

Vapor Delivery Systems for the Study of the Effects of Reformate Gas Impurities in HT-PEM Fuel Cells

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The reforming of methanol can be an alternative source of hydrogen for fuel cells because it has many practical advantages over hydrogen, mainly due to the technological limitations related to the storage, supply, and distribution of the latter. However, despite the ease of methanol handling, impurities in the reformate gas produced from methanol steam reforming can affect the performance and durability of fuel cells. In this paper different vapor delivery systems, intended to assist in the study of the effects of some of the impurities, are described and compared with each other. A system based on a pump and electrically heated evaporator was found to be more suitable for the typical flow rates involved in the anode feed of an H₃PO₄/PBI based HT-PEMFC unit cell assembly. Test stations composed of vapor delivery systems and mass flow controllers for testing the effects of methanol slip, water vapor, CO, and CO₂ are also illustrated. [DOI: 10.1115/1.4005123]

1 Introduction

It is well known by now that fuel cell technology is a potential game changer in the future of energy systems. Extensive work has been done to improve the reliability, durability, and cost of fuel cells, which are considered to be the main hindrances to their hitting the market in a larger scale. Some noticeable improvements have been achieved through the years, especially in the past decade, where, according to the U.S. Department of Energy (DOE), cost of production of fuel cells for transportation application had gone down from \$275 kW⁻¹ in 2002 to \$61 kW⁻¹ in 2009, and their lifetime was more than doubled in the same period [1]. However, it is clear that there is a need for standard test protocols in order to improve the level of uniformity of test conditions and provide a benchmark for fuel cell and fuel cell stack degradation and durability tests. DOE has released through the past years several test protocols, including accelerated stress test (AST) protocols, to assess the performance and durability of proton exchange membrane (PEM) fuel cell components for operations at temperatures below 100 °C [2]. DOE says that the protocols are not intended to be comprehensive, mainly because many issues critical to a transportation fuel cell (e.g., freeze/thaw cycles) were not addressed at the time of release of the protocols due to the design-specific nature of operating procedures. Even though these protocols can serve as guidelines for tests in other operation conditions, to the knowledge of the authors, there is no mention of dedicated

standard test protocols for higher temperature operations (above 100 °C).

This study is part of a series of planned experiments to test the effects of impurities on an H₃PO₄ doped PBI based high temperature proton exchange membrane fuel cell (HT-PEMFC). This is done assuming that an anode feed of hydrogen from the reforming of hydrocarbons is a cost competitive and infra-structurally more appealing solution compared to hydrogen storage. The anode feed gas, in this case, contains some impurities resulting from the reforming process. To investigate the effects of these impurities, which are basically all the constituents of a reformate gas other than H₂ gas, there is a need for a delivery system that simulates the anode feed gas from a reformer in a controlled manner. This is mainly because reformer technology is not yet mature enough, and therefore, it is easier and more reliable to control variations in the composition of reformate gas in a simulated environment than by controlling the operation conditions of a processor. The anode feed gas in the case of methanol reforming is composed of H₂, CO₂, water vapor, a small amount of CO, and unconverted methanol vapor.

Steam methanol reforming is an endothermic process shown in the reaction below, which takes place at temperatures of about 250 °C–300 °C. This has many practical advantages, including faster start-up and lower processor costs, with respect to the reforming of other hydrocarbon fuels, such as methane, which require temperatures of 800 °C–900 °C [3].



Vapor delivery, in addition to assisting in the investigation of effects of slips in HT-PEMFC, is important for the operation of some fuel cells. It is needed for the humidification of the anode feed gas to enhance the proton conductivity of some membranes, such as Nafion[®], the most commonly used membrane in low temperature proton exchange membrane fuel cells (LT-PEMFC). For this reason water management is a crucial part of system management in LT-PEMFCs. Proton conductivity, in this case, is strongly dependent upon the level of hydration of the membrane, other than its nanostructure. At low water contents, not all acid sites are dissociated, and the interaction among water molecules via hydrogen bonding is low, resulting in a low dielectric constant and low rate of proton transfer [4]. This calls for humidification, which is carried out by either external or internal humidifiers or simply by the water produced during the operation of the cell.

The interest in HT-PEMFCs is growing rapidly due to their advantages over LT-PEMFCs, such as improved reaction kinetics, improved catalyst tolerance to impurities, easier heat rejection, and simplified or no water management. For a more comprehensive reading the reader is directed to a review paper by Zhang et al. [5], where the numerous advantages related to operating a PEM fuel cell at temperatures above 100 °C and the challenges that can be encountered in doing so are discussed.

Proton transport in H₃PO₄/PBI-based HT-PEMFCs is enhanced by doping the PBI polymer in phosphoric acid as the name suggests. This makes humidification less of an issue, since phosphoric acid can conduct protons even in an anhydrous form, owing to its proton-solvating ability and self-ionizing behavior [6]. This is an advantage from a system design perspective, in which water management, a big part of design in LT-PEMFCs, is avoided. Nonetheless, water vapor, either introduced with the anode feed gas or formed on the cathode side and brought back to the membrane through back diffusion, is always present in the cell, and its effects need to be studied. Daletou et al. [7] in their description of the interaction between water vapor and an H₃PO₄-imbibed electrolyte PBI/polysulfone copolymer blend, saw that the permeation of water vapor through the membrane was more than that of the other gases in spite of the size of its molecules. They proposed that this was due to the solubility of water in phosphoric acid and its chemical interaction with the same compound in comparison to

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the other gases whose diffusivities through the doped membrane were negligible. This could bleach the phosphoric acid doping of the membrane, which if removed, being proton conduction media in a PBI based membrane electrode assembly (MEA) may cause reduction in the proton conductivity. Yu et al. [8] showed that phosphoric acid is mainly removed from the cathode side at higher temperature operations (180°C–190°C). On the other hand, there are studies that regard steam to have a positive effect on the performance of a phosphoric acid doped PBI membrane [7], with only steam formed in the cathode being sufficient to bring about the needed performance enhancement without any additional humidification of gases.

Regarding methanol vapor, in Ref. [9] it is reported that permeation via diffusion is the most dominating mechanism in PBI membranes, as the electro-osmotic drag coefficient of methanol was found to be zero. Effects of methanol on PBI membrane, however, still need to be investigated. It is suspected that it permeates through the membrane and electro-oxidizes on the cathode side, causing similar effects as hydrogen crossover.

2 Vapor Delivery Systems: An Overview

Vapor delivery for fuel cells can be carried out in different ways, among which the traditional bubbler systems, evaporator systems, water vapor effusing membranes, and nozzles can be mentioned. There are also cases where self-humidification from a fuel cell's operation brings about the necessary humidity level to prevent the drying out of humidity-dependent membranes. Moreover, there are numerous other solutions based on configurations that involve mass flow controllers. A liquid delivery system with vapor control, named Controlled Evaporator Mixer (CEM) is an example of a mass-flow-controller based apparatus from Bronkhorst® High-Tech. It is a system consisting of a liquid flow meter and a gas mass flow controller, each delivering their respective contents to the CEM unit, whose temperature is controlled by means of a heat exchanger. The system is said to be incomparably superior to bubbler systems [10], with the ability to deliver mixtures and the possibility to evaporate at much higher pressures than the atmospheric pressure.

In this work, vapor delivery is studied as a way to control the flow of a slip of unconverted methanol and water vapor in order to study their effect on an H₃PO₄/PBI based HT-PEMFC unit cell assembly. The other impurities in reformat gas, CO₂ and CO, are also objects of our research interests but are easily controlled using appropriate mass flow controllers. The research focus of the authors is the characterization of HT-PEMFCs; therefore, the study of vapor delivery was done with that perspective. However, it is possible that the study could be helpful for other applications as well.

For our purpose, a good vapor delivery system is defined as one with high precision, reproducibility of results, and simple and easy control of volume flow rates of the desired mixture of vapors.

In an attempt to simulate and investigate the poisoning effects of the constituents of a reformat gas on fuel cells, a number of studies were done on the effects of CO and CO₂ without taking into account the inevitable presence of methanol slip and water vapor in the anode feed gas. It is obvious that the inclusion of these vapors allows a more comprehensive study and simulates better the real life operation condition of a reformer - fuel cell system, as far as there is no processor that gives a 100% conversion of methanol. Moreover, the cost of processors increases with their conversion efficiency. In order to accomplish this comprehensive study, a controlled vapor delivery system is needed, and some attempts made at our laboratory to this purpose are described in the following sections.

2.1 Bubbler System. Bubbler systems are very common, and their performances with respect to vapor-delivery precision depend on their application. A bubbler system is composed of a

reservoir containing the liquid, whose vapor needs to be delivered and whose temperature is kept constant. A carrier gas is allowed to flow through this reservoir, and it takes up the vapor in the direction of where it needs to be delivered, which, in our case, is the anode feed stream of the fuel cell. Vapor delivery systems can also work without a carrier gas, where vapor flow in the outlet is either controlled by the vapor pressure of the liquid at a controlled temperature and manually restricting the flow in the outlet or, simply, by putting a mass flow controller in the outlet [10]. Many configurations were suggested to optimize bubbler systems, and a number of patent claims have been made on controlled vapor delivery using bubbler systems [11–15].

The complexity of the operation of a bubbler system increases with the need for more precision in the required vapor delivery. In a highly demanding vapor delivery, the parameters to control can include the temperature of the liquid, the pressure of the vapor at the headspace above the liquid, the temperature and flow rate of the carrier gas, the absorption rate of the vapor of the liquid into the carrier gas. This interaction between the liquid and the carrier gas at its time depends on the relative size of bubbles, the residence time of the carrier gas in the liquid, the temperature of the liquid, and the stability of the carrier gas flow into the reservoir where the liquid resides [16].

The relationship among these factors is expressed in Eq. (1) as reported in Ref. [13].

$$\dot{m} = F_c \cdot \frac{\alpha \dot{p}}{P_h - \dot{p}} \cdot \overbrace{f_x(F_c, T, L)}^{\text{correction factor}} \quad (1)$$

where \dot{m} is the vapor carryover, F_c is the carrier gas flow rate, P_h is the pressure of vapor at the headspace above the liquid, \dot{p} is the vapor pressure of the volatile liquid, α is a constant of the liquid, and f_x is an empirical correction factor. The correction factor at its time is a function of the bubbler temperature T , the liquid level in the bubbler L , and F_c , which add up to the already many factors influencing the vapor carryover. The Antoine equation shown in Eq. (2) can be used to calculate the vapor pressure, \dot{p} , of the liquid.

$$\log \dot{p} = A - \frac{B}{T + C} \quad (2)$$

where A , B , and C are component specific thermodynamic constants of the liquid. It can be seen from Fig. 1 that the vapor pressure of a liquid is strongly dependent on its temperature, which calls for a very strict temperature control for a bubbler system to work properly.

For low flow rates, like that of impurities in single cell tests, we can assume a linear trend between the carrier gas flow rate and the

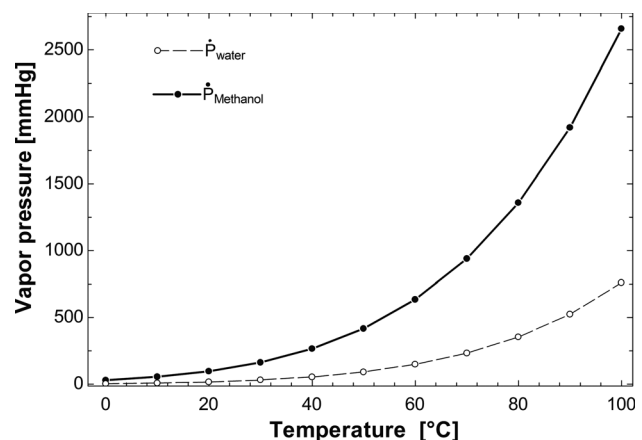
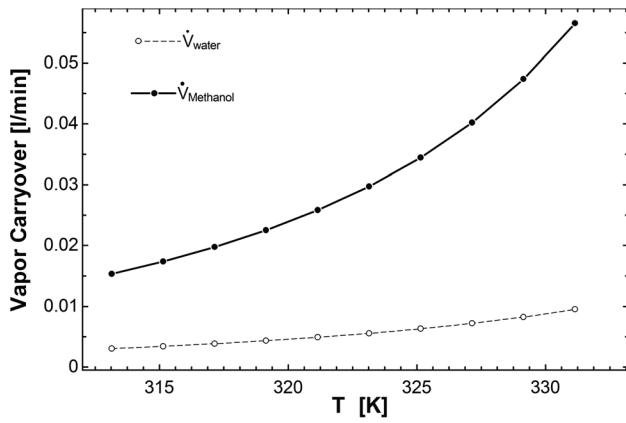
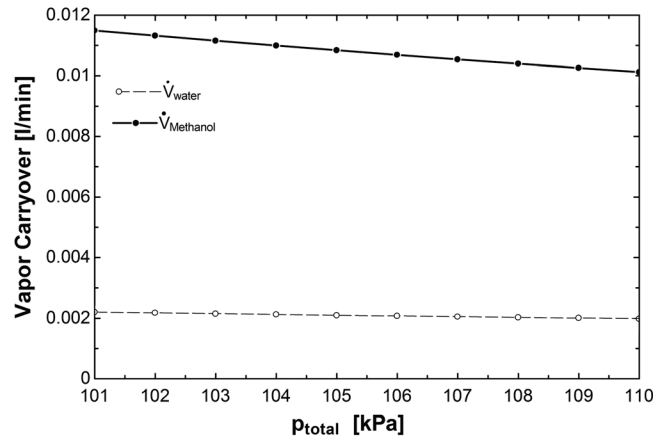


Fig. 1 Vapor pressure of methanol and water as a function of temperature



(a) Vapor carryover as a function of temperature



(a) Vapor carryover as a function of head-space pressure

Fig. 2 Dependence of vapor carryover on temperature and pressure in the case of a bubbler system

vapor carryover. This assumption is made based on the work of Love et al. [17], where we can see that the dependence between the carrier gas flow rate and vapor carryover for isothermal conditions deviates from its linearity only for carrier gas flow rates above 300 ml/min or 300 SCCM (note that SCCM denotes cubic centimeters per minute at standard temperature and pressure). This means that we can ignore the empirical correction factor f_z in Eq. (1), which takes into account the non-linear behavior due to changes in temperature caused by the evaporative heat losses. In doing so, it is assumed that there is enough residence time and enough liquid content to fully humidify the carrier gas and that the vapor carryover is independent of the liquid level in the reservoir, and thus, of the evaporative heat loss. Even though bubbler systems are claimed to suffer from poor reproducibility and the inability to deliver mixtures [10], the aim of the test is to see if these issues are minimized for lower flow rates with a lower number of controlling factors.

Equation (1) can, therefore, be reduced to Eq. (3) for carrier gas flow rates below the stated limit of 300 ml/min, where the typical flow rates of impurities in a unit cell also lie.

$$\dot{m} = F_c \cdot \frac{\dot{p}}{P_h - \dot{p}} \quad (3)$$

If the bubbler system is operated at atmospheric pressure and the temperature of the liquid is somehow kept constant, the vapor delivery is controlled by only controlling the carrier gas flow rate.

For an H₂/air unit cell assembly, flow rates were calculated based on the operation conditions of the planned tests. H₂ consumption of a fuel cell can be calculated from Faraday's law.

$$\dot{N}_{H_2} = \frac{I}{n \cdot F} \quad (4)$$

where \dot{N}_{H_2} is the hydrogen consumption [mol⁻¹], I is current [A], n are moles of electrons exchanged per mole of species, and F is Faraday's constant [96485 C mol⁻¹]. Coupling Eq. (4) with the ideal gas law and multiplying the result by the stoichiometric ratio gives the actual total volume consumption of H₂ gas. These steps are given by Eqs. (5) and (6).

$$\dot{V}_{H_2} = \dot{N}_{H_2} \cdot \frac{RT}{P} \quad (5)$$

$$\dot{V}_{H_2, total} = \lambda_{H_2} \cdot \dot{V}_{H_2} \quad (6)$$

where R is the gas constant [8.314 kJ kmol⁻¹ K⁻¹], T is temperature [K], P is pressure [kPa], and λ_{H_2} and λ_{air} are H₂ gas and air stoichiometric ratios, respectively.

The rest of the anode feed gas composition is then calculated based on the total volume flow of H₂ and on guesses of typical percentages of impurities found in reformat gases during real life operation of a reformer. Total volume flow of air can be calculated in the same way, but it is not of interest in the current study because there is no need for vapor delivery on the cathode side.

For the simulation of the overall flows, a model was prepared in Engineering Equation Solver (EES). It is based on the Non Random Two Liquid (NRTL) method, and it predicts the vapor pressures of water and methanol in a mixture at a given temperature and concentration. Based on the vapor pressures of the mixture, it then calculates the vapor carryover at a given temperature and pressure condition and carrier gas flow rates. The interaction coefficients used in the model for water and methanol are valid from 40 °C to 80 °C.

For our unit cell assembly of a total active cell area of 45 cm², λ_{H_2} of 1.2 and λ_{air} of 4 were taken. Considerations on the values of stoichiometric ratios were made based on compromises related to the real life operation conditions of a fuel cell, i.e., between the need for higher efficiency and lower mass transport losses [18]. Moreover, a fuel cell current of 15 A was used. Since the active cell area is 45 cm², the current density used for our calculation is 0.33 A cm⁻². The total volume flow of H₂ gas obtained was considered to be 70% of the total anode feed gas, and the remaining constituents were varied because plans are to do characterization tests at different compositions of impurities.

A carrier gas flow rate of 20% of the total anode feed gas flow rate was used to calculate the vapor carryover from a reservoir containing a 0.5 M solution of methanol in water, and simulations were made for different temperature and pressure conditions. Due to the stronger dependency of the vapor pressure of liquids on temperature, it was seen that the vapor carryover changes more with temperature than with head-space pressure. In Fig. 2(a), plotted at atmospheric pressure operation, it can be seen how methanol, which has a higher vapor pressure than water, is carried away faster. This gap between the amount of vapor carried over for the two species increases with temperature. This is one of the major drawbacks of bubblers as vapor delivery systems for mixtures of two or more liquids.

Figure 2(b) shows the dependence of the vapor carryover on the head pressure. It can be seen that this dependence is negligible, allowing us to focus only on the control of temperature, thereby simplifying the system control.

2.1.1 Experimental Setup. Based on the model above, a bubbler system was prepared in our laboratory to test the effects of the constituents of a reformat gas on an H₃PO₄-doped PBI membrane-based HT-PEMFC.

In Fig. 3 a test station for investigating the effects of impurities in a HT-PEMFC unit cell assembly is illustrated. In this setup, a bubbler system was used for the delivery of the vapor mixture of impurities. All components, including the bubbler system, are controlled and monitored by a computer running a control and data acquisition program written in LabVIEW. The bubbler, based on the assumptions made above, is controlled by controlling the temperature and carrier gas flow rate. The remaining volume flow rates are then calculated accordingly. The program measures the temperature of the liquid in the reservoir, compares it to the set temperature in the LabVIEW and then controls the heating power so that the two temperatures match and that the temperature in the reservoir is kept constant. This is a very crucial task for the proper functioning of the system but, at the same time, is very difficult to control as it is hard to account and compensate for all the heat transfers with only a heating element.

A mass flow controller, monitored and controlled in LabVIEW, delivers the desired amount of carrier gas. This gas, which is chosen to be CO₂ in our case but could have been H₂ or other inert gases as well, enters from the bottom of the reservoir and, by passing through the liquid, absorbs and carries up vapor. The vapor is then led to a stream of other gases, H₂ and CO, which are delivered by other mass flow controllers for a complete representation of a methanol reformat gas stream. Since the head space of the bubbler is assumed to be at atmospheric pressure condition, the LabVIEW control program controls the bubbler by only controlling the mass flow controller that releases the carrier gas necessary for the desired vapor delivery at a fixed temperature.

Experiments were run for few days at varying temperatures and carrier gas flow rates. Two measuring techniques were tried simultaneously, one in which a condenser was placed at the exit of the reservoir and another one where a transparent plastic tube

was placed next to the reservoir to show the level of the liquid. The results had no real trend, and therefore, the comparison between the two and to the expected estimates was not possible. This confirms the fact that bubblers do suffer from a lack of reproducibility [10], and this is the case even for low flow rates (< 300 ml/min). The reason for this could be that the assumptions made are too many, or perhaps the temperature control did not keep the liquid temperature within admissible fluctuation ranges. The fluctuation measured was less than 2°C, and temperature being the main parameter causing irreproducibility, this shows how stringent temperature control is as a factor in bubbler systems.

The model could probably be validated by means of more sophisticated gas analysers or mass spectrometers. This would, however, nullify the advantage of a very cheap in-house preparation and control for which bubbler systems were considered for the study. The scope of the study was to achieve a cost effective, simple, and at the same time precise and reproducible vapor delivery for the range of typical flow rates of impurities in a unit cell assembly. The experiment showed, though, that bubbler systems do not fulfill these requirements.

Therefore, another solution based on a dosing pump and an electrically heated evaporator was tested. The system is described in the following section.

2.2 Evaporator System. As an alternative to bubblers for the delivery of methanol and water vapor in a simplified and precise way, a Grundfos DME dosing pump was tested. Downstream of the pump is placed an electrically heated evaporator that boils all the mixture of liquids or the pure liquid passing through it. The pump is a self-priming diaphragm pump, and both the pumps

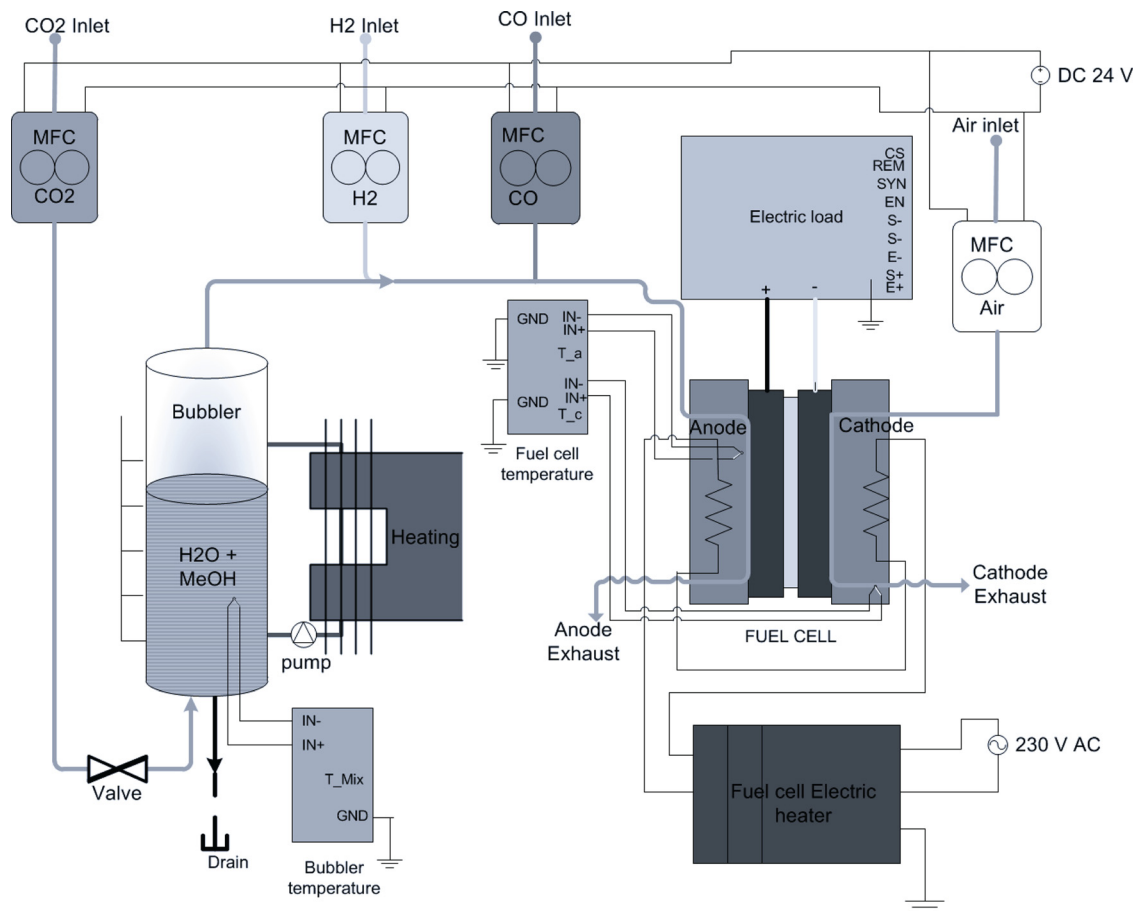


Fig. 3 HT-PEMFC unit cell test setup with a bubbler system for vapor carryover

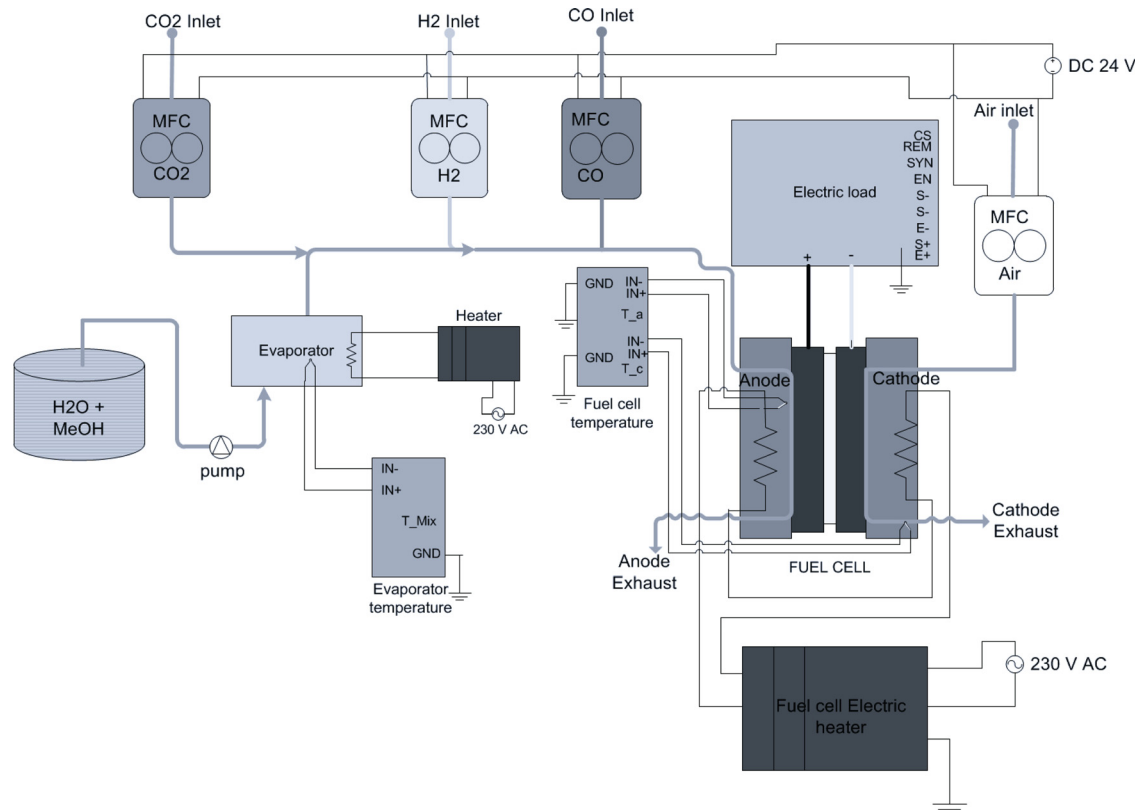


Fig. 4 HT-PEMFC unit cell test setup with an evaporator system for vapor carryover

suction strokes and the heating of the evaporator are controlled in LabVIEW. Figure 4 illustrates the new experimental setup with a vapor delivery system based on the pump and the evaporator. The dosing pump pumps the liquid mixture from the reservoir to the evaporator, which is kept at constant temperature, well above the boiling point of either of the liquids, of around 150 °C. The vapor is then directed to the anode inlet along with a stream of the other gases composing the reformat gas, H₂, CO₂, and CO. The flow rates of these gases are controlled by appropriate mass flow controllers.

A mixture of water and methanol does not form an azeotrope, meaning there is no composition ratio in which the boiling point of the solution is higher or lower than either of the pure liquids. This allows validation experiments to be carried out with water alone and conclusions to be drawn from the mixture. This is possible because the boiling point of the solution, at any composition, lies in the temperature range between 64.6 °C–100 °C, which are boiling points of methanol and water at atmospheric pressure, respectively. Therefore, tests were performed with water alone, and they showed that with a pump that allows such small liquid flow rates there is satisfactory vapor carryover. There is, though, a very little risk of condensation when the flow rates and the distance to the fuel cell increase.

The heating power needed to boil the liquid flowing through the evaporator can be calculated by using Eq. (7).

$$P = q\rho c\Delta T \quad (7)$$

where P is the required heating power [kW], q is the liquid flow rate [m^3s^{-1}], ρ is the density of liquid [kg m^{-3}], c is the specific heat capacity of liquid [$\text{kJ kg}^{-1} \text{K}^{-1}$], and ΔT is the temperature difference between the reservoir and the evaporator [K].

As in the case of the bubbler system, the temperature of the evaporator is continuously monitored, and the heating power is regulated by comparing the measured temperature with the temperature set in LabVIEW. This way, temperature is kept constant,

and a continuous flow of vapor is ensured. Unlike in the case of the bubbler system, here temperature control is not so crucial because it is set high above the boiling point of water.

The same operation conditions as in the setup with the bubbler system and the same considerations on hydrogen consumption and impurities proportions were considered. The volume flow rate of the methanol-water mixture was taken to be 10% of the total anode feed gas, the equivalent of 0.025 ml/min in liquid phase. Tests were performed for liquid flow rates of up to 0.05 ml/min for eventual operation of the same unit cell assembly at higher fuel cell current densities. It was observed that all the liquid boiled and was carried away as vapor. A special attention, though, needs to be paid to the length and insulation of tubes that take the vapor from the evaporator to the fuel cell because temperature drop at the exit from the evaporator may cause condensation. The length of the tubes need to be minimized, and they need to be well insulated, as the condensation may enter a non-operating fuel cell and bleach the acid doping of the PBI membrane. This is however facilitated by the fact that the temperatures of the evaporator and an operating HT-PEMFC are very similar, and the two can be placed as close to each other as possible and thereby avoid heat loss between them.

Medium flow rates between 0.08 ml/min and 0.5 ml/min were also tested and results showed that there is good vapor carryover in this range as well. This makes such a vapor delivery system a suitable candidate not only for unit cell testing at higher current densities and higher stoichiometric ratios but also for small fuel cell stack testing.

Finally tests were done for higher flow rates of liquid flow rates of above 3 ml/min, where a slow temperature drop down to below the boiling point of water was registered. This temperature would then remain constant at a couple of degrees Celsius below the boiling point of water and cause the dripping of water droplets along with the vapor. However, these flow rates are way above the typical liquid mixture flow rates necessary for single cell tests, and hence, the use of the evaporator system is suitable enough for

Table 1 Observation on the performance of the evaporator system

Liquid flow rates [ml/min]	Application	Vapor carryover
0.025–0.05	Unit cell testing at low stoichiometry	No condensation
0.08–0.5	Unit cell at high stoichiometry and small stacks testing	No condensation
≥3	Fuel cell stack testing	Condensate formation

the study of the effects of methanol and water vapor slips in H_3PO_4 /PBI based HT-PEMFC unit cell assembly. These observations are summarized in Table 1. Vapor carryover without condensation may be achieved even for these flow rates by increasing the size of the evaporator and the heating power supplied.

3 Discussion

From assumptions made based on the literature on bubbler systems, the non-linear function, which relates the different factors controlling the vapor carryover, can be simplified into a linear function that depends only on the flow rate of the carrier gas and the temperature of the volatile liquid. The assumptions made are that the operating pressure is the atmospheric pressure and that the flow rates are low enough to justify linearity of such function. Validation of the model, however, is not an easy task because the flow rates of interest are very small, and it takes a long time to perceive vapor carryovers with the naked eye. This makes it difficult to collect data for model validation.

An evaporator system on the other hand, consisting of a Grundfos DME dosing pump and a simple evaporator, is easier to control and more suitable for the delivery of methanol and water vapor into an H_3PO_4 /PBI based HT-PEMFC unit cell assembly. It is easier to validate because there are less parameters to control unlike bubblers, where the factors affecting the system's precision are many. Moreover, an evaporator system does not suffer from a lack of reproducibility, which makes it more reliable with respect to the bubbler system. Even though this solution is more costly due to the involvement of mainly a relatively high precision dosing pump, it can be considered a more suitable solution from a practical stand point. The temperature control is not crucial, as it is kept high above the boiling point of the liquid mixture. Another practical advantage is the fact that it is easier to control the delivery of single phase liquid, which then evaporates completely, than to directly deal with two phases, both liquid and vapor mixtures in one reservoir as in the case of the bubbler system.

A good vapor carryover obtained for medium-range liquid flows makes the vapor delivery system based on pump and evaporator suitable, not only for unit cell assembly but also for tests on small fuel cell stacks.

4 Conclusion

This paper has examined the use of vapor delivery systems to assist in the study of the effects of some of the reformat gas

impurities present on an H_3PO_4 /PBI based HT-PEMFC unit cell assembly.

It can be concluded that the reformat anode feed gas can be simulated by means of a system comprising a vapor delivery system and mass flow controllers. A vapor delivery system comprising of a dosing pump and an evaporator is found to be more suitable for this purpose. It allows easy control of vapor contents, and, combined with easy control of the gaseous species via mass flow controller, it makes a valuable unit cell testing station. This is important as the reformer technology itself is not mature, and therefore, vapor delivery systems to simulate different compositions of anode feed gas are needed for testing the effects of reformat impurities in a fuel cell. It has the advantage of a better control over the composition of the feed gas compared to when reformat is supplied from a reformer because all controls and monitoring can be done in a computer running LabVIEW. This way the effects of the constituents of a reformat gas can be studied under various conditions and at different concentrations.

References

- [1] U.S. Department of Energy, 2011, "Fuel Cell Technology Challenges," http://www1.eere.energy.gov/hydrogenandfuelcells/fuelcells/fc_challenges.html
- [2] Garland, N., Benjamin, T., and Kopasz, J., 2007, "DOE Fuel Cell Program: Durability Technical Targets and Testing Protocols," *ECS Transactions*, **11**(1), pp. 923–931.
- [3] Methanex Corporation®, 2006, "Technical Information and Safe Handling Guide for Methanol."
- [4] Choi, P., Jalani, N. H., and Datta, R., 2005, "Thermodynamics and Proton Transport in Nafion," *J. Electrochem. Soc.*, **152**(3), pp. E123–E130.
- [5] Zhang, J., Xie, Z., Zhang, J., Tang, Y., Song, C., Navessin, T., Shi, Z., Song, D., Wang, H., Wilkinson, D. P., Liu, Z.-S., and Holdcroft, S., 2006, "High Temperature PEM Fuel Cells," *J. Power Sources*, **160**(2), pp. 872–891.
- [6] Yan, L., Zhu, S., Ji, X., and Lu, W., 2007, "Proton Hopping in Phosphoric Acid Solvated Nafion Membrane: A Molecular Simulation Study," *J. Phys. Chem. B*, **111**(23), pp. 6357–6363.
- [7] Daletou, M. K., Kallitsis, J. K., Voyiatzis, G., and Neophytides, S. G., 2009, "The Interaction of Water Vapors With H_3PO_4 Imbibed Electrolyte Based on PBI/Polysulfone Copolymer Blends," *J. Membr. Sci.*, **326**(1), pp. 76–83.
- [8] Yu, S., Xiao, L., and Benicewicz, B. C., 2008, "Durability Studies of PBI-based High Temperature PEMFCs," *Fuel Cells*, **8**(3–4), pp. 165–174.
- [9] Li, Q., Jensen, J. O., Savinell, R. F., and Bjerrum, N. J., 2009, "High Temperature Proton Exchange Membranes Based on Polybenzimidazoles for Fuel Cells," *Prog. Polym. Sci.*, **34**(5), pp. 449–477.
- [10] Boer, H., 1995, "Mass Flow Controlled Evaporation System," *J. Phys. IV*, **05**(C5), pp. 961–966.
- [11] Lynch, B., Narasimham, P. L., and Partus, F. P., 1986, "Methods and Apparatus for Vapor Delivery Control in Optical Preform Manufacture," U.S. Patent No. 4,582,480.
- [12] Mcmenamin, J., 1984, "Vapor Mass Flow Control System," U.S. Patent No. 4,436,674.
- [13] Mcmenamin, J., 1983, "Vapor Mass Flow Control System," U.S. Patent No. 4,393,013.
- [14] Partus, F., 1980, "Vapor Delivery System and Method," U.S. Patent No. 4,220,460.
- [15] Ross, E., 1977, "Saturated Liquid/Vapor Generating and Dispensing," U.S. Patent No. 4,051,886.
- [16] Karlicek, T. A., and Lee, D. H., 2008, "Considerations in the Selection of Vapor Delivery Sub-Systems," *Gases and Instrumentation*, **2**.
- [17] Love, A., Middleman, S., and Hochberg, A. K., 1993, "The Dynamics of Bubblers as Vapor Delivery Systems," *J. Cryst. Growth*, **129**(1–2), pp. 119–133.
- [18] Andreasen, S. J., Mosbæk, R., Vang, J. R., Kær, S. K., and Araya, S. S., 2010, "EIS Characterization of the Poisoning Effects of CO and CO₂ on a PBI Based HT-PEM Fuel Cell," ASME 28th International Conference on Fuel Cell Science, Engineering and Technology, **1**, pp. 27–36.