Available online at www.sciencedirect.com
ScienceDirect
International Journal of Heat and Mass Transfer 50 (2007) 5323–5327
International Journal of HEAT and MASS TRANSFER
www.elsevier.com/locate/ijhmt

Technical Note

Heat transfer and pressure drop in serpentine μDMFC flow channels

Shou-Shing Hsieh *, Bing-Shyan Her

Department of Mechanical and Electro Mechanical Engineering, National Sun Yat-Sen University, Kaohsiung 80424, Taiwan, ROC

Received 2 December 2006; received in revised form 20 July 2007
Available online 20 September 2007

Abstract

In this paper, a 3-D mathematical model incorporated with Fluent computer code is described to investigate the flow and heat transfer for developing laminar flow in the micro direct methanol fuel cell (μDMFC) with serpentine flow fields. The continuity, momentum, and energy equations are simultaneously solved by a general computational fluid dynamics code. Local, channel-mean, bended region-mean, and overall channel mean friction factors and Nusselt numbers were thus calculated and discussed. Finally, overall channel mean friction factor and Nusselt number were correlated in terms of the relevant parameters.

Keywords: Heat transfer; Pressure drop; μDMFC; Flow channel

1. Introduction

With the advances in MEMS technology, various microsystems such as micro heat sinks, micro-biochips, and micro fuel cells have been developed in recent years. Among these micro fuel cells, the micro direct methanol fuel cell (μDMFC), using polymer membrane as electrolyte, are considered to be one of the most promising power sources, especially for 3C products because of its high efficiency, clear, quiet, easy handling for fuel delivery, simple cell design, and fast start-up even at low temperature [1,2].

An elementary μDMFC consists of two thins, porous electrodes (an anode and a cathode), which are separated by a polymer membrane that passes only protons. In order to achieve high utilization of the electrochemically active surfaces, a planar architecture is frequently used [3], in which the reactants, namely methanol and oxygen or air are forced through the slots or grooves etched on fluid distribution plates. The slots may be of different patterns i.e., mesh, serpentine, or intendigitated channels [1,2]. For a superior performance, good and proper distribution of the reactants to minimize the pressure drop in the fluid flow through the channels is essentially needed as pumping power reduces the overall efficiency of the cell.

During the past, considerable attention has been given to numerical simulations to predict fuel cell performance and to proceed cell optimum design by using one and two dimensional, even three-dimensional mathematical model recently. However, most of the existing research are limited to conventional PEMFC [3–6] or DMFC if applicable. There are quite a few papers available to deal with flow configurations in micro fuel cells both experimentally and numerically [3,4].

This study is motivated by a need to broaden a fundamental understanding of the flow in the channels of micro fuel cells and to develop design correlations for the friction factors (f) and Nusselt numbers (Nu) of straight channels and 90° bend regions in serpentine flow configurations in the parametric range of interest to designers of μDMFCs. The typical serpentine flow channels with the coordinate system used are shown in Fig. 1a. Detailed configurations of the flow channels of interest are shown in Fig. 1b. Relevant dimension and size of the present domain of calculation were listed in Table 1. The FLUENT code (version 6.1) was employed with proper assumptions [7] and boundary conditions.

* Corresponding author. Tel.: +886 (07) 5252000x4215; fax: +886 (07) 5254215.
E-mail address: sshsieh@mail.nsysu.edu.tw (S.-S. Hsieh).

0017-9310/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijheatmasstransfer.2007.07.041

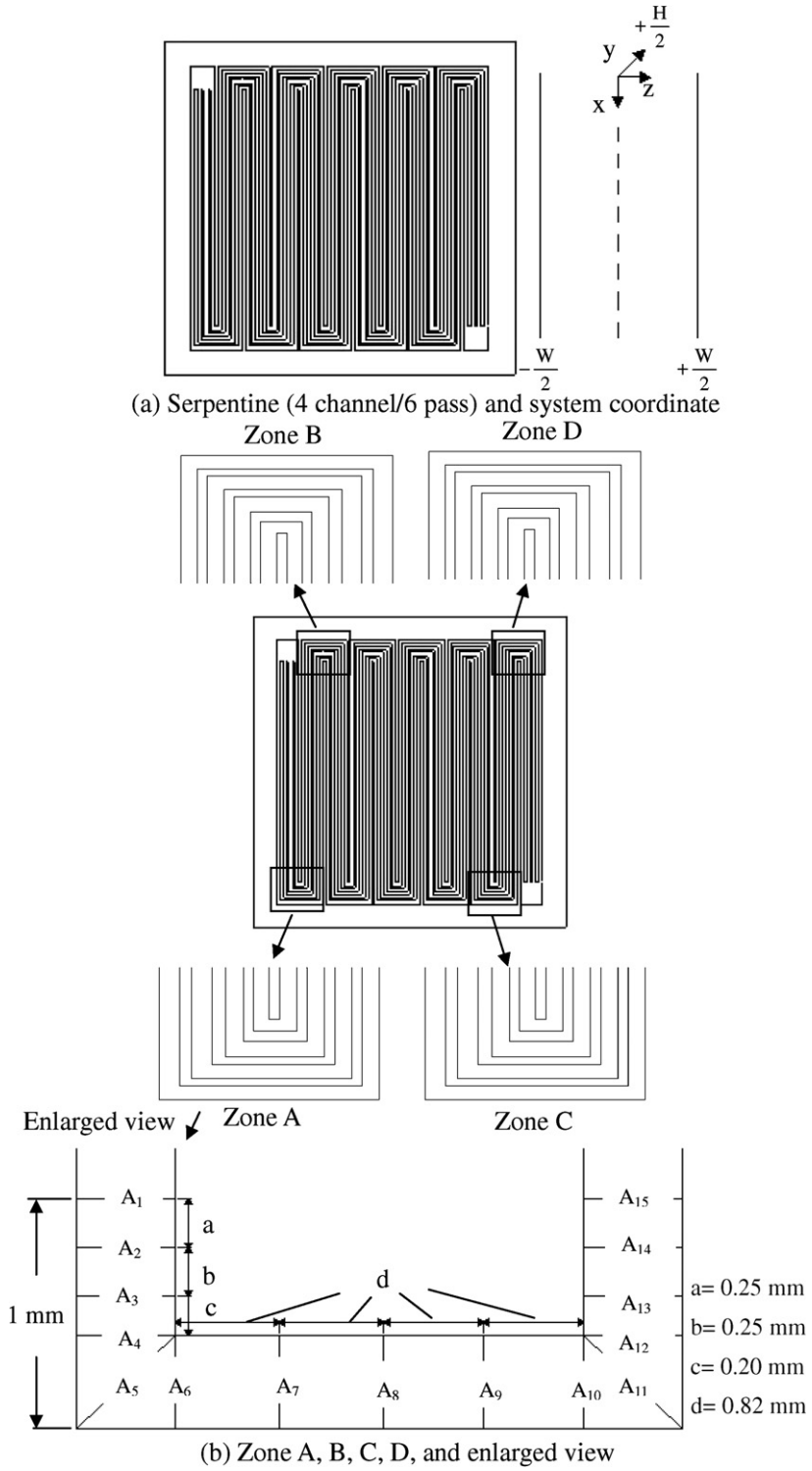


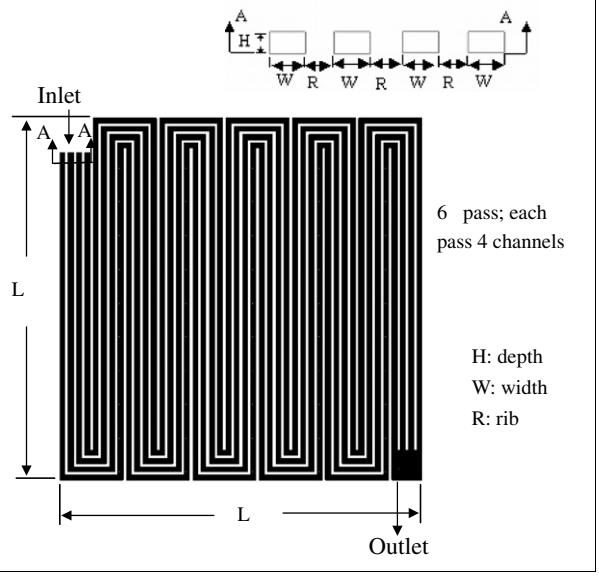
Fig. 1. Serpentine flow channel (on xz plane, $y = 0$) of interest for the present study. (a) Serpentine (4 channel/6 pass) and system coordinate. (b) Zone A, B, C, D, and enlarged view.

2. Results and discussion

Unless otherwise stated, these local values were represented on middle plane ($y = 0$; xz plane) with pressure as well as velocity fields, respectively, at different Re. The overall channel mean velocity U and temperature T was calculated by averaging the local velocity (spanwise averaged) over the total channel length. With these U and T, the corresponding Reynolds number, local, channel-mean, bended region-mean, and overall channel mean friction factor ($\bar{f} = 2\Delta P/\rho U^2 L_t$) and heat transfer coefficient ($\bar{h} = 1/L_t \int_0^{L_t} h\,\mathrm{d}x$) as well as the corresponding mean Nusselt

Table 1
Channel size and dimension and velocity/temperature boundary conditions

Geometry	L (μm)	H (μm)	R (μm)	W (μm)
	22359	200	213	300
Boundary Conditions	temperature inlet (K)	outlet pressure (Pa)		temperature outlet (K)
	313.15	101325		293.15
Wall Boundary Conditions	wall heat transfer coefficient h (W/m^2K)			wall temperature (K)
	5			298.15
Methanol	density, ρ (Kg/m^3)	thermal conductivity, k (W/mK)		viscosity, μ (Kg/ms)
	785	0.2022		0.0005495



number ($\overline{Nu} = \bar{h}d/k$) were deduced, presented, and discussed.

Vector plots of the velocity on the middle plane ($y = 0$; xz plane) for a sharp 90° bend for zone A, B, C, and D at $Re = 421.4$ are presented in Fig. 2. Separation (indicated as sp in Fig. 2a) and flow reattachment can be seen from the marked region in Fig. 2a. The recirculation area intensity and size depend on Re. As Re increase (not shown), the intensity and size increases. The recirculation area size can occupy 35% of the channel width at $Re = 421.4$. The flow was redeveloped after passing through the first bend region as the flow proceeds downstream, and it seems never fully developed for entire cases before the flow approaching the last (the 6th) pass. To observe the flow in xy plane (i.e. $z = 0$), Fig. 2b shows the accompanied plots of Fig. 2a. Again, flow separation also occurs in the bended region with two rotating symmetric clockwise vortices and seems much stronger. The axial symmetry exists along the straight channels.

The temperature distribution for both straight channels and bend regions (zone A, B, C, and D) at $Re = 84.9$, 238, and 421.4, were computed. Generally, the average temperature of the channels is about 310 K and the difference between the maximum and minimum temperature is about 8 K at $Re = 421.4$. It is found (not shown) that a relatively uniform temperature can be obtained for straight portions of the channel. As the flow approaching the bend region either zone A, B, C, or D, the temperature field in these regions is significantly distorted as the corresponding velocity vector profile does.

Since the present micro-channel flow is laminar ($Re \leqslant 421$), diffusion would expect to be dominant. Such effect can be examined by the ratio between the mass transport due to pressure driven and that due to methanol molecular diffusion. This ratio is a dimensionless number, the Peclet number (Pe), given as $Pe = Ud/\alpha$ where d is the hydraulic diameter (~240 μm) of the channel, U is overall channel mean velocity, and α is the thermal diffusivity. With Pe in hand, the present overall channel mean Nusselt number can be correlated in the form of $\overline{Nu} = 1.2Pe^{0.064}$, which can be found in Fig. 3a. The exponent of the correlation seems small (~0.064). Besides, $\overline{Nu}$ values are small, as compared to those in conventional larger systems (~3.66 for fully developed value). However, the power is still significant somehow especially in micro-fluidic situations. The correlation indicates that in the present micro-channels, using Pe number as a parameter seems more relevant than that of Re and Pr for Nu correlation development in the conventional systems. In fact, the Reynolds number dependence of the Nusselt number in micro-channels is not apparent, which indicates the major transport process is molecular diffusion.

Another feature of the present flow involving the Pe is the difference between Taylor dispersion flow and pure convective flow. The present Pe(~600–3000) is about one or two order of magnitude higher than the length (L) to width (W) ratio (~80). Consequently, Taylor dispersion is weak. Taylor dispersion is a superposition phenomenon which includes direct movement of flow due to convection and some molecules of flow diffuse from low velocity area to high velocity area and vice versa. This somewhat big difference ($Pe \gg L/W$) again explains that the axial convection still exists, as stated previously. Furthermore, the present $\overline{Nu}$ was compared to Qu et al. [9] whose work was dealt with heat transfer for water flow in trapezoidal silicon micro-channels. The present results seem higher than those reported ($d = 114.5$ μm) in [9] as also illustrated in Fig. 3a. This difference may be because the present study has a larger d(=240 μm) and different working medium (methanol) with hydrophilic surface. Nevertheless, the agreement is not bad and again, this proves that the present numerical simulation works in μDMFC flow channels.

Although the present $\overline{Nu}$ seems not to have the form of Reynolds number dependence (using Pe instead) as it usually does in conventional larger systems, the overall channel mean frication factor (f) can still be correlated in

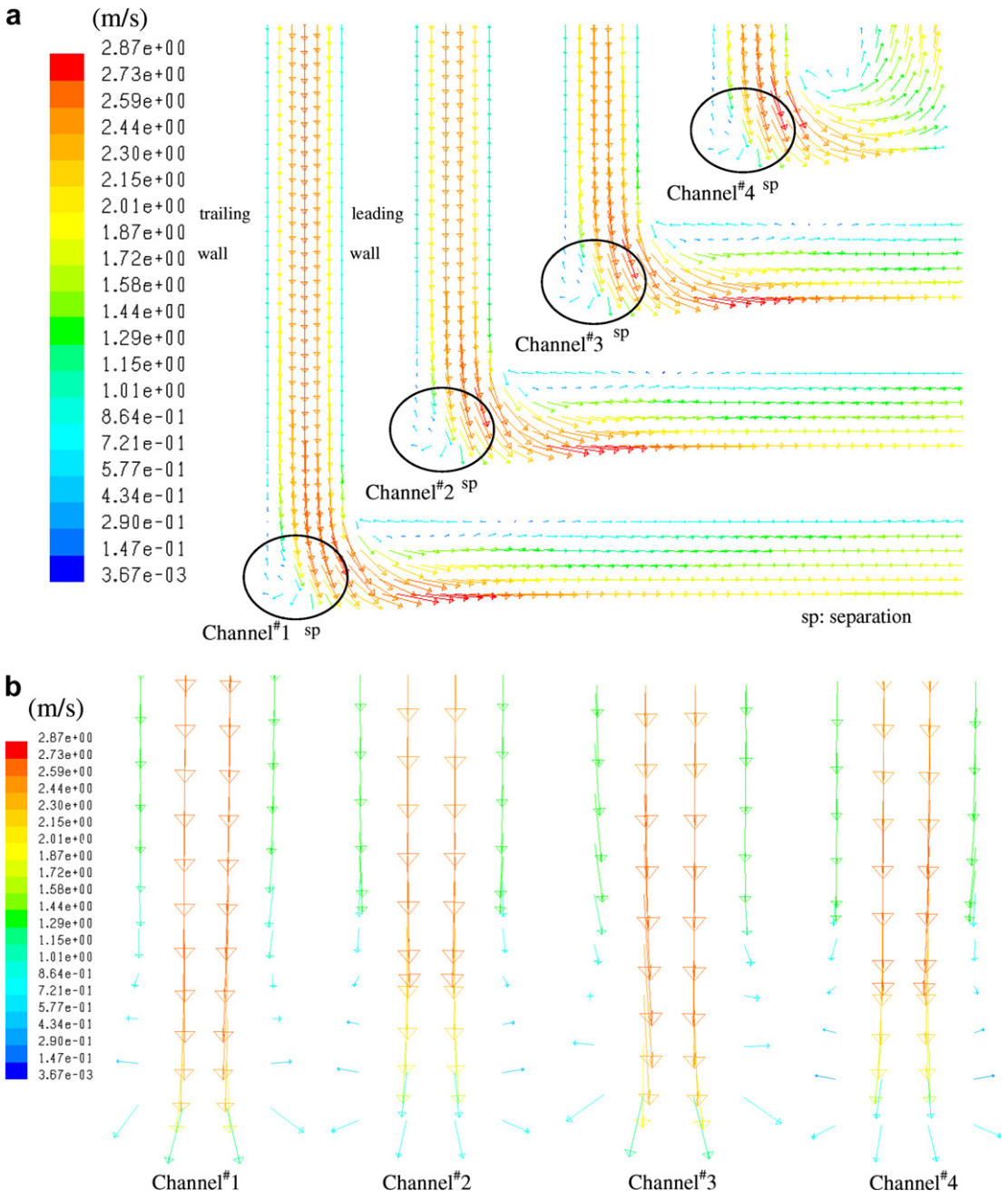


Fig. 2. Velocity vector plot of bended regions for zone A (on xz and xy plane) at $Re = 421.4$.

terms of Reynolds number with a smaller power dependence as compared to those of conventional channels (-0.87 vs -1) as shown in Fig. 3b. Nevertheless, the friction factor is also strongly dependent on Reynolds number. This finding is similar to those of previous studies [3,4] with different working medium. Moreover, the results show that the present $\bar{f}$ values are 30–40% higher than those of the conventional larger systems. This is again due to the methanol fluid with the hydrophilic surface microchannel, which is opposite to the findings from Hsieh et al. [8] where there is hydrophobic surface in deionized water flow microchannels.

3. Conclusion

A 3-D numerical simulation was successfully performed to investigate the flow and heat transfer in a laminar developing flow in μDMFC flow channels (4 channels and 6 pass) for $10 \leqslant Re \leqslant 421.4$. Local, channel-mean, bended region-mean, and overall channel mean frication factor as well as the corresponding Nusselt number were calculated. Detailed velocity and temperature distributions in sharp U-bend regions were obtained and discussed. Flow separations were found in bended regions for all the cases under study.

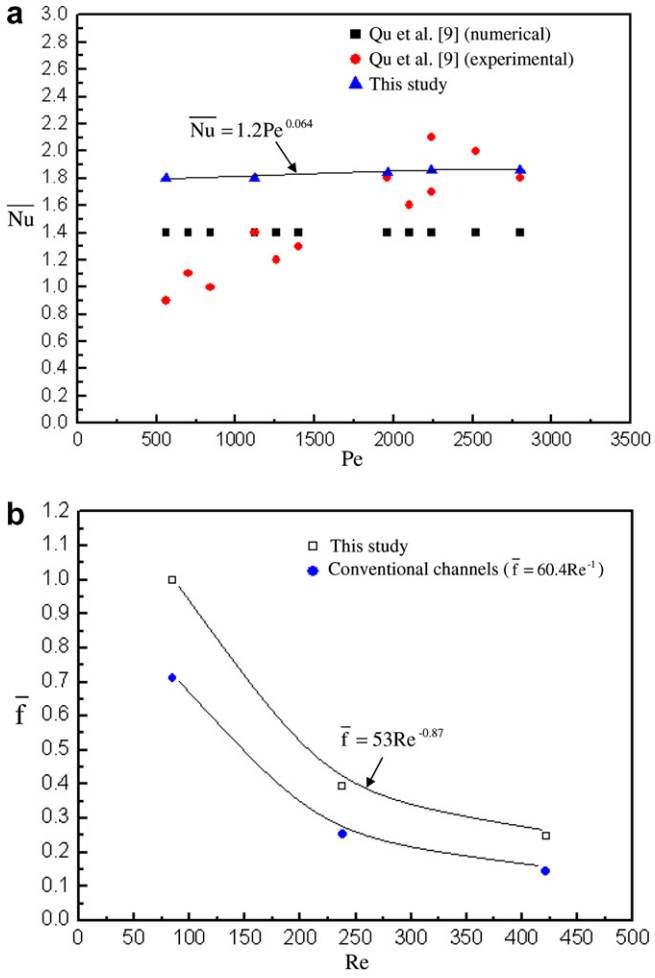


Fig. 3. $\overline{Nu}$ vs Pe and $\bar{f}$ vs Re and their comparisons with those of previous studies.

The values of channel mean frication factor $\bar{f}$ are consistently higher (~30–40%) than those of conventional larger systems at the corresponding Reynolds number. While for Nusselt number, the present channel gives a relatively lower value than that in conventional larger channels. Moreover, pressure drop in the U-bend regions was found to be negligible as compared to that in straight channels. This behavior is the same as that in straight conventional larger systems.

Although the channel considered only for four channel and six pass, the number of channel and pass is not limited as long as the serpentine flow channel is applied. Furthermore, this study also proves conventional Fluent computer code can still be employed in micro-fluidics with liquid as working medium at $Re \leqslant 421$ based on the present study.

References

[1] S.-S. Hsieh, J.-C. Kuo, S.-F. Hwang, H.H. Tsai, A novel design and microfabrication for a micro PEMFC, Microsyst. Technol. 10 (2004) 121–126.
[2] S.-S. Hsieh, C.-F. Hwang, C.-F. Kuo, H.-H. Tsai, S.-H. Yang, SU-8 flow field plates for a micro PEMFC, J. Solid. State Electron. 9 (2005) 121–131.
[3] S. Msharudrayya, S. Jayanti, A.P. Deshpande, Pressure losses in laminar flow through serpentine channels in fuel cell stacks, J. Power Sources 138 (2004) 1–13.
[4] H-H. Jung, W.-Y. Lee, J.-S. Park, C.-S. Kim, Numerical analysis of a polymer electrolyte fuel cell, Int. J. Hydrogen Energ. 29 (2004) 945–954.
[5] G. Hu, J. Fan, S. Chen, Y. Lin, K. Cen, Three-dimensional numerical analysis of proton exchange membrane fuel cells (PEMFCs) with conventional and interdigitated flow fields, J. Power Sources 136 (2004) 1–9.
[6] P.H. Oosthuizen, M. Austin, Channel-to-channel pressure differences in serpentine minichannel flow systems, Microscale Therm. Eng. 9 (2005) 49–61.
[7] H.Y. Wu, P. Cheng, An experimental study of convective heat transfer in silicon microchannel with different surface conditions, Int. J. Heat Mass Transfer 46 (2003) 2547–2556.
[8] S.-S. Hsieh, C.-Y. Lin, C.-F. Huang, H.-H. Tsai, Liquid flow in a microchannel, J. Micromech. Microeng. 14 (2004) 435–436.
[9] W. Qu, G.M. Mala, D. Li, Heat transfer for water flow in trapezoidal silicon microchannels, Int. J. Heat Mass Transfer 43 (2000) 3925–3936.