outlets was developed and analyzed. The equivalent electrical resistance network model was used to calculate the flow distribution in the microchannel reactor which was validated by computational fluid dynamics (CFD). The influences of structural parameters on flow distribution in the A-type were investigated quantitatively. The calculated results showed that longer microchannels with a higher aspect ratio and a small side length in the manifolds were beneficial for attaining uniform flow distribution in the A-type microchannel reactor. Furthermore, it was found that flow distributions among the microchannels in the A-type were much more uniform than those in the conventional Z-type microchannel reactor with one inlet/one outlet. Finally, an optimization strategy was proposed to optimize the manifold geometries to obtain a comparatively even flow distribution among microchannels.

1. Introduction

As environmental pollution and the energy crisis grow, the fuel cell, a clean and powerful technology, is receiving increasing attention. The polymer electrolyte membrane fuel cell (PEMFC) is one of the most promising fuel cells, which provides many advantages such as high power density, high efficiency, low operating temperature and no pollutant emissions [1,2]. During the past decades, PEMFC technology has been developed quickly. However, the hydrogen supply restrained PEMFC's further development. Hydrogen production on site via reforming hydrocarbons such as methane, alcohol, methanol, dimethyl ether, etc., can be an available method to cope with this limitation. Among these approaches, steam reforming of methanol on site shows more advantages on account of its safety and high efficiency [3]. To enhance the performance of hydrogen production via steam reforming of methanol, a microchannel reactor is an attractive option for its high heat and mass transfer capabilities which has been applied in many fields [4].

Flow distribution among microchannels plays a critical role in the performance of microchannel reactors, which strongly depends on the geometrical structure of the microchannel reactor. Flow maldistribution can lead to uneven residence

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Nomenclature

A	sectional area of channel, mm^2
$2N$	quantity of microchannel
D_H	hydraulic nominal diameter, mm
E	microchannel depth, mm
$H^\#$	ratio of H_{in}/H_{out} to $(Y_{in} + R_{in})/(Y_{out} + R_{out})$
H_{in}	side length of distribution manifold, mm
H_{out}	side length of collection manifold, mm
i	integer variable
L_c	microchannel length, mm
ΔP	pressure drop, Pa
Q	volumetric flow rate, mm^3 s^{-1}
$Q_c(i)$	volumetric flow rate of the ith microchannel, mm^3 s^{-1}
$Q_{cm}(i)$	volumetric flow rate of the ith collection region, mm^3 s^{-1}
$Q_{dm}(i)$	volumetric flow rate of the ith distribution region, mm^3 s^{-1}
Q_T	total volumetric flow rate, mm^3 s^{-1}
R	flow resistance, Pa s mm^{-3}
$R_c(i)$	flow resistance in the ith microchannel, Pa s mm^{-3}
$R_{cm}(i)$	flow resistance in the ith collection region, Pa s mm^{-3}
$R_{dm}(i)$	flow resistance in the ith distribution region, Pa s mm^{-3}
R_{in}	radius of inlet, mm
R_{out}	radius of outlet, mm
V	flow velocity, mm s^{-1}
$V_c(i)$	mean velocity in the ith microchannel, mm s^{-1}
V_m	average flow velocity, mm s^{-1}
W_A	reaction zone width, mm
W_c	microchannel width, mm
W_s	width of the space between microchannels, mm
X	horizontal coordinate, mm
$X^\#$	ratio of X_{out} to W_A
X_{in}	the horizontal distance from microchannel to inlet, mm
X_{out}	the horizontal distance from microchannel to outlet, mm
Y	vertical coordinate, mm
$Y^\#$	ratio of Y_{in}/Y_{out} to L_c
Y_{in}	the vertical distance from microchannel to inlet, mm
Y_{out}	the vertical distance from microchannel to outlet, mm
Greek symbols	
λ_{NC}	non-circular coefficient
μ	viscosity, Pa s
$\sigma_V\%$	the standard deviation of velocity distribution

time of the reactants which can deteriorate the reaction efficiency severely. On the contrary, even flow distribution is beneficial for a high reaction rate and selectivity of the process. Many research works concentrating on improving velocity distribution uniformity through optimizing the geometrical structure have been carried out including numerical and analytical studies. Tonomura et al. [5] have investigated the features of the flow pattern in a plate-fin micro-device with rectangular manifold and also proposed a manifold optimization method based on CFD. Using a three-dimensional model, Delsman et al. [6] have found that the inertia effects began to influence flow distribution as the flow rate beyond a transitional value. Liu et al. [7] have studied the effects of bifurcation geometries on the flow distribution uniformity in a bifurcation configuration using numerical models. Analytical models have also been adopted to study the influences of geometrical structures. Commenge et al. [8] have developed an approximate pressure drop model to investigate the flow distribution among the microchannels. Amador et al. [9] have studied the flow distribution in two configurations, consecutive and bifurcation. For a microchannel reactor with complex manifold geometries, Pan et al. [10] have proposed an optimization procedure for even flow distribution. A similar analytical model was adopted by Zheng et al. [11] to improve the flow distribution among microchannels.

According to the manifold structure, the majority of microchannel reactors employed in much of the literature could be classified into two typical types, i.e. bifurcation configuration [9,12] and Z-type configuration [8,10,11,13], as shown in Fig. 1(a) and (b), respectively. In the bifurcation configuration, the fluid flow is divided into two parts equally and merged into one in the bifurcation levels. While in the Z-type configuration, the flow inlet and outlet are located at two diagonal corners. The bifurcation configuration offers several advantages such as lower pumping power, higher heat transfer capabilities and more even flow distribution [12]. Nevertheless, the flow vortex appearing at the inlet deteriorates the flow uniformity. Moreover, the large manifold area demand seriously lowers its compactness. Compared with the bifurcation configuration, though flow distribution in the Z-type configuration is a bit less uniform, the Z-type configuration is more attractive because of its compactness which has led to frequent usage in chemical reactors. Zhou et al. [14] have constructed a novel microchannel reactor for hydrogen production via methanol steam reforming using porous copper fiber sintered felt (PCFSF) as catalyst support to improve the adhesion of the catalyst, prolong the catalyst life and increase the methanol conversion. In our previous works, an improved microchannel reactor with micro-pin-fin arrays (MPFAR) was proposed and fabricated in order to further increase the heat and mass transfer for hydrogen production [15,16]. Apart from the bifurcation and Z-type configuration, some other configurations were also proposed. Balaji et al. [17] have found that flow distribution in the micro heat exchanger with two inlets and four outlets, in line with the microchannels, exhibited more homogeneity under various flow conditions. Hao et al. [18] have found that a microchannel reactor with certain microchannel inclination angles and one central inlet/outlet was beneficial for flow distribution uniformity.

So far, many structural designs of microchannel reactors aimed at uniform flow distribution among microchannels have been studied by many researchers, mostly concentrating on bifurcation and Z-type configuration. However, maldistribution