

Effect of pervaporation plate thickness on the rate of methanol evaporation in a passive vapor-feed direct methanol fuel cell

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Abstract. In a passive vapor-feed direct methanol fuel cell (DMFC), methanol vapor is typically obtained using a pervaporation plate in a process by which liquid methanol contained in the fuel reservoir undergoes a phase change to vapor in the anodic vapor chamber. This work investigates the effect of pervaporation plate thickness on the rate of methanol evaporation using a three-dimensional simulation model developed by varying the plate thickness. A. The rate of methanol evaporation was measured using Darcy's law. The rate of methanol evaporation was found to be inversely proportional to the plate thickness, where the decrease in thickness inevitably lowers the resistance along the plate and consequently increases the methanol transport through the plate. This shows that the plate thickness has a significant influence on the rate of methanol evaporation and thereby plays an important role in improving the performance of the passive vapor-feed direct methanol fuel cell.

1. Introduction

Methanol in a direct methanol fuel cell (DMFC) can be used as fuel in its liquid or vapor form. However, the vapor feed DMFC has an advantage over the liquid feed system as it has the potential to have a higher operating temperature, increase the reaction rates and power outputs, enhance the mass transfers, and reduce methanol crossover. It is reliable for high methanol concentration and therefore can increase the fuel cell performance [1, 2].

In terms of fuel and oxidant delivery schemes, DMFCs can be classified either as active-feed or passive-feed. An active DMFC operates with the help of external devices such as a liquid pump for methanol delivery and a gas blower or fan for oxygen delivery, while a passive DMFC can perform stand-alone operations that eliminate the need for any external devices [3, 4].

Since early 1990s, methanol evaporation is achieved in an active vapor feed DMFC by utilizing an external device, such as an electric vaporizer or heater. However, these devices can suffer from excessive complexity that causes significant parasitic power losses, along with increased system volume and cost, especially in the case of small scale power sources. A passive vapor feed DMFC is therefore preferable for portable application devices because of its simplicity, small volume and weight and a more compact design. Vapor phase operation at high temperatures is incompatible with

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the need for passive approaches for portable DMFCs [5] and thus pervaporation plate can be used as a medium to vaporize methanol fuel in order to operate passively at ambient temperature.

Abdelkareem et al. investigated the effect on the performance of a passive DMFC under closed circuit conditions due to the usage of a porous carbon plate (PCP) as the vaporizer with different methanol concentration ranging from 1M to neat methanol. As a result, a maximum power density of 24 mW cm^{-2} was achieved at room temperature with a 2M solution without the PCP, and the result can be reproduced at 16M with the PCP. A novel PCP with better durability than other pervaporation medium was also developed [6, 7]. In this study, a model for a pervaporation plate as the vaporizer in a passive vapor feed DMFC that utilizes high concentration methanol was developed. The effect of the plate thickness on the rate of methanol evaporation is investigated by using COMSOL Multiphysics 4.3 software (COMSOL Inc., USA).

2. Methods

A schematic of a half-anode side layer in a passive vapor feed DMFC system operating with neat methanol is depicted in figure 1. Generally, the function of the vaporizer is to adsorb liquid methanol from the methanol reservoir and evaporate it as methanol vapor. The model utilized to describe mass transport in a pervaporation process in this simulation work is the pore flow model. This model assumes that the concentrations of solvent and solute within a plate are uniform and a pressure gradient is used to express the chemical potential gradient across the plate [8]. According to the pore flow model, three steps are included to describe mass transport in the pervaporation process: (i) the permeant is transported through the liquid-filled portion of the pore, (ii) a liquid-to-vapor phase change takes place inside the pore and (iii) the permeant is transported through the vapor-filled portion of the pore [9].

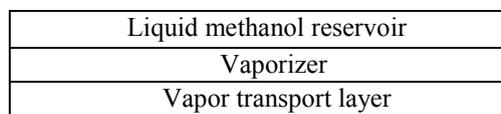


Figure 1. Schematic of half-anode side layer.

2.1. Model Development

The pervaporation process is a phenomena that affects the phase change of methanol from liquid to vapor. A three dimensional pervaporation plate model was developed using COMSOL Multiphysics. The effects of plate thickness on the performance of the vaporizer were investigated by measuring the rate of methanol evaporation. The range of thickness values used is 0.08-0.30 mm and the plate active area is 10 x 10 mm.

2.1.1. Model Assumptions. Model assumptions are as given below:

- The system is isothermal.
- The system operates under steady state condition.
- There is no chemical reaction through the plate.
- The pervaporation plate is a porous media.
- Vaporization of methanol from the liquid phase to the vapor phase occurs due to the pressure gradient in plate.
- Methanol vapor generated at the vapor phase will not condense.

- Loss of methanol vapor through the vent during the CO₂ releasing process is neglected.
- Only methanol species exists in the vaporizer.

To make the complicated model more tractable, the following simplifications are listed below:

- Methanol fed into the system is neat methanol with vapor pressure 13.02 kPa at 20°C.
- For all the thickness values in the model, the inlet pressure going into the plate is 101.325 kPa, as methanol in the reservoir is at atmospheric conditions. The outlet pressure going away from the plate is 12.0 kPa, which is assumed to be below the vapor pressure of methanol.

2.1.2. Model Description. The model consists of two compartments separated by a plate of thickness, L , as shown in figure 2 below. The following three phases have been considered: (i) the pure methanol in liquid phase (phase 1) in the upstream compartment is at atmospheric pressure ($P_1 = 1$ atm) and well-stirred so that no concentration gradient exists, (ii) the plate (phase 2) is assumed to be filled with homogeneous permeants within the media and (iii) the methanol vapor (phase 3) in the downstream compartment is maintained at a pressure lower than the vapor pressure of methanol.

In liquid phase, methanol permeates from the reservoir tank to the surface of the pervaporation plate that interfaces the methanol reservoir. In the plate phase, methanol diffuses through the pervaporation plate and follows a path defined by pressure gradient, which is the major driving force. Methanol is transported from the high pressure region to the low pressure region, which leads to evaporation. Finally, methanol vapor desorbs from the pervaporation plate surface.

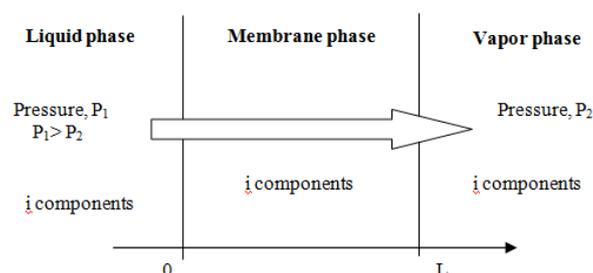


Figure 2. A schematic of the pervaporation plate.

3. Results and discussion

3.1. Rate of methanol diffusion

Figure 3 shows the profile of the rate of methanol diffusion into the plate for varying thickness values with neat methanol as fuel. The inlet pressure is higher than the outlet pressure as the pressure in the plate gradually decreases until the end of the plate thickness. As the outlet pressure is lower than the methanol vapor pressure, the methanol can diffuse completely through the plate and converted to vapor. The rate of methanol diffusion is seen to increase from the inlet to the outlet of the plate.

At low pressure, the distance between the plate molecules is larger. Thus, the space that allows for methanol molecules going through the plate becomes larger. Therefore, the rate of methanol diffusion through the plate is also higher. In contrast, the pressure at the beginning of the plate is high. Therefore, the distance between the plate molecules is closer and results in a smaller space for the methanol molecules to go through the plate. Thus, the rate of methanol diffusion through the plate is lower.

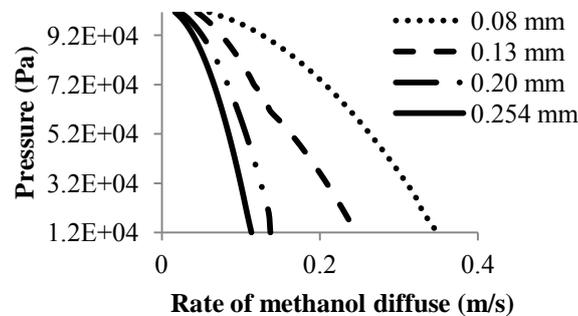


Figure 3. Effect of pressure on the rate of methanol diffusion varies thickness of plate.

From figure 3, methanol diffuses through the plate and starts undergoing a phase transition from the liquid phase to the vapor phase at 13.02 kPa as a result of the methanol vapor pressure. At 12.0 kPa, all the liquid methanol has been transformed to the vapor phase. Hence, the rate of methanol evaporation was started at end of the plate when the pressure was at 12.0 kPa. The rates of methanol evaporation for the plate thickness 0.08, 0.13, 0.20 and 0.254 mm are 0.348, 0.245, 0.137 and 0.113 m/s, respectively.

Figure 4 - 7 show the visual profile of the rate of methanol diffusion through the plate for the thickness values of 0.08, 0.13, 0.20 and 0.254 mm, respectively. The pressure difference between the upstream (inlet) and downstream (outlet) compartments is kept constant. It induces methanol to flow through the plate in a perpendicular direction to its surface, i.e. in a positive x-axis direction. The color indicators show a similar trend for all the profiles, i.e. the methanol diffusion starts at a very slow rate and increases gradually as it goes from inlet to outlet.

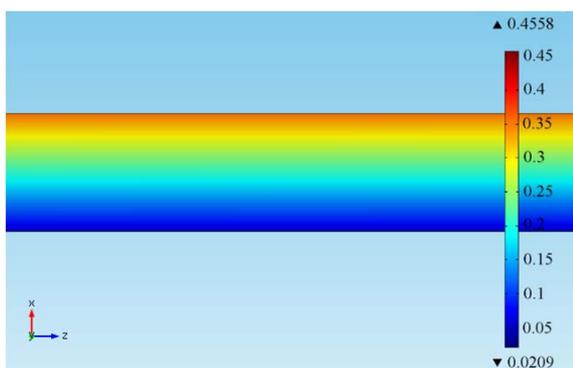


Figure 4. Profile of rate of methanol diffusing through plate for 0.08 mm thickness.

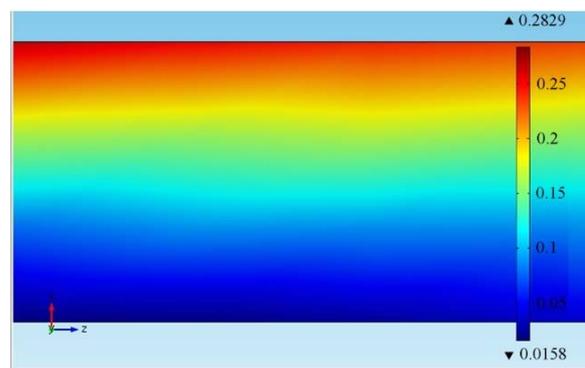


Figure 5. Profile of rate of methanol diffusing through the plate for 0.13 mm thickness.

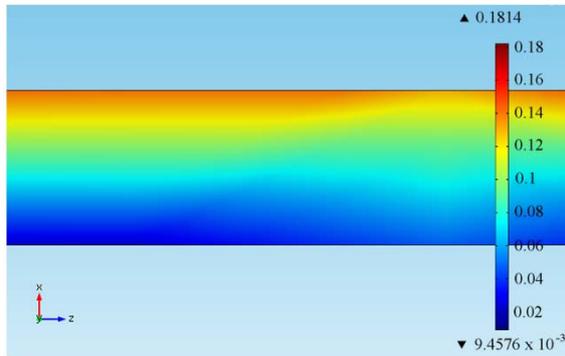


Figure 6. Profile of rate of methanol diffusing through the plate for 0.20 mm thickness.

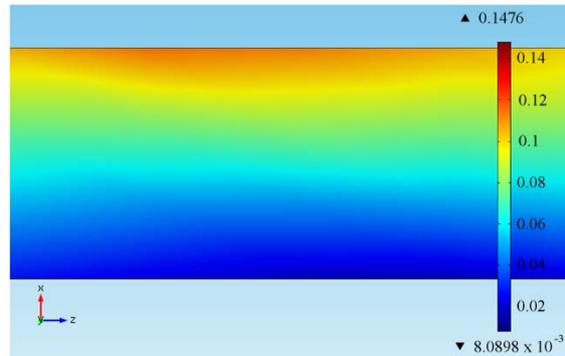


Figure 7. Profile of the methanol diffusion rate through a plate with 0.254.

3.2. Comparison between the rates of methanol diffusion

The rate of methanol diffusion for the plate thickness value of 0.13 mm in figure 8 is shown to have a total difference of 0.21 m/s, while the difference before methanol evaporation is 0.10 m/s. Whereas, the rate of methanol diffusion through a 0.254 mm thick plate in figure 9 is shown to have a total difference of 0.10 m/s and before methanol evaporation of 0.02 m/s.

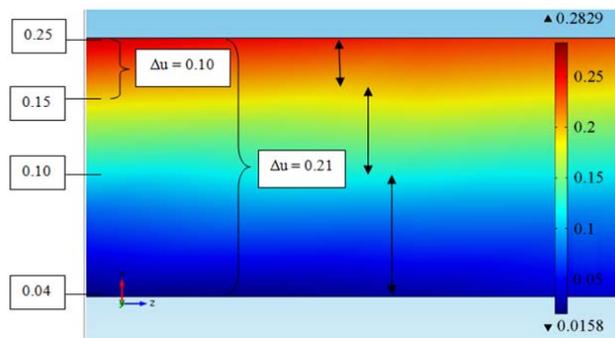


Figure 8. Detail information for the rate of methanol diffuse through the plate for 0.13 mm thickness.

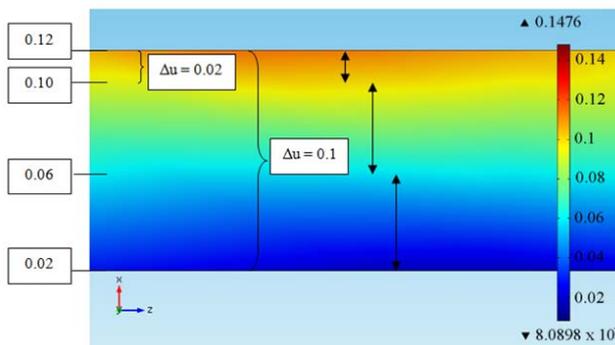


Figure 9. Detail information for the rate of methanol diffuse through the plate for 0.254 mm thickness.

From figure 8 -9, it can be deduced that the total difference in the rate of methanol diffusion and the difference in the rate of methanol evaporation for the thinner plate is larger. This indicates that the rate of methanol evaporation increases as the methanol diffusion along the thinner plate proceeds at a higher rate. Therefore, it can be concluded that plate thickness has a significant influence on the rate of methanol evaporation.

Figure 10 shows the relationship between the rate of methanol evaporation and the plate thickness. The graph shows that the rate of methanol evaporation is indirectly proportional to the plate thickness and the rate of methanol evaporation will increase with decreasing thickness of the plate. This trend is probably because the thinner the plate is, the less resistance is experienced by the methanol molecules that are being transported through the plate.

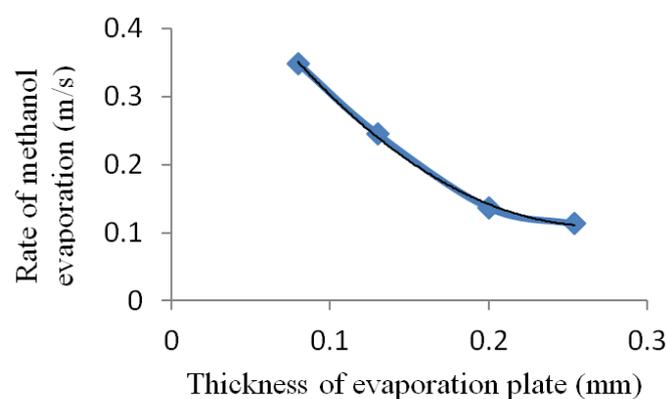


Figure 10. Rate of methanol evaporation versus the thickness of plate.

4. Conclusion

This paper reports the simulation study based on the performance of passive vapor feed DMFC operated with neat methanol as a fuel. The effect of the plate thickness on the rate of methanol evaporation was carried out. The rate of methanol evaporation is found to be inversely proportional to the plate thickness. Therefore, as the thickness of the plate decreases, the rate of methanol evaporation increases, and this will in turn improve the methanol vapor feed into the direct DMFC.

5. Acknowledgements

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6. References

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