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Experimental study of two-phase flow in a proton exchange membrane fuel cell in short-term microgravity condition

Hang Guo [a,*], Xuan Liu [a], Jian Fu Zhao [b], Fang Ye [a], Chong Fang Ma [a]

[a] MOE Key Laboratory of Enhanced Heat Transfer and Energy Conservation, Beijing Key Laboratory of Heat Transfer and Energy Conversion, College of Environmental and Energy Engineering, Beijing University of Technology, Beijing 100124, China

[b] Key Laboratory of Microgravity, Institute of Mechanics, Chinese Academy of Sciences, Beijing 100190, China

HIGHLIGHTS

- Two-phase flow in PEMFC cathode channels is observed in different gravity environments.
- The PEMFC shows different operating behavior in normal and microgravity conditions.
- Water tends can be removed in microgravity conditions at high water production regime.
- Liquid aggregation occurs in microgravity conditions at low water production regime.
- Effect of gravity on performance and two-phase flow at two operating regimes is studied.

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ABSTRACT

Water management is important for improving the performance and stability of proton exchange membrane fuel cells (PEMFCs) for space applications. An in situ visual observation was conducted on the gas–liquid two-phase flow in the cathode channels of a PEMFC in short-term microgravity condition. The microgravity environment was supplied by a drop tower. A single serpentine flow channel with a depth of 2 mm and a width of 2 mm was applied as the cathode flow field. A membrane electrode assembly comprising of a Nafion 112 membrane sandwiched between gas diffusion layers was used. The anode and cathode were loaded with 1 mg cm^{-2} platinum. The PEMFC shows a distinct operating behavior in microgravity because of the effect of gravity on the two-phase flow. At a high water production regime, cell performance is enhanced by 4.6% and the accumulated liquid water in the flow channel tends can be removed in microgravity conditions to alleviate flooding. At a low water production regime, cell performance deteriorates by 6.6% and liquid aggregation occurs in the flow channel because of the coalescence of dispersed water droplets in microgravity conditions, thus squeezing the flow channel. The operating behavior of PEMFC in microgravity conditions is different from that in normal gravity conditions. Further studies are needed on PEMFC operating characteristics and liquid management for space applications.

1. Introduction

A proton exchange membrane fuel cell (PEMFC) is a prospective alternative power source for short-term space missions because of the following characteristics: high-energy conversion efficiency, zero emission, low temperature, and regenerative operation [1–3]. In space engineering, PEMFCs with polystyrene membranes were first applied to the GEMINI spacecraft in the 1960s [4]. Alkaline fuel cell (AFC) systems were used for the APOLLO mission and other space shuttle missions of the National Aeronautics and Space Administration (NASA). The AFC was gradually replaced by PEMFC during the 1990s because of the technological breakthroughs in PEMFC and the disadvantages of AFC. Several researchers have studied PEMFCs for space applications [4–8]. St-Pierre and Jia [5] completed a PEMFC life test by using hydrogen and oxygen feed streams. The fuel cell was operated for more than 11,000 h, which meets the NASA requirement of a 10,000-h life. The PEMFC showed satisfactory characteristics such as low degradation rate, low cell performance standard deviations, and potential potable water production. Sone et al. [6] designed, manufactured, and tested a fuel cell system without a humidifier in a closed environment. A serpentine channel with a width of 1.60 mm and a depth of 1.25 mm was used. Approximately 99.99999% of high-grade

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[*] Corresponding author. Tel.: +86 10 67391612x8311; fax: +86 10 67392774.
E-mail address: hangguo@sohu.com (H. Guo).

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hydrogen and oxygen without humidification were applied in their experiments. The authors operated the fuel cell system intermittently for over 100 h.

The water management of PEMFC aims to maintain a balance between water production and water removal to achieve efficient and reliable operations. Some researchers have concerned water removal problem in PEMFCs [9–11]. Excess water in the cathode side will result in cathode flooding, which will deteriorate the fuel cell performance and reduce the longevity of fuel cell components. Water management is important to remove excess water in time. An understanding of two-phase flow in fuel cells is needed for effective water management. The two-phase flow inside PEMFCs has a significant impact on reactant transport [12–14], e.g., transport limitation. Visualization method is an effective way to observe the two-phase flow, which has been used for tube [15] or mini-channel [16] recently. Researchers have studied the two-phase flow caused by liquid water inside PEMFCs by using the direct visualization method and transparent PEMFCs [17–27]. Yang et al. [19] applied an optical PEMFC to study the mechanics of liquid water transport. They used gold-plated stainless steel plates with seven straight gas channels as current collectors. In their transparent fuel cell, the main mechanisms of liquid water removal were water droplet coalescence and water droplet migration along the hydrophilic surfaces of the gas channel. Liu et al. [21] investigated the water flooding and two-phase flow behavior in the cathode side of transparent PEMFCs. Three types of flow fields, namely, parallel flow field, interdigitated flow field, and cascade flow field, were used in their study. They found that high temperatures and high cathode gas flow rates help alleviate water-flooding problems; however, excessive high temperatures and cathode gas flow rates will decrease fuel cell performance. Weng et al. [24] used a transparent fuel cell to investigate the effects of cathode gas flow rates on water flooding and PEMFC performance. Acrylic transparent windows were used in their fuel cell, and serpentine channels with a width of 2 mm and a depth of 2 mm were applied in the anode and cathode sides. Their results showed that water flooding was severe at low cathode gas flow rates and low cell temperatures. Hussaini and Wang [26] visually studied in situ the cathode flooding of a transparent PEMFC. A flow map was used to present the two-phase flow pattern. Two-phase pressure drop coefficient and voltage loss, along with wetted area ratio, were used to present the influence of flooding.

The above studies on the two-phase flow in the PEMFC and the effect of this two-phase flow on cell performance were all performed in Earth's gravity (normal gravity). However, the gravity effect was not considered. Many studies have revealed the importance of gravity effect on the performance and water management of PEMFC by changing the orientation of the fuel cell. Kimball et al. [28,29] observed the liquid water motion in PEMFC by changing the PEMFC orientation. Different characteristics were observed with different orientations of the flow channels. These characteristics demonstrated that gravity plays an important role in PEMFC flooding. Chen and Wu [30] investigated the effect of gravity on water discharge in a PEMFC. They completed a number of experiments at anode-upward and cathode-upward and compared the performance of fuel cells. The removal of liquid water in the cathode at the cathode-upward is easier than that at the anode-upward. Morin et al. [31] presented evidence that gravity affected the performance of PEMFC. They suggested that liquid water most probably accumulates in the vertical parts of the channel. Lee et al. [32] studied the effects of gravitational force on the performance of a PEMFC with serpentine flow channels. The fuel cell was operated in normal and horizontal positions. They suggested that orientation, flow direction, and flow channel distribution affect the removal of liquid water in the cathode. Lu et al. [33] investigated the effect of gravity on the two-phase flow in a PEMFC by changing the channel orientation. The results indicated that vertical channel orientation causes lower water accumulation than horizontal channel orientation. Najjari et al. [34] developed a 1D model to investigate the effect of gravity on water transport. Their results showed that gravity is negligible when studying PEMFC performance. Yu et al. [35] designed a number of experiments to study the influence of gravity on the performance of a PEMFC stack. They compared the performance of the fuel cell stack under different gas intake modes and gravitational angles. Their results revealed that gravity has a significant effect on the performance of the PEMFC stack.

Changing the orientation of fuel cell emphasizes the change of gravity direction. This phenomenon is different from microgravity conditions, wherein almost no gravitational force is detected. The microgravity experiments of direct methanol fuel cells (DMFCs) [36–40] and PEMFC [41] have been reported. In our previous studies, transparent DMFCs with gold-plated stainless steel bipolar plates [36] and graphite bipolar plates [37] were applied to observe a two-phase flow in the anode side in microgravity conditions. The results indicated that the gravity affects the two-phase flow in DMFCs, including bubble size, bubble velocity, and flow pattern. Ye et al. [40] observed in situ a two-phase flow in the anode channels of a liquid-fed DMFC and measured the cell voltage and current of DMFC in different gravity environments. They found that the size of carbon dioxide bubbles decreases with the increasing feeding flow rate of the methanol solution. Furthermore, the change in methanol flow rate cannot eliminate the effect of gravity. Moreover, research shows that the liquid/gas fluid flow in microgravity conditions is significantly different from that in normal gravity conditions because of the absence of the gravity [42–46]. Therefore, PEMFCs may show distinct types of behavior in a reduced gravity environment. Studies on fluid flow inside the PEMFC, as well as on the cell performance under microgravity conditions, will provide an approach for the reference of PEMFC operating characteristics and liquid management in a reduced gravity environment, e.g., in space.

This paper presents an in situ visual observation of the two-phase flow in the flow channel of an operating transparent PEMFC with a single serpentine channel in a short-term microgravity environment. The effects of operating current density on the two-phase flow characteristics in the cathode flow channel under microgravity conditions were studied experimentally. The PEMFC operating behavior was examined in normal gravity and microgravity conditions under certain operating conditions.

2. Experimental

2.1. Microgravity environment

The microgravity environment was obtained in a drop tower at the Key Laboratory of Microgravity, Institute of Mechanics, Chinese Academy of Sciences. Fig. 1 shows the microgravity experiment facility. This drop tower supplied a closed microgravity environment by a free-falling drop capsule with a gravity level of 10^{-2}–10^{-3} g; the closed microgravity environment was measured by an accelerometer. The effective height of the free-falling drop capsule was 83 m, and the microgravity environment duration time was 3.6 s. The experiment system was installed in the drop capsule. A recovery string bag was mounted at a height of 22 m from the ground to recover the capsule and experimental setup.

2.2. Transparent PEMFC

A transparent PEMFC with a single serpentine flow channel was designed to study the in situ gas liquid two-phase flow inside the

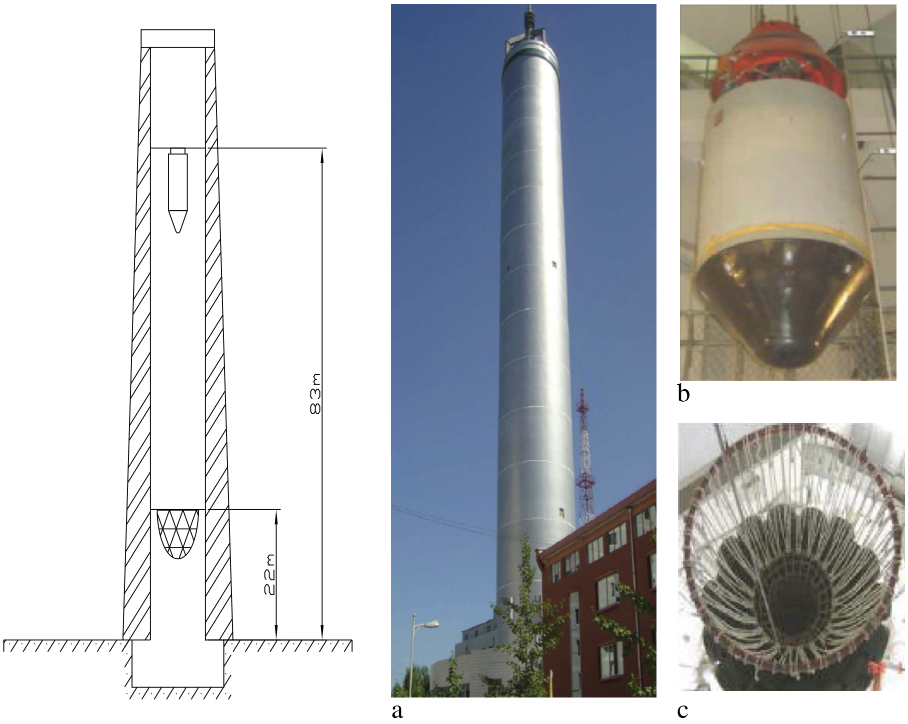


Fig. 1. Microgravity experiment facility: (a) drop tower, (b) drop capsule, and (c) recovery string bag.

PEMFC. Fig. 2 shows the transparent PEMFC and the fluid flow passages. Graphite plates were used as the flow field and current collector, and a transparent plate made of plexiglass covered the flow field. The thickness of the graphite plate used for the cathode flow field was 2 mm, and a serpentine slot of 2 mm width was cut in the graphite plate. A directly visible serpentine flow channel was formed when the graphite plate was installed between the transparent plexiglass and membrane electrode assembly (MEA). Glass fiber cloth-coated silica gel with a slot matching the graphite plate slot was used for sealing. A 6 mm-thick graphite plate with a mirrored flow channel configuration was installed at the anode. Two aluminum alloy end plates were used for clamping and support; one of the aluminum alloy end plates was set as a window wherein the liquid water and flow behavior could be observed directly in the cathode flow channel. The cell temperature was controlled by an electrical heater connected to a temperature controller unit, and the fuel cell was operated at a temperature of 35 °C in all experiments.

This study used an MEA with 25 cm^2 active area (BCS FUEL CELLS INC., USA). The MEA was composed of a Nafion 112 membrane sandwiched between the gas diffusion layers. Both the anode and cathode were loaded with platinum of 1 mg cm^{-2}.

2.3. Reactant supply system

Given the space limitations of the drop capsule and the operation regulation requirements of the drop tower, we developed a

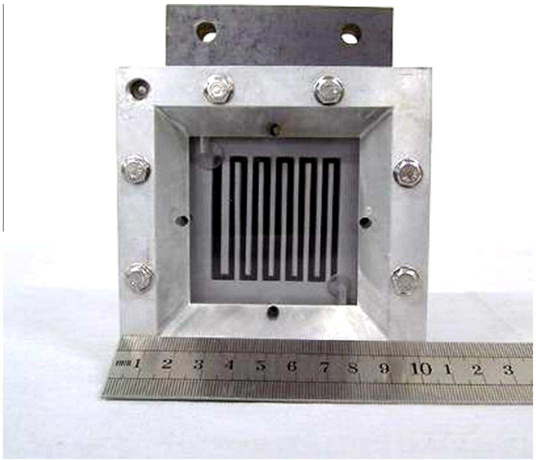


Fig. 2. Transparent PEMFC.

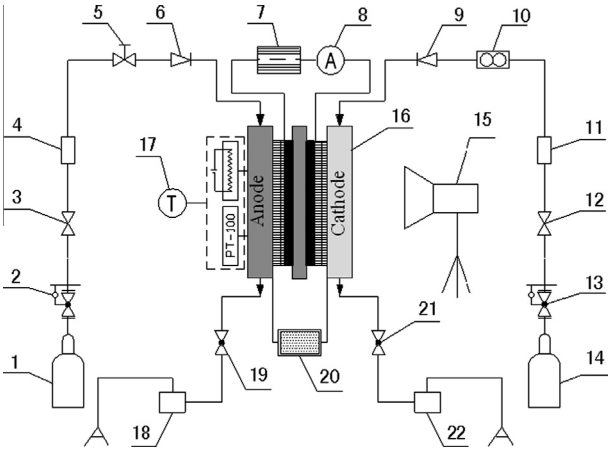


Fig. 3. Experimental setup. 1, hydrogen tank; 2, hydrogen pressure reducing valve; 3, hydrogen electromagnetic valve; 4, hydrogen gas filter; 5, hydrogen regulator; 6, hydrogen one-way valve; 7, load; 8, current transmitter; 9, oxygen one-way valve; 10, mass flow controller; 11, oxygen gas filter; 12, oxygen electromagnetic valve; 13, oxygen pressure reducing valve; 14, oxygen tanker; 15, high-speed video camera; 16, transparent fuel cell; 17, temperature controller unit; 18, hydrogen/water separator; 19, hydrogen spherical valve; 20, voltage transmitter; 21, hydrogen spherical valve; and 22, oxygen/water separator.

PEMFC test system without a humidifier. The produced water from the electrochemical reaction was collected by the gas/liquid separator before the excess reactant gas was released. Fig. 3 shows the schematics of the experimental setup.

Pure hydrogen (99.999%) and oxygen (99.999%) were supplied as fuel and oxidant reactant without humidification. The gas flow rates were quantified by the mass flow controller (Core-Parmer, CZ-32907-67, USA), which can control the reactant gas flow rate from 0 SCCM to 1000 SCCM (standard cubic centimeter per minute) with a precision of 0.5% at full scale. The oxygen and hydrogen were supplied at a fixed flow rate of 120 and 180 SCCM, respectively. A nitrogen purge system was applied to clean the residual fuel and oxidant reactant in the test system pipelines and fuel cell. A normal load with fixed resistance other than the electronic load was applied in the external circuit of the tested fuel cell.

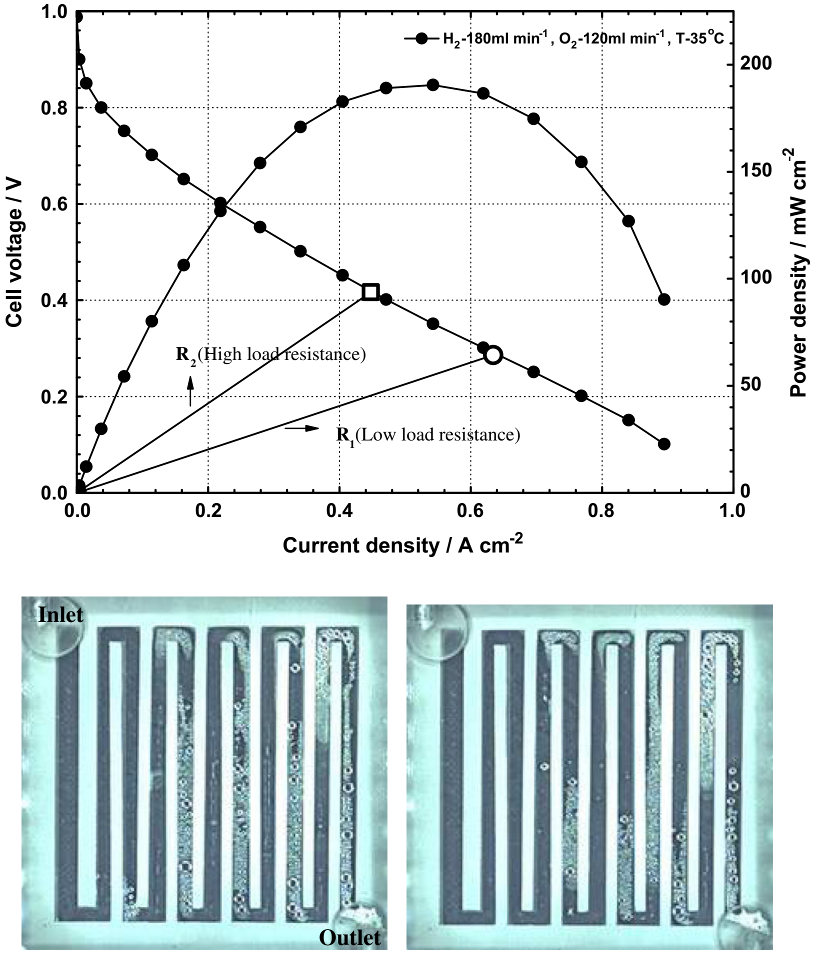
2.4. High-speed video recording system

The video and photo imaging system of a high-speed digital CMOS video camera (VITcam CTC; AOS Technologies AG, Switzerland) was used to capture images of the two-phase flow characteristics of liquid water and reactant gas in the cathode flow field. By using the zoom function of the standard C-Mount Lens (SE2514, NSK, Japan), the images of the cathode fluid were captured by the CMOS and recorded in a memory embedded in the video camera. A shutter speed of 1/1000 s and a recording speed of 1000 frames s^{-1} were selected to visualize and record the flow patterns. A group of light-emitting diodes was used to satisfy the lighting requirement for capturing images.

The distinct feature of this video camera is the option to pre-trigger the time setting to create a multi-sequence recording. Time can be pre-triggered by typing the desired percentage and separating the buffer of the memory into two parts: pre-trigger and post-trigger. When the video camera operates in pre-trigger mode, the image will be recorded in the buffer of the pre-trigger round until a trigger signal initiates a new sequence recording in the post-trigger buffer. The video camera will stop recording when the memory is fully recorded. In this study, the percentage of the pre-trigger buffer was set to 50% to record a 4 s video in normal conditions and another 4 s sequence video in microgravity environment.

2.5. Data collection and control system

The data acquisition and control system was a computer-based system. A multi-function data logger system was used for data collection, including cathode flow rate, operating temperature, current density, cell voltage, and gravity level. The data collection mode was set by control software. The trigger signal to start the data logger was sent from a programmable logic controller. An eight differential analog input board was used for the data acquisition, and data were collected at a total sampling rate of 200 kHz. In this study, the trigger time of the data logger for data collection was 10 s ahead of the release time of the drop capsule. A time relay powered off the data logger after working for 40 s.



High current density with R_1 Low current density with R_2

Fig. 4. Transparent PEMFC performance and operating condition.

3. Results and discussion

3.1. Cell performance and operating conditions

Fig. 4 shows the representative *I–V* polarization curve of the transparent fuel cell used for the microgravity experiment test. An electric heating unit at 35 °C heated the cell. Sufficient reactant gas was supplied to the fuel cell with hydrogen and oxygen at 180 and 120 ml min^{-1}, respectively. The cell performances were tested in normal gravity. The hollow points represent the experiments before the release of the drop capsule. Note that the cell performance curve was tested in normal gravity environments two weeks before the hollow points test. The cell performance curve depicted in Fig. 4 shows that the hollow points agree well with the polarization curve, which demonstrates the reproducibility of the fuel cell experiments. The PEMFC operating behavior was investigated in two operating conditions, namely, high current density with low load connection and low current density with high load connection. Fig. 4 also shows the visualizations of the two-phase flow in the cathode flow channel under these two operating conditions.

3.2. High current density operating regime

Fig. 5 shows the current density and cell voltage of the operating PEMFC from a normal gravity environment to a microgravity environment at high current density. The figure also shows the gravity level distinguished by the drop capsule movement. This paper only displayed the gravity level qualitatively. The exact quantitative gravity level cannot be supplied because of the poor precision of the gravity acceleration sensor. Before the release of the drop capsule, the drop capsule was steadily suspended at the top of the drop tower, and the PEMFC in the capsule operated at normal gravity. After the release of the drop capsule, the drop capsule supplied a microgravity environment for PEMFC by free falling. When the drop capsule fell into the recovery string bag, the

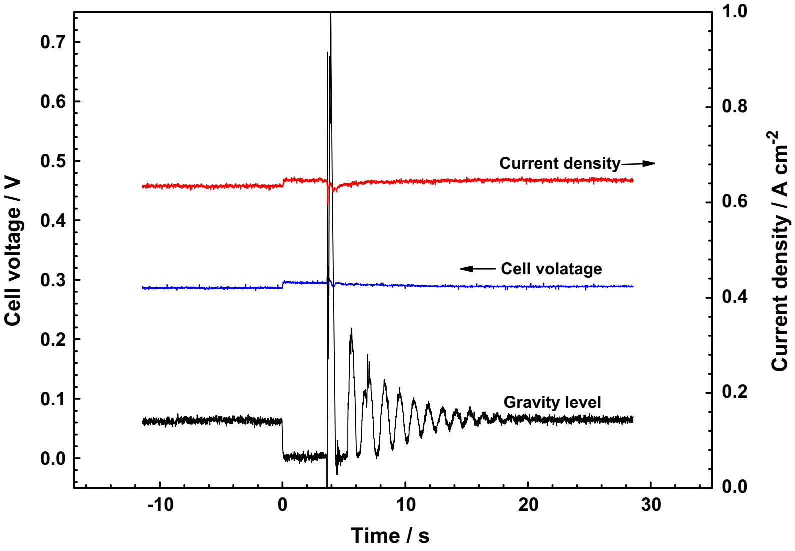


Fig. 5. PEMFC behavior with varying gravity level at high current density.

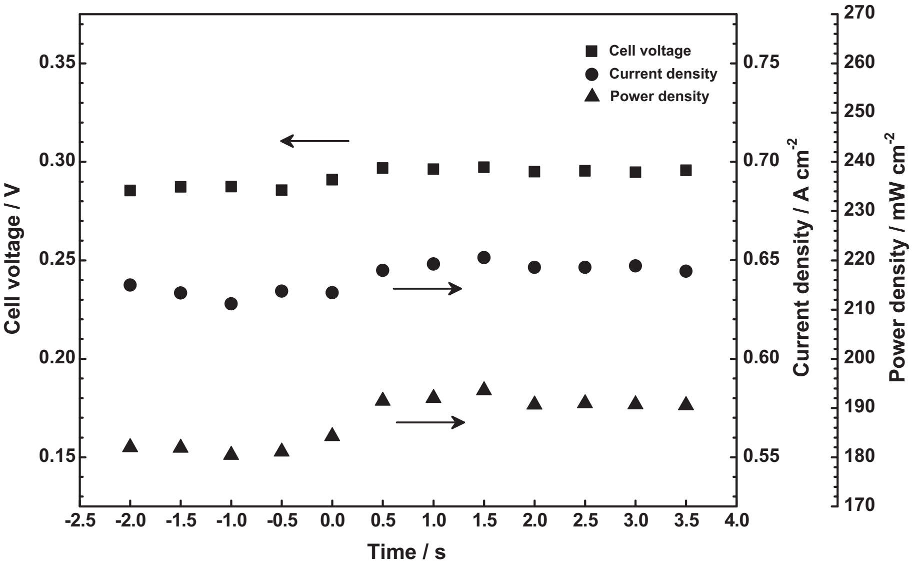


Fig. 6. Cell performance of PEMFC in normal/microgravity conditions at high current density.

Fig. 7. Two-phase flow in the cathode flow channel under normal gravity/microgravity conditions at high current density.

gravity level shows oscillation changes. The PEMFC was operated at least one and a half hours in the normal gravity environment before it entered into microgravity environment. It means that the PEMFC has already reached a steady state before it entered into microgravity environment. Although the microgravity lasts for only 3.6 s, Fig. 5 shows that the current density and cell voltage increase suddenly as the gravity shifts from the normal gravity environment to the microgravity environment.

Fig. 6 shows that the cell performance varies with the operating time from normal gravity conditions to microgravity conditions at high current density. The current density, cell voltage, and power density are marked in Fig. 6 at every half second. A time of 0.0 s marked at the time axis is the release time of the drop capsule. Four points in the normal gravity environment and seven points in the microgravity environment are displayed in Fig. 6 to show the effect of gravity on cell performance. Fig. 6 shows that the current density, cell voltage, and power density increases with the operations of the PEMFC from normal gravity conditions to microgravity conditions. This increase indicates that the performance of the fuel cell in the microgravity environment is higher than the performance of the fuel cell in the normal gravity environment. However, the change value is insignificant, thus indicating that the performance of the PEMFC is slightly enhanced in the microgravity environment. When the PEMFC shifts from the normal gravity environment to the microgravity environment, no operation conditions have been changed except for gravity. Thus it can be sure that the variation of performance is related to the gravity effect.

Fig. 7 shows the visualization results of the two-phase flow characteristics in the cathode flow channel in normal gravity and microgravity conditions corresponding to the times shown in Fig. 6. The time of 0.000 s was the transition point from normal to micro gravity condition. Before the moment of 0.000 s, the value of time is negative, which means that it is in normal gravity

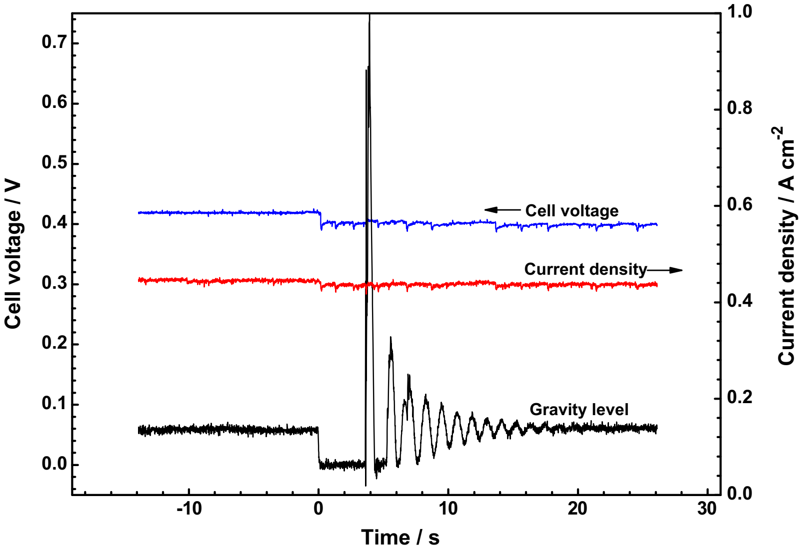


Fig. 8. PEMFC behavior with varying gravity level at low current density.

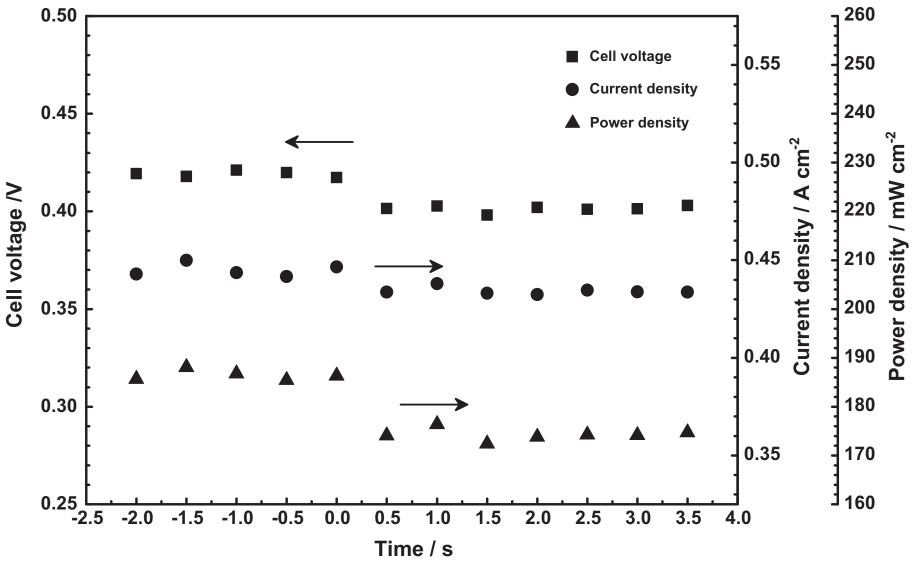


Fig. 9. Cell performance of PEMFC in normal gravity/microgravity condition at low current density.

condition. After the moment of 0.000 s, the positive value of time represents duration in microgravity environment. The visualization results show that a two-phase transport phenomenon occurs with flow field/channel flooding. In the normal gravity environment, liquid water accumulates at the bottom of the vertical parts of the serpentine channel. In the vertical parts of the serpentine channel, an upward movement of liquid water because of the inertial effect of the gas phase can be observed; however, most of the liquid water falls to the bottom because of the separation of the liquid phase from the gas phase caused by gravity. In the microgravity environment, the pressure of the reactant gas will dominate because the buoyancy lift is weak and almost no gravitational force exists. The liquid water is continuously removed by the reactant gas to the outlet of the flow channel. The separation of the liquid phase from the gas phase does not occur, and the liquid water and reactant gas move forward to the outlet with a stable phase interface. Fig. 7 shows that the accumulated liquid water in the vertical parts of the flow channel is removed easily by the reactant gas in the microgravity environment. Therefore, the cell performance is enhanced in the microgravity condition because the flooded area in the flow channel is repeatedly exposed to the reactant gas. Several publications proved that enhancing the reactant gas transport can improve PEMFC performance [14,21]. However, the cell performance in the microgravity conditions is only 4.6% higher than that in normal gravity conditions.

3.3. Low current density operating regime

Fig. 8 shows the current density and cell voltage of the operating PEMFC from a normal gravity environment to a microgravity environment at low current density. The figure also shows that the current density and cell voltage change suddenly as the fuel cell operates from a normal gravity environment to a microgravity environment. At the low current density operating regime, the current density and cell voltage decreases suddenly in the microgravity environment; this result is opposite to that in the high current density operating regime (Fig. 5).

-2.000 s -1.500 s -1.000 s

-0.500 s 0.000 s 0.500 s

1.000 s 1.500 s 2.000 s

2.500 s 3.000 s 3.500 s

Fig. 10. Two-phase flow in the cathode flow channel under normal gravity/microgravity conditions at low current density.

Fig. 9 shows that the cell performance varies with the operating time from a normal gravity environment to a microgravity environment at low current density. The current density, cell voltage, and power density are marked in Fig. 8 at every half second. The time at the axis is similar to the time indicated in Fig. 6. Fig. 9 shows that the current density, cell voltage, and power density all decreases slightly with the operation of the PEMFC from a normal gravity environment to a microgravity environment. The PEMFC performance in the microgravity environment is worse than the PEMFC performance in the normal gravity environment.

Fig. 10 shows the visualization results of the two-phase flow characteristic in the cathode flow channel in normal gravity and microgravity conditions corresponding to the times shown in Fig. 9. The liquid water distribution and the two-phase flow pattern in the flow channel shown in Fig. 10 are significantly different from that in Fig. 7. The operating current density was decreased by increasing the load resistance, thus leading to a reduction of water production and liquid water formation in the flow channel. Fig. 10 shows that in the normal gravity environment, liquid water droplets emerge in the flow channel because of the insufficient flow field pressure drop, which cannot remove the liquid water droplets in time. The water droplets are distributed separately on the surfaces of the flow channel walls and MEA. The water droplets are stable because the gravity of the water droplets is balanced by the surface tension and inertial effect of the gas phase. Almost no liquid aggregation in the flow channel exists. When the operating PEMFC shifts from the normal gravity to the microgravity condition, the balanced condition of the multi-force effect is altered because of the absence of gravity. Fig. 10 shows that the stationary water droplets begin to move along the gas flow direction in the microgravity condition. A big liquid aggregation formation is visible in the flow channel because of the coalescence of water droplets during water droplet movement. In the microgravity environment, the liquid water aggregation increases to 2 mm in diameter, which is comparable

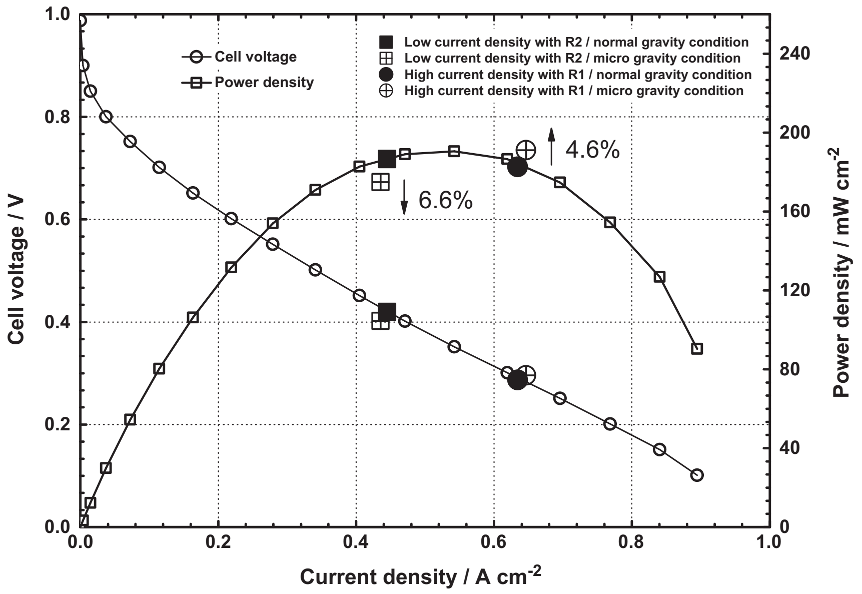


Fig. 11. Cell performance of PEMFC at different gravity levels.

to the cross-sectional dimension of the flow channel. This liquid aggregation is not removed by the gas flow in the experiment. The liquid aggregation stays near the corner of the flow channel and vibrates up and down until the end of the microgravity duration time. In the microgravity environment, dispersed water droplets coalesce to pinch off the flow channel, thus deteriorating the cell performance and reducing operation reliability. The cell performance in microgravity condition is 6.6% lower than the cell performance in normal gravity conditions.

The *I–V* polarization curve of the PEMFC under the hydrogen flow rate of 180 ml min^{-1}, oxygen flow rate of 120 ml min^{-1}, and cell temperature of 35 °C in normal gravity condition is shown in Fig. 11. The cell performances in microgravity under different operating current densities are also shown in Fig. 11. Note that the cell performance curve in Fig. 11 was tested in normal gravity environments several weeks before the microgravity experiment. The operating points of PEMFC in the normal gravity and microgravity environment in Fig. 11 were performed in the microgravity experiment before and after the release of the drop capsule, respectively. The current density, cell voltage, and power density in Fig. 11 show the operating behavior of PEMFC in microgravity condition and are the arithmetical average of the data collected during the microgravity condition duration. The operating points of PEMFC in the normal gravity environment are in good agreement with the cell performance, thus implying that the PEMFC used in this study operated stably.

For each operating regime, no operating condition is changed except for gravity. The results show that the cell performance and two-phase flow characteristic inside the PEMFC in normal gravity are different from that in microgravity, thus implying that the distinct operation behavior of PEMFC will occur with the PEMFC application in space. Further studies are needed to understand the PEMFC operation behavior, including the two-phase flow, cell performance and operating reliability, in microgravity conditions to supply the approach for the reference of PEMFC operating characteristics and liquid management for space applications.

4. Conclusions

The cell performance and visualization of the two-phase flow characteristic in the flow channel of PEMFC in short-term microgravity environments is reported in this paper. PEMFC shows a distinct operation behavior in microgravity conditions because of the effect of gravity on the two-phase flow.

1. At a high water production regime, liquid water accumulates in the vertical parts of the flow channel in normal gravity conditions. However, the accumulated liquid water in the flow channel needs to be removed in microgravity conditions to alleviate flooding.
2. At a low water production regime, the liquid water droplets are distributed separately in the flow channel. Liquid aggregation occurs in the flow channel with the coalescence of dispersed water droplets in microgravity to pinch off the flow channel.
3. The effect of gravity level on PEMFC operation behavior is complex under different operating conditions. Further research contributions are needed for PEMFC operating characteristics and water management for space applications.

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