Experimental investigation of dynamic responses of a transparent PEM fuel cell to step changes in cell current density with operating temperature [†]

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Abstract

The dynamic responses of a proton exchange membrane fuel cell (PEMFC) are closely related to the novel water management technique used for the efficient operation of automotive PEMFCs. In order to better understand the dynamic water transport during cell transients, this paper presents an experimental investigation of the transient response of a cell under fully humidified conditions. The cell dynamic performance was measured by employing a transparent cell and investigated with visualization images of the water distribution in the flow channels. Furthermore, the effect of the operating temperature on the cell transients was examined. The results show that the cell dynamic behavior for the tested operating temperature (30-50 ℃) conditions is mainly governed by water transport characteristics related to cathode flooding. Also, we show that the time needed for the cell to reach steady-state after a current density step increase is retarded due to excessive water accumulation inside the cell at lower operating temperatures.

Keywords: Dynamic response; Fuel cell; Water transport; Transparent cell; Flow channel; Operating temperature

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1. Introduction

In recent years, proton exchange membrane fuel cells (PEMFCs) have attracted significant attention as efficient and clean power sources in both mobile and stationary applications. In particular, the main reasons for the heightened interest in PEMFCs are due to their low temperature operation, rapid start-up capability, high-power density, low noise operation, and ultra-low pollution. Currently, PEMFCs are considered to be viable candidates for powering next-generation vehicles (in a future hydrogen economy) that can replace the traditional internal combustion engine by reducing CO_2 emission and improving power-train efficiency [1]. Therefore, research on PEMFCs has been of great interest among fuel cell researchers and engineers from automotive industries worldwide. Accordingly, intensive studies have been performed to achieve the best performance and highest power density from the PEMFCs for automotive use.

However, in order to successfully commercialize automotive PEMFCs, there are still some technical challenges to overcome. Along with performance and durability issues, the water management of PEMFCs (related to proper humidification of the membrane and the efficient removal of excessive product water, etc.) is regarded as one of the major issues because of PEMFCs' moderate working temperatures (60 – 90℃). Actually, liquid water transport still constitutes a basic, significant barrier to improved performance and efficiency of automotive PEMFCs. To enhance fuel cell performance and efficiency, a novel water management technique should be established that can effectively prevent both local membrane dehydration and flooding in the flow channel, gas diffusion layer (GDL), and electrode.

Moreover, the transient response of a PEMFC be-

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comes a critical issue, particularly in automotive applications, because the cells undergo large and frequent variations in load during vehicle operation. This transient response is caused by a sudden power demand when a vehicle is accelerated or decelerated [2]. Therefore, a fundamental insight into the dynamic behavior (in the case of sudden changes in current density and cell voltage) of the PEMFC is of paramount importance for the optimization of system component design and operating strategy and robust control of the automotive fuel cell system [3]. However, transient phenomena are still poorly understood at present because of the complex nature of the various time scales of PEMFCs. It is generally recognized that the PEMFC performance during transients is governed directly by the charging/discharging of the electrochemical double layer, reactant gas transport, membrane water uptake, and heat transfer. The PEMFC exhibits a relatively good transient response under fully humidified operating conditions. However, in some situations, the time scale of the PEMFC in an actual fuel cell is significantly longer (order of minutes) than expected [4]. This may be due to the combined effect of slow membrane hydration/dehydration, liquid water transport in the GDL, and heat transfer processes [4]. Therefore, it is a challenging design and operational issue for water management to understand water transport and its distribution throughout the PEMFC during transients in order to achieve optimized performance and efficiency.

According to a review of the literature, most of the studies on water and heat management focus on the steady state operation of PEMFCs. Although there are some previous studies on the transient behavior of the PEMFCs, most of the studies conducted up to now are concentrated on the modeling of water transport [3-12] and an experimental investigation of the dynamic behavior, such as overshooting or undershooting in fuel cell performance (current-voltage characteristics) [2, 13-15] under normal fuel cell operating temperatures (above 60°C). However, there exist almost no experimental studies focusing on an in-situ investigation of liquid water transport during the transient operation of a PEMFC.

Moreover, PEMFCs for automotive use should also exhibit robust characteristics with a rapid response with respect to load changes (such as those occurring during start-up and shut-down of the fuel cell system for lower operating temperature conditions). Systematic research on the transient response of PEMFCs at these lower operating temperature conditions needs to be done. However, to the authors' knowledge, no experimental studies have been presented so far. Actually, under the aforementioned conditions, the standard modeling approaches have some basic limitations and are not readily applicable because of the complex two-phase nature of water transport inside the cell. In spite of the recent progress in various experimental techniques on the investigation of liquid water in fuel cells, some experimental methods have problems concerning limited time resolution under dynamic load conditions [15]. Also, it is not sufficient to characterize the physicochemical processes associated with two-phase transients only by using widely adopted techniques, such as current-voltage curves and electrochemical impedance spectroscopy (EIS) [15].

The purpose of the present study is to provide an additional experimental investigation of the transient response of a fully humidified cell in terms of dynamic water transport in a flow channel and GDL top surface under lower operating temperature conditions (30 – 50°C). For this purpose, the transient cell voltage responses to a step change in the cell current are obtained by employing a transparent single fuel cell that enables the visualization of the liquid water distribution in a cathode flow channel under different operating temperatures. First, the cell voltage response after a step increase or decrease in the current density is investigated in terms of the time constant for gaseous species diffusion. Then, visualization images of the water distribution in the flow channels during the current step change for three different operating temperatures are presented, along with transient cell voltage output data. Finally, the effect of the operating temperature on the cell dynamic performance is discussed in terms of the water transport characteristics inside the fuel cell.

2. Experimental

2.1 Transparent fuel cell

Fig. 1 shows a schematic representation of the transparent unit fuel cell used for this study. In this study, a single cell with an active surface area of 25 cm^2 was tested. The acrylic cover plate on the cathode side was machined and used as a transparent plate to visualize the water droplet images in cathode flow channels and on the GDL top surface. The cathode flow fields were made of graphite and were machined
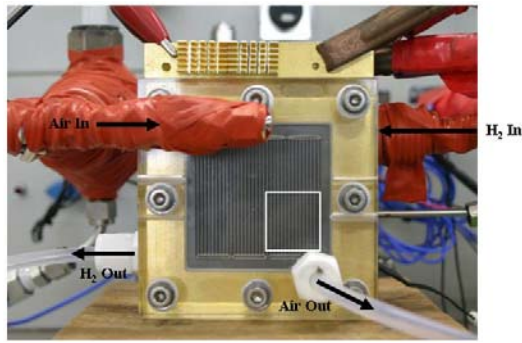
Fig. 1. Schematic representation of the transparent unit fuel cell used for this study.

into a thin plate with a thickness of 1 mm. The cathode flow channels had the following dimensions: 35 channels of width 0.7 mm, separated by 0.8 mm wide ribs. The flow fields were parallel-serpentine on the both cathode and anode sides. To provide efficient mass transfer characteristics, anodic and cathodic gases were supplied into the fuel cell in a counter-flow mode, as depicted in Fig. 1. The proton exchange membrane (PEM) used was Nafion® 112 (which has a thickness of 50 m), and the platinum catalyst loading on each electrode side was 0.4 mg cm^{-2}. To ensure a good electrical connection, a current collector (made of gold-coated brass) was applied on each side (cathode and anode).

2.2 Fuel cell test system

The fuel cell test bench was composed of five main parts, including a humidification unit, flow rate control unit, gas supply system, temperature control unit, and electronic load unit. Ultra-high purity hydrogen (99.999%) and high purity air (99.9%) were used as reactant gases on the anode and cathode sides. The mass flow rates of each gas were controlled by two digital mass flow controllers. To humidify the supplied gases, a bubbler-type humidifier was employed. It can provide temperature-controlled humidification by regulating the temperature of the supplied gases that enter the humidification bottles. The temperatures of the gas feeding line, fuel cell, and humidifier were regulated by PID-type temperature controllers. The total pressure of the supplied gases was maintained by using back-pressure regulators.

Current-voltage (*I-V*) curves were obtained with an electronic load system that was controlled by a personal computer. Experimental parameters such as the

Table 1. Details of the operating conditions used for this study.

Case	Temperature (°C)	Relative humidity	Stoichiometry (Air / H$_2$)	Pressure (atm)
Case 1	30	Fully humidified	2.0 / 1.2	1
Case 2	40	Fully humidified	2.0 / 1.2	1
Case 3	50	Fully humidified	2.0 / 1.2	1

temperature, flow rate, relative humidity of the supplied gases, along with the cell temperature, etc. were recorded by using a user-friendly self-developed LabVIEW™-based data acquisition system used for the data analysis.

2.3 Test conditions and procedure

The test conditions for transient operation of the transparent unit fuel cell are summarized in Table 1. The transient responses of a PEMFC are generally influenced by various operating parameters such as temperature, pressure, flow rate (stoichiometry) of the reactant gases, and the degree of humidification of the reactants, etc. In this study, the operating temperature was selected as a main operating variable of interest. In order to solely investigate the effect of the operating temperature on the transient response of the PEM fuel cell, other operating parameters (stoichiometric ratio, operating pressure, relative humidity etc.) were held constant during all the experiments. Prior to a new run, the operating temperature was changed in advance to achieve the stabilized cell performance.

The air and H$_2$ were introduced to the single cell at a constant flow rate for a given operating temperature. The cathodic and anodic gases were supplied at ambient pressure during all the experiments. The gases were supplied at fully humidified conditions. For this, the humidification temperature of the gas bubbler was set equal to the cell temperature. To avoid the condensation of water inside the lines, the gas feeding lines between the humidifiers and fuel cell inlets (Air and H$_2$) were heated to a temperature that is 5 - 7°C higher than the humidification temperature of the bubbler. During all the experiments, the temperature and relative humidity of the supplied gases were monitored in-situ at the inlet of the fuel cell.

At a current density of 0.6 A cm^{-2}, the stoichiometric ratio of air was set equal to 2.0 and the stoichiometric ratio of H$_2$ was set equal to 1.2.

The MEA underwent an activation process to ensure stable cell performance. The step change in cur-

rent density was made according to the cell current profile described in Fig. 2. The main steps of the adopted fuel cell operation procedure for the dynamic response experiments were as follows:

- The single cell was maintained at open circuit voltage (OCV) for 5 min.
- The current density of the cell was increased by 0.05 A cm^{-2} per second until the current density reached 0.3 A cm^{-2}.
- The cell was operated at a current density of 0.3 A cm^{-2} and the cell voltage was logged at a rate of 100 Hz. The current density of the cell was stepped to 0.6 A cm^{-2}.
- The cell was maintained at a current density of 0.6 A cm^{-2} for 5 min. The cell voltage data were recorded at a rate of 100 Hz.
- The current density was abruptly decreased from 0.6 to 0.3 A cm^{-2}.
- At the end of each run, nitrogen gas was supplied into the single cell to minimize the effect of prior cell operating conditions.

To record the water distribution images in the flow channels during cell transients, a digital camera (Lumenera) equipped with macro lens (Nikon) was used. The marked zone in the cathode flow channels of Fig. 1 was chosen as the main visualization area because this zone would be likely to correspond to the main flooding area. During the experiments, the images were taken at a time interval of 1 s.

2.4 Time constants for PEMFCs

To be used for automotive applications, the PEMFCs need to respond to load changes rapidly. It is quite important to understand the cell dynamic response in terms of the time response in order to further the research on automotive PEMFCs. The time response of a PEMFC is generally governed by
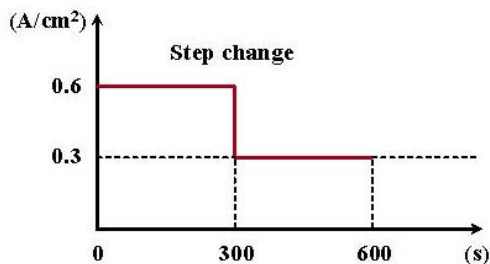

Fig. 2. Current density profile adopted for the experiment on the transient response of a PEM fuel cell.

three main processes: the charge/discharge process of the electric double layer in the catalyst layer, gaseous species transport in the GDL, and membrane hydration/dehydration [7]. It is well known that the undershoot/over-shoot behavior is closely related to the time response of a change in the cell operating conditions [5, 7].

The time constant of the charge/discharge of the electrochemical double layer can be expressed as

$$\tau_{cd} = \delta_{CL} A C \left(\frac{1}{\sigma_s} + \frac{1}{\sigma_m} \right) \tag{1}$$

where δ_{CL} is the catalyst layer thickness, A is the effective specific reactive surface area, C is the electric capacity, and σ_s and σ_m are the electrode and electrolyte conductivity. The time constant describing the charging or discharging of the electrochemical double layer is estimated to be 1.5×10^{-7} according to the normal parameters reported by Ref. [7]. This value is small enough to be ignored in the dynamic modeling work done on automotive PEMFCs.

The time constant of the gaseous species diffusion in the GDL can be evaluated as [16]

$$\tau_{di} = \frac{\delta_{GDL}^2}{D_g^{eff}} . \tag{2}$$

where δ_{GDL} is the GDL thickness and D_g^{eff} is the effective gas diffusivity. Using the typical GDL thickness and effective gas diffusivity (based on a Bruggeman correlation), the time scale of the gas diffusion in the GDL is on the order of $0.1 - 1$ s, as reported in Ref. [16].

The time constant associated with membrane hydration/dehydration is related to transient water transport. It is thought that the transient water transport was mainly influenced by two main factors. One factor is the membrane hydration/dehydration response to changes in the cell operating conditions. The other is electrode flooding resulting from excessive water produced under high current density operating conditions. These two factors are associated with complicated two-phase water transport processes inside the cell. Since these two factors are relatively slow processes, they have a dominant influence on the dynamic cell performance. For example, for the case of a dry

membrane being hydrated by water generated at a constant current density of (1 A cm^{-2}), the time constant for water accumulation in the membrane is about 25 s for Nafion® 112 at 30°C, as presented in Ref. [5].

The time constants describing gaseous transport and membrane hydration/dehydration are sufficiently long and are closely linked to water transport characteristics. It can be said that these factors play quite an important role in determining the cell dynamic performance [7]. Therefore, the quantitative evaluation of the key time constants under various operating conditions is essential for understanding the dynamic behavior of PEM fuel cells.

In this study, we mainly focus on an experimental investigation of the transient phenomena associated with gaseous transport inside the cell under fully humidified conditions.

3. Results and discussion

In this section, the transient responses of the tested single fuel cell based on the polarization characteristics (current-voltage (*I-V*) curve) as a function of cell operating temperature are compared and discussed. Then, the effect of the cell operating temperature on the transient dynamics (voltage under-shoot/overshoot) of the PEM fuel cell operation is investigated and discussed, along with visualization images of the water distribution in the cathode flow channels.

3.1 Dynamic response of the fuel cell to a step increase in current density with different operating temperatures

Fig. 3 compares the cell voltage responses to a step increase in the current density from 0.3 to 0.6 A/cm^{-2} with different operating temperatures (30-50 °C). It is observed that the cell responds to a step increase of the operating cell current density simultaneously, and reaches a new voltage level. This can be explained by the fact that the time for the transient charging process of the electrical double layer is short enough to be neglected [5]. It appears that the dynamic response of the cell voltage is almost instantaneous under fully humidified conditions, as shown in Fig. 3.

Fig. 4 shows an enlarged view of Fig. 3. It is found that, after a step increase in the current density, the cell voltage gradually changes and reaches a new steady-state. The under-shoot (which is on the order of 0.5 – 1 s) in cell voltage is observed for
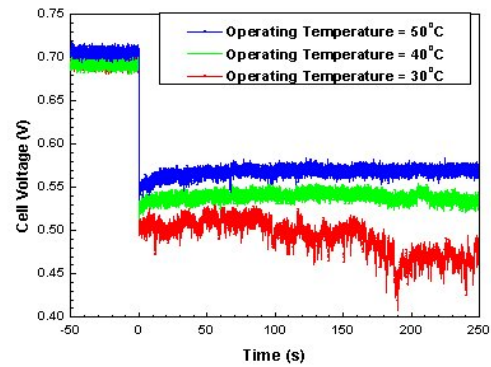

Fig. 3. Dynamic response of the cell voltage with respect to a step current change from 7.5 A(0.3 A cm^{-2}) to 15 A(0.6 A cm^{-2}) for three different operating temperatures.
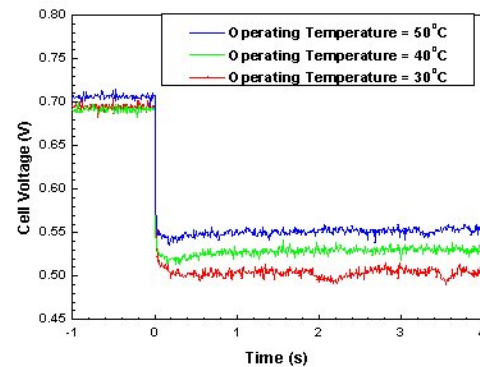

Fig. 4. Expanded view of the plot in Fig. 3.

an operating temperature of 40 or 50°C. This is consistent with the time constant of species diffusion for the fully humidified case presented by Ref. [5]. This also suggests that, for the fully humidified case, the transient response of a PEM fuel cell is dominated by gaseous diffusion to the reaction sites, unlike for the low humidity condition. Thus, it can be said that the under-shoot behavior is caused by the starvation of species (especially oxygen on the cathode side) in the high current density region. Specifically, in H$_2$/air PEM fuel cells, the oxygen concentration reaches the equilibrium condition much slower than hydrogen because of the big difference in gas diffusivity when the load changes. The lower diffusivity of oxygen on the cathode side is the main cause of the significant concentration reduction during load transients [7].

Moreover, under the lower operating temperature conditions, this under-shoot behavior after a step increase in the current density is also caused by the poor oxygen mass transport resulting from cathode side

flooding. This can be understood from the fact that the liquid water blocks the open porous network in the GDL, preventing the oxygen from diffusing towards the reaction sites in the catalyst layer.

From the *I-V* polarization curves shown in Fig. 4, it follows that the degree of under-shoot increases with a decrease of operating temperature within the tested temperature range of this study. This can be understood by the fact that oxygen transport becomes more sluggish when the cathode is severely flooded, which is the case for lower operating temperatures. This trend can be also confirmed through an investigation of the water distribution of the flow channel, which is presented in Fig. 5.

As presented in Fig. 4, the cell voltage fluctuation after a step increase in the current density at an operating temperature of 30°C is much larger than that at other cell working temperatures. Furthermore, it is shown that the cell voltage for an operating temperature of 30°C cannot reach the steady-state. After 100 s, even the drop of the cell voltage is found in Fig. 4. This also suggests that the cell performance cannot recover from its voltage reduction in a short period [14]. This can be explained by the fact that the increased water accumulation due to the high current density operation at the electrode and GDL limits the oxygen transport towards the catalyst reaction sites as time elapses. The situation can become more serious for the lower operating temperature case, because the excess liquid water may cause flooding in the gas flow channel and shut-down the reactant flow.

Fig. 5 shows the visualization images of the water distribution in the flow channels and the GDL top surface after a step increase in the current density from 0.3 to 0.6 A cm^{-2} at an operating temperature of 30°C. In the images presented in Fig. 5, the flat part corresponds to the channel land, and the bumpy part corresponds to the cathode channel through which the air flows. The white part of the visualization image represents the area of water.

Although the increase in operating cell current density is made almost immediately, the water distribution inside the fuel cell cannot respond as quickly as the step increase in the current density. After 1 s (which is on the order of the time constant for the gaseous transport through the GDL), a noticeable change in the water distribution in the flow channel is not still observed (compared with that under the previous current density conditions). As can be seen from Fig. 5, the water content in the flow channel starts to increase in addition to an enhancement in water production, which results from high current density operation at about 7 – 10 s after the load changes. This can be confirmed by comparing the water distribution in the marked area of Fig. 5 at 10 s with that at 1 s. Therefore, these results show that there exists an additional time delay in altering the water distribution in the flow channel after the load change, which can be explained as follows.

The liquid-water production rate inside the fuel cell is increased as the applied current density increases. In general, this changes the balance between the
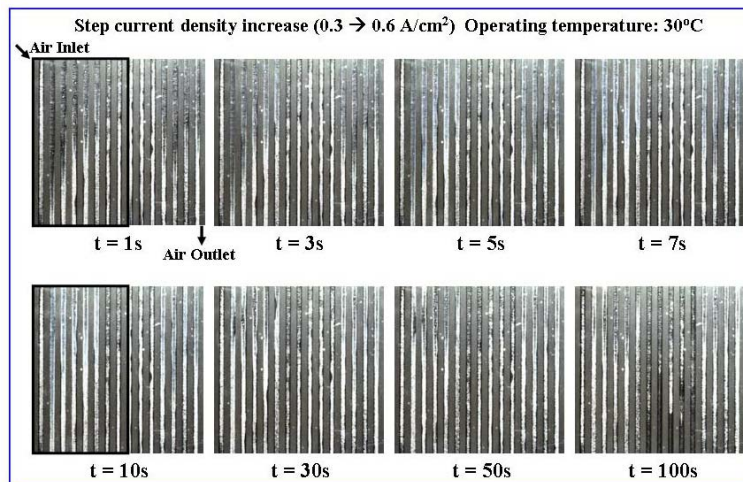

Fig. 5. Selected images of the water distribution in the flow channels with time at an operating temperature of 30°C after a step increase in the current density from 0.3 to 0.6 A cm^{-2}.

amount of water removed and water produced. Initially, the water content in the membrane and catalyst layer increases with the increase of the current density. Accordingly, the water distribution in the GDL and cathode flow channel is influenced sequentially.

As indicated in Fig. 5, cathode flooding occurs locally in the flow channels under higher current density conditions. This causes an increase in resistance to reactant flow, and prevents the effective transport of oxygen towards the catalytic reaction sites at the electrode surface, hence contributing to the mass-transport loss in cell performance.

As already mentioned in Fig. 3, the cell voltage drop at an operating temperature of 30°C after a step increase in the current density is much larger than that at any other operating temperature conditions. This suggests that the variation of water distribution in the flow channel and GDL and, especially, the occurrence of flooding (such as local flow channel clogging) has a substantial influence on the performance loss as the operating temperature becomes lower. It also implies that the cell performance at an operating temperature of 30°C is more sensitive to mass transport limitations under higher current density operations.

Afterwards, it can be seen that the water distribution in the flow channel fluctuates with respect to the specified current density condition, as depicted in Fig. 5. It is believed that the fluctuations of the water distribution cause an unstable variation in the operating cell voltage, as shown in Fig. 3.

Figs. 6-7 display the visualization images of the water distribution in the flow channels after a step increase in the current density from 0.3 to 0.6 A cm^{-2} at operating temperatures of 40°C and 50°C, respectively. Similar to the 30°C operating temperature case, noticeable changes in the water distribution in the flow channel are observed at about 7 – 10 s after the load change. As indicated in the images of Figs. 6-7, water accumulation in the flow channel decreases as the operating temperature increases. In particular, it is thought that, at an operating temperature of 50°C, the water accumulation in the flow channel significantly decreases (as shown in Fig. 7). This is because an increase in the operating temperature contributes to a higher water removal rate due to a higher evaporation rate [17]. The increased air flow rate (occurring at higher operating temperatures) is also thought to help effectively remove the liquid water in the flow channel.

Afterwards, the water distribution in the flow channel gradually changes with time, as shown in Figs. 6-7. As illustrated in Fig. 3, the fluctuation in cell voltage becomes smaller for an operating temperature of 40 or 50°C, as compared to an operating temperature of 30°C. The smaller voltage fluctuation can be attributed to the changes in the liquid water accumulation rate and water removal rate in the catalyst layer and GDL. The smaller fluctuation also suggests that, at the operating temperatures of 40 and 50°C, the cell performance is less sensitive to the water accumulation in the catalyst layer and GDL.
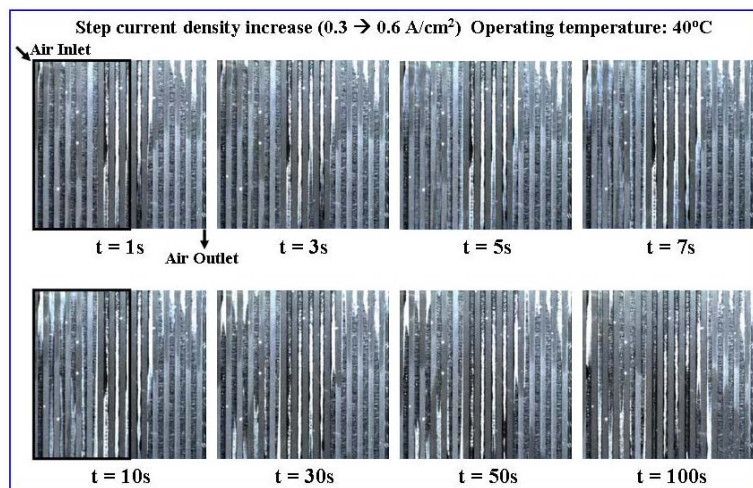

Fig. 6. Selected images of the water distribution in the flow channels with time at an operating temperature of 40°C after a step increase in the current density from 0.3 to 0.6 A cm^{-2}.
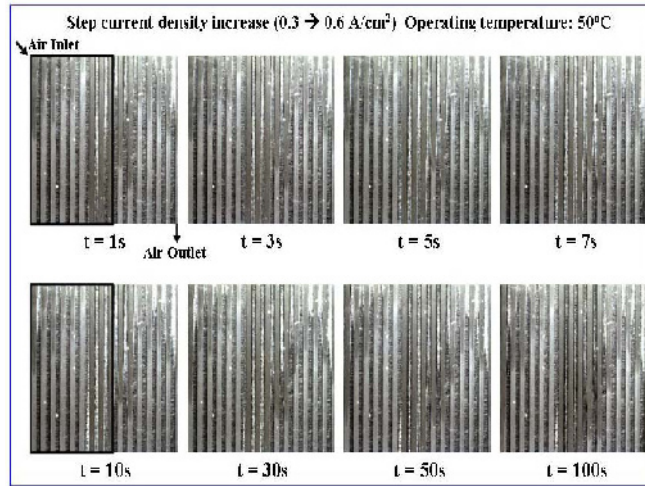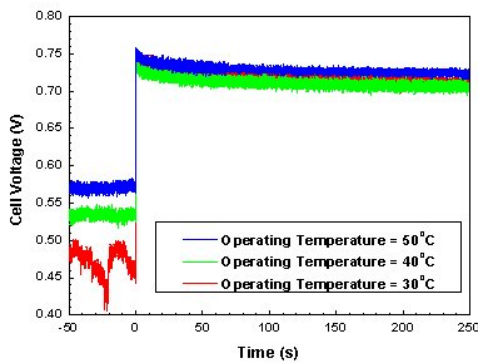
Fig. 7. Selected images of the water distribution in the flow channels with time at an operating temperature of 50ºC after a step increase in the current density from 0.3 to 0.6 A cm^{-2}.

Fig. 8. Dynamic response of the cell voltage with respect to a step current change from 15 A (0.6 A cm^{-2}) to 7.5 A (0.3 A cm^{-2}) for three different operating temperatures.
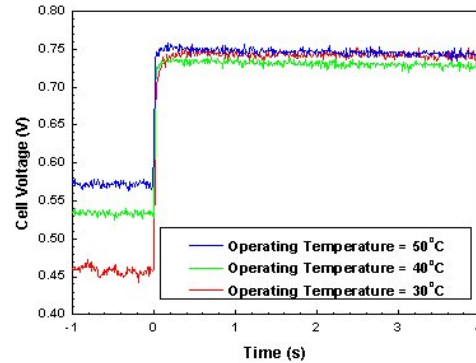
Fig. 9. Expanded view of the plots in Fig. 8.

3.2 Dynamic response of the fuel cell to a step decrease in current density with different operating temperatures

Fig. 8 presents a comparison of the time responses of the cell voltage with respect to a step decrease in the current density from 0.6 to 0.3 A cm^{-2} at three different operating temperatures (30 – 50ºC). As shown in Fig. 8, as in the case of a step increase in the cell current, the cell voltage responds almost immedi-

ately to a step decrease in cell current density.

Fig. 9 shows an expanded view of Fig. 8. Some publications [3, 5] report that an over-shoot (a time delay of about 1 s) occurs under fully humidified conditions at the initial stage after the step decrease in current density. However, the cell voltages do not exhibit a clear over-shoot behavior in this case.

Generally, as the applied cell current is decreased, the operating voltage is increased. As shown in Fig. 8, the cell voltages corresponding to a current density of 0.3 A cm^{-2} are in the range of 0.71 and 0.74 V for all three operating temperatures. It is seen that the cell is operating at relatively high voltage (i.e., low current density) conditions for the three different operating temperatures. For high-voltage operation, the fuel cell

performance is affected more by reaction kinetics than the enhanced mass transport of reactants (especially oxygen). This suggests that the enhanced oxygen transport through the GDL does not have a meaningful role in determining the dynamic behavior of the fuel cell at low current densities as compared to the high current density conditions.

Also, unlike the case of a step increase in the current density, only minor oscillations in the cell voltage are observed after the load changes, as shown in Fig. 8. This implies that the cell performance after a step decrease in the cell current density becomes more stable in a short period compared to the case of a step increase in the current density. In particular, this trend holds true for the case of a lower operating temperature (30°C). These results indicate that the cell performance after a step decrease in the current density is less influenced by the mass transport limitations due to the liquid water accumulation in the catalyst layer and GDL [17].

Fig. 10 presents visualization images of the water distribution in the flow channels at an operating temperature of 30°C. As in the case of the step current increase, the water distribution in the flow channel cannot respond to a step decrease in the cell current density instantaneously. As observed in Fig. 10, the water distribution in the cathode flow channel decreases after about 7 – 10 s. It is thought that this is also due to the slow transport characteristics of liquid water in the cathode catalyst layer and GDL.

The cell voltage increases up to about 0.74 V (which is almost the same voltage level for an operating temperature of 40 or 50°C), as presented in Fig. 8. This suggests that, despite the local flooding still observed in the flow channels, this decreased water distribution has a favorable effect on the cell performance under lower operating temperature conditions.

Figs. 11-12 present the selected visualization images of the water distribution in the cathode flow channels at operating temperatures of 40 and 50°C, respectively.

Compared to the case of an operating temperature of 30°C, it can be seen that the water distribution in the flow channel decreases as the operating temperature increases. As the operating temperature is increased, the water-vapor transport is also increased [18]. Thus, the increased water-vapor transport rate clearly has significant effects on enhancing the removal rate of liquid water in the flow channel.

Minor oscillations in the cell voltage are also seen to occur after 10 s (as indicated in Fig. 8). This is attributed to the change in the membrane water content by the liquid water that is removed and accumulates in the catalyst layer and GDL with changes in the operating parameters. It is also known that this is related to the complicated interaction between the drag force and capillary force [17].

It can be concluded that the operating temperature has a substantial influence on the cell dynamic performance during and after step changes in the current density.
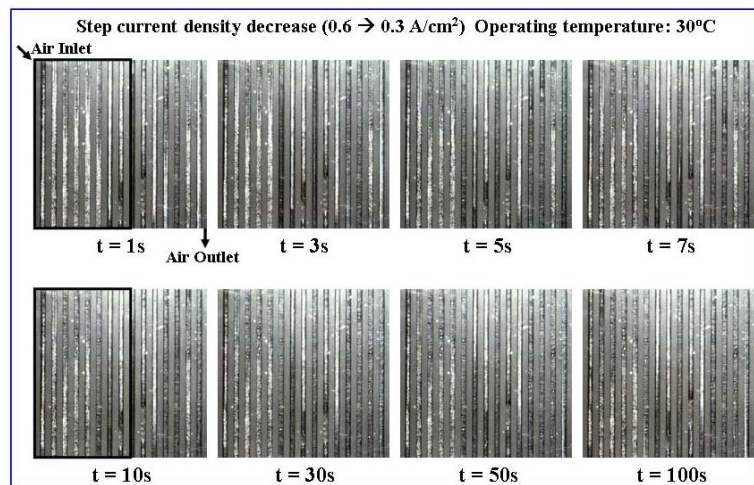

Fig. 10. Selected images of the water distribution in the flow channels with time at an operating temperature of 30°C after a step decrease in the current density from 0.6 to 0.3 A cm^{-2}.
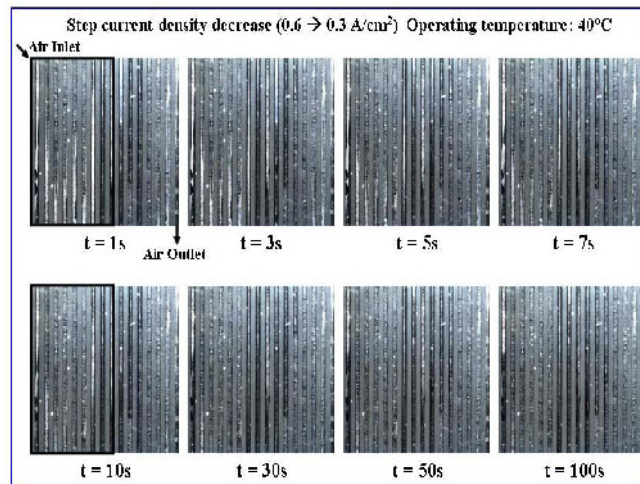
Fig. 11. Selected images of the water distribution in the flow channels with time at an operating temperature of 40°C after a step decrease in the current density from 0.6 to 0.3 A cm^{-2}.
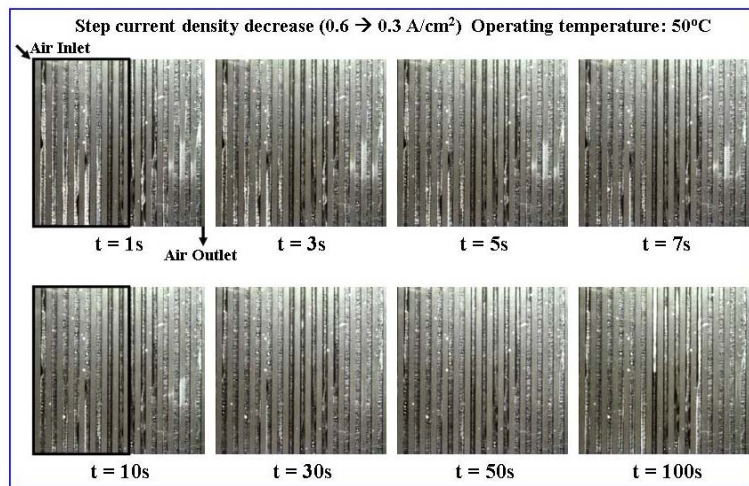

Fig. 12. Selected images of the water distribution in the flow channels with time at an operating temperature of 50°C after a step decrease in the current density from 0.6 to 0.3 A cm^{-2}.

4. Conclusions

In an attempt to better understand the dynamic processes within an operating PEM fuel cell during load transients in terms of water transport characteristics, an experiment was performed to study the dynamic response of a transparent, single fuel cell with respect to load changes.

The dynamic response of the cell voltage during a step change in the current density and visualization images of the liquid water distribution in the cathode flow channels were simultaneously investigated. The effects of the cell operating temperature on the cell dynamic performance were also studied. The main conclusions drawn from the experimental studies can be summarized as follows:

- In a fully humidified fuel cell, the under-shoot (which is on the order of 0.5 − 1 s) in the cell voltage is observed in response to a step increase in the current density within the operating conditions of this study. It is thought that this is due to a starvation of oxygen resulting from the retardation of gaseous transport on the cathode side.
- The cell voltage under-shoot increases slightly with a decrease in the operating temperature

within the tested temperature range. This is because the oxygen transport becomes more retarded in the presence of cathode flooding for a lower operating temperature.

- It is found that the water content in the flow channel and on the GDL surface cannot respond as quickly as the step change in current density. Under the conditions tested in this study, it takes about 7 – 10 s to alter the water distribution in the flow channel for a step change (increase or decrease) in current density. The additional time delay is caused by the slow water transport through the catalyst layer and GDL, and depends on the cell operating conditions.

- For an operating temperature of 30°C, the voltage fluctuations after a step increase in the current density increase become larger and the cell voltage cannot reach a steady-state after a long period. This suggests that the cell performance is influenced by the produced water not being effectively removed by evaporation at the lower operating temperature conditions. On the other hand, after a step decrease in the current density, only minor oscillations of the cell voltage are observed, and the cell voltage is well-stabilized in a short period of time for three different operating temperatures.

- The approach adopted in this study can be a valuable tool for experimentally investigating the transient response of a PEM fuel cell in terms of water and reactant gas transport characteristics. The knowledge gained from the current study can be used as an effective means of providing basic insight into the transient response of PEM fuel cells.

Acknowledgments

Nomenclature————————————————

A : Effective specific reactive surface area per unit volume (m^2/m^3)

C : Electric capacity (F/m^2)
D_g^{eff} : Effective diffusivity of gas (m^2/s)
σ_m : Electrolyte conductivity (S/m)
σ_s : Electrode conductivity (S/m)
δ_{CL} : Catalyst layer thickness (μm)
δ_{GDL} : Gas diffusion layer thickness (μm)
τ_{cd} : Time constant of the charge/discharge (s)
τ_{di} : Time constant of the gaseous species diffusion in the GDL (s)

Greek letters

σ : Conductivity (S/m)
δ : Thickness (μm)
τ : Time constant (s)

Superscripts

eff : Effective

Subscripts

cd : Charge/discharge
CL : Catalyst layer
di : Diffusion
g : Gas
GDL : Gas diffusion layer
m : Electrolyte
s : Electrode

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