Available online at www.sciencedirect.com
ScienceDirect
Journal of Power Sources 180 (2008) 227–231
JOURNAL OF POWER SOURCES
www.elsevier.com/locate/jpowsour

Short communication

Effect of channel-to-channel cross-flow on local flooding in serpentine flow-fields

K.B. Shyam Prasad, S. Jayanti *

Department of Chemical Engineering, Indian Institute of Technology Madras, Chennai 600036, India

Received 29 September 2007; received in revised form 26 October 2007; accepted 14 January 2008
Available online 12 February 2008

Abstract

Serpentine flow-fields have long been used in polymer electrolyte membrane (PEM) fuel cells for effective transportation of reactants from the flow-field to the reaction sites. It has been observed in the literature that localized flooding near the U-bend region of serpentine flow-fields occurs at high current densities. This has been attributed to the boundary layer separation and recirculation of flow in the U-bend. In the present study, it is established, using computational fluid dynamics (CFD) simulations, that this is due to lower channel-to-channel cross-flow in the electrodes between consecutive serpentine channels rather than to the flow-field in the gas distribution channels.

Keywords: Cross-flow; Serpentine flow-field; Polymer electrolyte membrane fuel cell; Computational fluid dynamics; Water evacuation

1. Introduction

The design of flow-fields grooved in the bipolar plates of polymer electrolyte membrane fuel cells becomes important at high current densities. Many flow-field designs are being studied to enhance the current density and homogeneity of the reactants and overcome the pressure losses and removal of water from the cathode [1]. Conventional parallel flow-fields transport the reactants at a low pressure drop through a diffusion-dominated process. By contrast, a serpentine flow-field does this both by diffusion and convection (through cross-flow via the gas-diffusion electrode (GDE) from one channel to the adjacent one [2,3]) but requires a significantly higher pressure drop than the parallel flow-field. Since the cross-flow assists in both the feeding of the oxidant and the removal of water vapour from the catalyst layer, serpentine flow-fields give higher current densities compared with parallel flow-fields. Considerable literature is available on channel-to-channel cross-flow [2–8]. There has, however, been no study on water vapour distribution due to channel-to-channel cross-flow and its effects on liquid water flooding.

In a recent paper, Spernjak et al. [9] conducted an extensive in situ observation of a single serpentine flow-field, where flooding of the cathode had been captured under different operating conditions and in three GDEs. They found extensive local flooding in the U-bend region of the serpentine flow-field and attributed this to corner flow effects at the U-bends within the main gas stream. In the present study, an alternative possibility, namely, the absence of cross-flow and its evacuation of the water vapour in the U-bend region, is investigated. The scenario studied is as follows. One of the features of a serpentine flow-field is the high-pressure drop in the flow direction [10]. This creates a significant pressure difference between two neighbouring channels that may lead to the cross-flow provided the electrode has a sufficiently high permeability. Since the pressure difference across neighbouring channels varies along the length, the strength of the cross-flow also varies significantly and will be less in the U-bend region. This may cause insufficient evacuation of water vapour in the region and lead to build-up and eventual local flooding. In the present paper, this scenario is verified by means of computational fluid dynamics (CFD) simulations. This would indicate that measures which improve local cross-flow may lead to a better design of the flow-field.

2. Problem formulation

The present calculation methodology is based on CFD simulations in which the fundamental equations governing the flow, namely, conservation of mass and conservation of momentum

* Corresponding author. Tel.: +91 4422574168.
E-mail address: sjayanti@iitm.ac.in (S. Jayanti).

0378-7753/$ – see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.jpowsour.2008.01.074

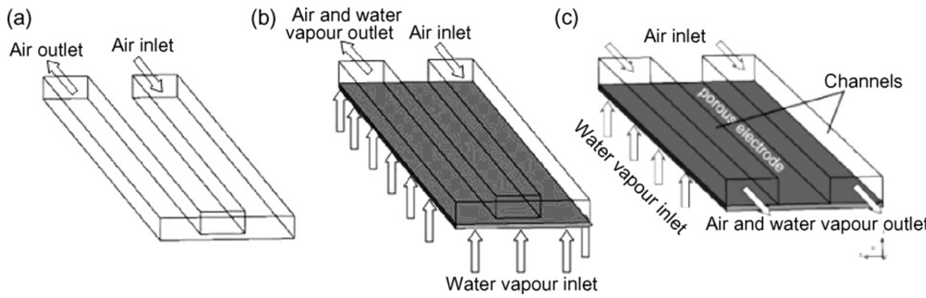

Fig. 1. (a) Serpentine tube without GDE; (b) serpentine channel with GDE; (c) parallel flow-field with GDE.

for an incompressible isothermal flow, are solved numerically. CFD simulations have previously been used, even by the present authors [10–12], to study different aspects of flows related to fuel cells. The primary interest in the present study is to determine how effectively water vapour is evacuated as a result of diffusion and advection both in the electrode and in the gas channel. Accordingly, the problem is formulated in terms of a single-phase flow of a binary mixture, which has been used earlier by the present authors to study water vapour distribution in an interdigitated flow-field [12]. Here, the two components of the mixture, namely, air and water vapour, are assumed to be intimately mixed and the mixture mass and momentum equations are solved along with a scalar transport equation that represents the mass conservation of the water vapour species. The mass fraction of air, which is the only other component, is obtained by difference. The thermophysical properties of the mixture such as the density and the viscosity are obtained on a mole fraction basis. A Darcy-formulation (see [11]) is used to calculate the flow-field in the porous part of the flow-field through the electrode. The governing equations, etc. for this formulation can be found in [12].

The flow-field is calculated in three flow domains (see Fig. 1), namely, in a single U-turn serpentine gas channel with and without the GDE and a pair of parallel channels of dimensions identical to those of the serpentine channels, where applicable. The flow domain thus represents a unit cell on the cathode side or the anode side in which reactants and products pass through the gas channel and the porous electrode on their way to or from the catalyst layer. Taking the extreme case in which all the water vapour is evacuated from the cathode side, the boundary conditions, with reference to Fig. 1, imposed on the flow domain are as follows: mass flow rate of air at the upstream ‘inlet’; fully developed flow condition specified at the downstream ‘outlet’; no-slip condition on the side walls; mass flow rate of water vapour at 80 °C at the electrode membrane interface corresponding to an assumed current density of $1\ \mathrm{A\,cm^{-2}}$. All the simulations were carried out using the commercial CFD code *CFX* Version 5.7 of ANSYS, USA. The overall accuracy of the discretization of the equations is nominally second order. A residual reduction factor of 10^{-8} for the mass conservation equation has been used to monitor the convergence of the iterative scheme.

3. Results and discussion

The single serpentine channel with a single U-bend considered in the present study has a width of 2 mm, a height of 1 mm, a rib width of 2 mm, and a length of 102 mm. The porous electrode has a thickness of 0.2 mm and a permeability of $10^{-10}\ \mathrm{m^2}$. A uniform water flux of $2.798 \times 10^{-7}\ \mathrm{kg\,s^{-1}}$ corresponding to a current density of $1\ \mathrm{A\,cm^{-2}}$ is specified as the boundary con-

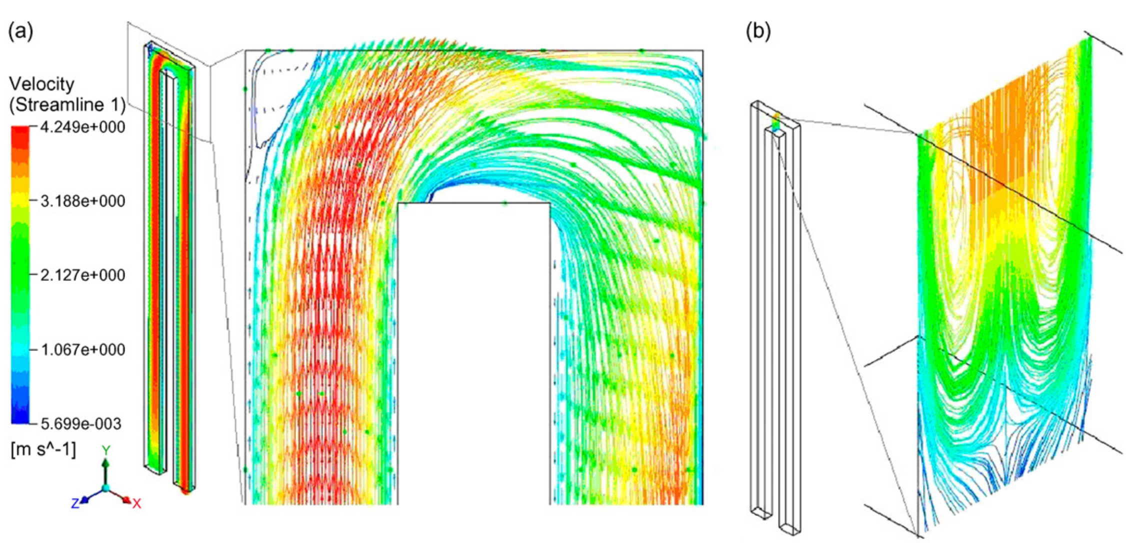

Fig. 2. Stream line plot in a channel without GDE: (a) at mid-channel height in *x*–*y* plane; (b) at half-distance in bend in *y*–*z* plane in which *z* is main flow direction in straight section of serpentine channel.

dition at the porous electrode facing the cathode catalyst layer. An air flow rate corresponding to a stoichiometric factor of four is specified at the inlet.

Initially a flow analysis of the serpentine channel without GDE was carried out to verify the recirculations and boundary layer separation of the flow in the U-bend. Fig. 2a presents a streamline plot at the mid-channel height in the U-bend region. The plot shows three low velocity regions: one at the top left-hand corner and two adjacent to the rib. The velocity contours given in Fig. 2b at mid-distance into the bend confirm that the flow near the inner bend region is of low velocity. The predicted streamlines in the two planes shown in Fig. 2 are in very good agreement with the observations made by Martin et al. [13] in their particle image velocimetry studies on single serpentine channels at a low Reynolds number of 109. The existence of these vortices is considered [9] to have the effect of water vapour/liquid water accumulation in this bend region leading to local flooding in the U-bends. The effect of a GDE attached to the flow channel is found to be only marginal on the main gas flow-field; due to cross-flow, the velocity near the bend region is lower (by about 10%) compared with channels without GDE.

An estimate can be made of the strength of the cross-flow through the GDE. The computed pressure variation along the axis in the upstream and downstream is shown in Fig. 3a. The pressure decreases linearly in both the upstream and the downstream channels, as it would be for an incompressible laminar flow. The pressure drop in the serpentine channel without the GDE is higher because there is no channel-to-channel cross-flow. The pressure difference between the upstream and downstream channels along the length shows a decrease and becomes negligible at the U-bend. Correspondingly, the cross-flow through the electrode across the rib, which is driven by this pressure difference, varies considerably along the length of the serpentine channel and becomes negligible in the U-bend region. This is confirmed in Fig. 3b which shows the computed cross-flow velocity component at mid-height of the electrode all along the length of the channel. The cross-flow velocity is quite small under the gas channels and varies considerably under the rib; it is low at the U-bend and is highest at the inlet. The water vapour mass fraction contours at mid-height of the electrode in Fig. 3b show that, in general, it increases in the main flow direction because, ultimately, it is evacuated through the outlet alone. The highest concentrations of the water vapour, however, are not found near the exit but in the U-bend region. Thus, there is a tendency for water vapour to accumulate *in the electrode itself* near the U-bend.

In order to determine further the relation between the water vapour mass fraction and cross-flow, the flow and vapour fraction fields have been calculated for several cases, namely: in a parallel-flow channel at the same current density; in a serpentine channel at air stoichiometric factors of 1, 2, 4 and 8; in a serpentine channel at a lower permeability of $10^{-14}\,m^2$ for a stoichiometric factor of 4. The contours of water vapour mass fractions at mid-height of the electrode for these cases are shown respectively in Fig. 4a–f. In the parallel channel, there is no cross-flow in the electrode; hence the vapour mass fraction (Fig. 4a) has a peak value under the rib that is higher than that at the exit. In a serpentine channel, as the stoichiometric factor increases, the volumetric flow rate of air increases. For the same rate of water vapour generation, this has the effect of diluting the concentration of water vapour. Also, the pressure drop along the channel increases as the flow rate increases. This leads to a higher cross-flow which, in turn, results in more effective evacuation of the water vapour from under the rib. These effects are clearly seen in Fig. 4b–e; it can be noted that the high concentration of water vapour under the rib in the last two cases is limited to a small zone near the U-bend. Finally, with lower permeability of the electrode, the cross-flow velocity decreases for the same pressure difference across two adjacent channels of a serpentine flow-field. This has the effect of increasing the tendency for water vapour accumulation under the rib, as can be seen in Fig. 4f.

The above results show that there is a strong link between cross-flow and the water vapour accumulation within the electrode. By contrast, such a strong connection is not found to exist between the flow-field in the main gas flow channel and

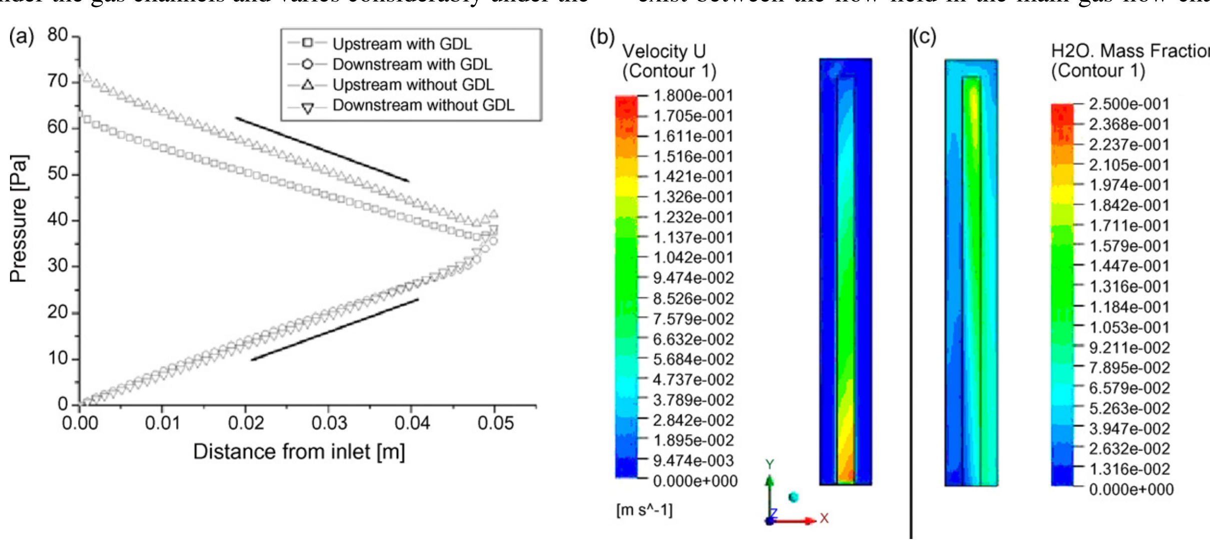

Fig. 3. (a) Pressure variation along axis of upstream and downstream of serpentine with and without GDE (arrow indicates direction of flow). (b) Velocity contour at mid-height of GDE, (c) Water vapour mass fraction contour at mid-height of GDE with a stochiometric factor of 4.

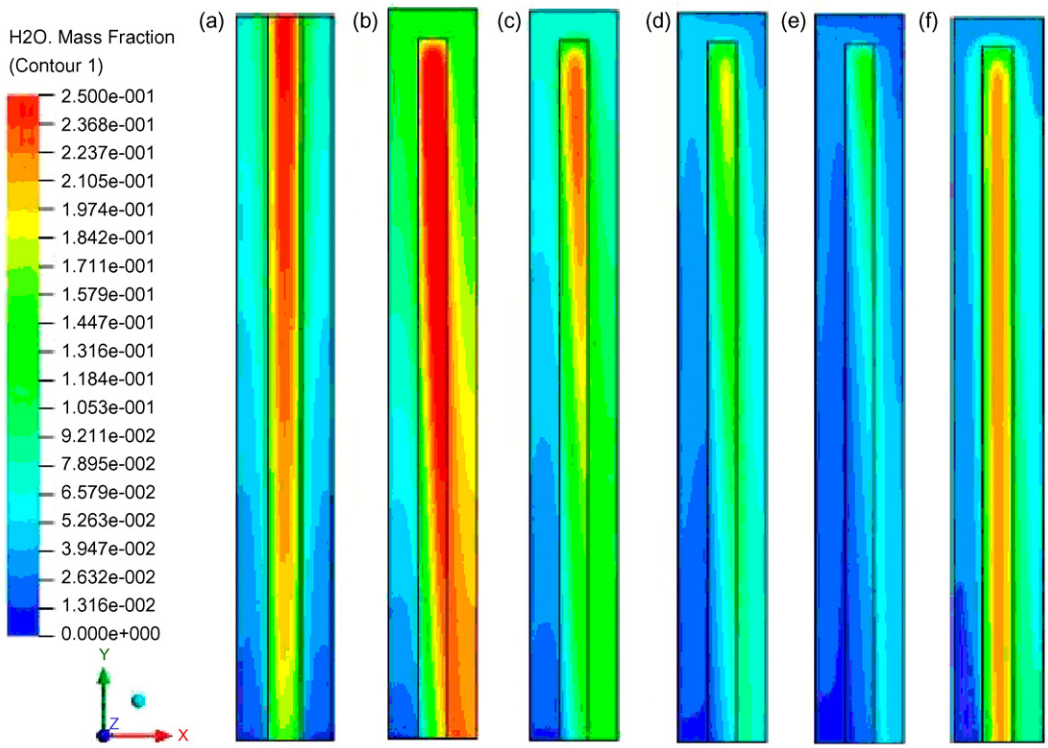

Fig. 4. Water vapour mass fraction contours at mid-height of electrode in (a) parallel flow-field with stochiometric factor of 4; serpentine flow-field with stochiometric factor of (b) 1, (c) 2, (d) 4 and (e) 8; (f) serpentine flow-field with permeability of 10^{-14} m^2 and stochiometric factor of 4.

the water vapour distribution. The predicted water vapour mass fraction at 0.1 mm above the GDE, i.e., within the gas channel, is given in Fig. 5 for the case of a stoichiometric factor of 4. Fig. 5a shows the variation in the entire serpentine channel while Fig. 5b presents a magnified view of the variation near the U-bend. The distribution of water vapour within the gas channel is seen to be little different from that in the electrode (Fig. 3c). The effect of the recirculations within the gas channel on the water vapour distribution is thus fairly small; the latter is determined more strongly by the distribution within the electrode that is governed

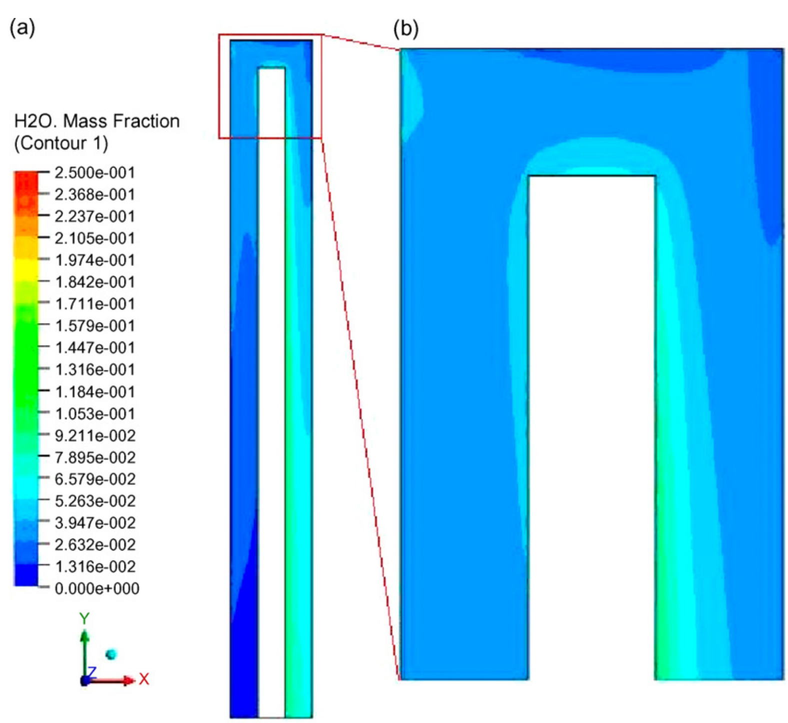

Fig. 5. Water vapour mass fraction contours in gas channel at height of 0.1 mm from GDE for stoichiometric factor of 4 and at current density of 1 A cm^{-2}; (a) serpentine channel; (b) magnified view near U-bend.

primarily by diffusion and convection arising from cross-flow. It can be concluded therefore that the localized flooding near the U-bends is attributable to the lack of cross-flow within the GDE rather than to corner flow effects in the main gas channel.

4. Conclusions

The present calculations establish a link between the cross-flow between adjacent channels in a serpentine flow-field and water vapour distribution in the electrode. If the electrode permeability or the pressure drop is high, then significant cross-flow can be established and will lead to more effective evacuation of the water vapour. The superior performance of the convection-enhanced serpentine flow-field [14] may also be attributed to this. Hence, cross-flow can be used as an additional parameter in arriving at the optimum design of a flow-field.

Acknowledgement

The work has been carried out as part of a project funded by the Department of Science and Technology, India.

References

[1] X. Li, I. Sabir, Int. J. Hydrogen Energy 30 (2005) 359–371.
[2] M.V. Williams, H.R. Kunz, J.M. Fenton, J. Electrochem. Soc. 151 (2004) A1617.
[3] P.H. Oosthuizen, L. Sun, K.B. McAuley, Appl. Therm. Eng. 25 (2005) 1083–1096.
[4] W. Suna, B.A. Peppley, K. Karan, J. Power Sources 144 (2005) 42–53.
[5] T. Kanezaki, X. Li, J.J. Baschuk, J. Power Sources 162 (2005) 415–425.
[6] Q. Ye, T.S. Zhao, C. Xu, Electrochim. Acta 51 (2006) 5420–5429.
[7] J. Park, X. Li, J. Power Sources 163 (2007) 853–863.
[8] J.P. Feser, A.K. Prasad, S.G. Advani, J. Power Sources 161 (2006) 404–412.
[9] D. Spernjak, A.K. Prasad, S.G. Advani, J. Power Sources 170 (2007) 334–344.
[10] S. Maharudrayya, S. Jayanti, A.P. Deshpande, J. Power Sources 138 (2004) 1–13.
[11] K.B. Shyam Prasad, S. Maharudrayya, S. Jayanti, J. Power Sources 159 (2006) 595–604.
[12] K.B. Shyam Prasad, S. Jayanti, Proceedings of Fuel Cell Science Engineering and Technology Conference, New York, 2007.
[13] J. Martin, P. Oshkai, N. Djilali, J. Fuel Cell Sci. Technol. 2 (2005) 70–80.
[14] C. Xu, T.S. Zhao, Electrochem. Commun. 9 (2007) 497–503.