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Experimental Study on a 1000W Dead-End H_2/O_2 PEM Fuel Cell Stack with Cascade Type for Improving Fuel Utilization

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Abstract

Proton exchange membrane fuel cells (PEMFCs) with a dead-ended anode and cathode can obtain high hydrogen and oxygen utilization by a comparatively simple system. Nevertheless, the accumulation of the water in the anode and cathode channels might cause a local fuel starvation degrading the performance and durability of PEMFCs. In this study, a brand new design for a polymer electrolyte membrane (PEM) fuel-cell stack is presented which can achieve higher fuel utilization without using hydrogen and oxygen recirculation devices such as hydrogen pumps or ejectors that consume parasitic power and require additional control schemes. In this manuscript the basic concept of the proposed design is presented. Concept of the proposed design is to divide the cells of a stack into several stages by conducting the outlet gas of each stage to a separator and reentering it into the next stage in a multistage construction of anode and cathode electrodes. In this design, a higher gaseous flow rate is maintained at the outlet of the cells, even under dead-end conditions resulting in reduced purge-gas emissions by avoiding the accumulation of liquid water in the cells. Moreover, fluctuation of voltage in hydrogen and oxygen cells in the dead-end mode is investigated. Furthermore, the utilization factor of hydrogen and oxygen at different powers is presented. Overall, the results show that the proposed design has the same polarization curve as an open-end mode one, resulting in a higher PEMFC performance.

1. Introduction

Proton exchange membrane fuel cells (PEMFCs) are considered to be a main power source alternative for automotives, steady power stations, and submarines due to their high energy conversion efficiency, high power density, quick startup, and low environmental pollution [1-4]. Pure hydrogen is normally used as

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a fuel in such PEM fuel cell systems, and unused hydrogen is discharged along with inert gases into the atmosphere [2]. However, for maximum system efficiency and safety it is better if these systems consume as little fuel as possible for a given output power and to minimize the emitted hydrogen.

The ratio of hydrogen usage for generating thermal and electrical energy to the total hydrogen supplied to a fuel-cell is known as the fuel utilization. Therefore, for a 100% fuel utilization (or in dead-end mode), the amount of hydrogen fed into the anode would be the same as the flow rate of hydrogen required for the electrochemical reactions. However, in dead-end operation there is a high risk of fuel starvation at the outlet of the fuel cell, which can result in unstable cell voltages and cell degradation [5-7]. The major causes of fuel starvation are the accumulation of liquid water at anode and cathode sides [7-8]. Liquid water back-diffuses from the cathode to the anode side when too much water is collected at the former, causing flooding phenomenon at catalytic active sites [9]. The fuel utilization of a PEM fuel-cell system can be improved by employing a suitable hydrogen recirculation method or by designing a stack that avoids flooding.

Several studies have been carried out on improving fuel utilization. Nishikawa et al. [10] demonstrated a fuel utilization of 96% for a 5 kW-class PEM fuel cell stack that adopted an internal counter-flow humidification and stack separation method; the stack was divided into two blocks such that the exhaust hydrogen gas exiting the first block was fed into the second one after being separated from liquid water. Uno et al. [11] proposed a pressure swing recirculation system that operated using two check valves and fluid control devices without any recirculation pumps. In addition, they investigated the performance of this system in a single fuel cell; the operation of the single cell was stable over 10 h, but the cell voltage of the single cell fluctuated somewhat with the pressure changes.

Yongtaek et al. [12] experimentally studied the characteristics of water transport through the membrane for various values of operating parameters such as the relative humidity, air stoichiometry, current density, location of humidification, and membrane thickness. They applied the dead-end mode in the PEMFC system to evaluate the water-transport characteristics by observing the performance degradation of the PEMFC and by visualizing the accumulation of water. They reported that as the humidity of the reactant gas increased, the voltage drop accelerated and the amount of water accumulation at the anode increased.

Joong Kwon et al. [13] developed a flow field design by using CFD simulation, experimental testing and in-situ three-channel impedance analysis. They reported that in-situ three-channel impedance analysis successfully predicted the experimental result and explained the performance of each channel with a heterogeneous stack. They showed that in-situ multi-channel impedance had the advantages of reducing the analysis time and gathering synchronous data from several cells.

Hou et al. [14] systematically investigated the dynamic characteristics of actual hydrogen consumption under the step load variation and hydrogen purge operation of PEMFC through experimental tests on the self-developed fuel cell test platform. They improved the dynamic model of hydrogen consumption considering the effects of hydrogen purge operation and validated it with the test data under 3 different operating conditions. They reported that for each individual stack, the delay time in the step-up load stage was generally shorter than in the step-down one. Their suggested model indicates better agreement between test and simulation, especially in the working condition of hydrogen purge operation compared with the previous model.

Chen et al. [15] analytically and experimentally investigated an anode purge strategy of a single cell based on nitrogen accumulation. The dynamic model for the simulation has been presented in their previous work. Experiments were applied to calibrate the model and validated the simulation results. They confirmed that the cycle duration decreases with increasing current density when a single cell's anode is in the dead-end mode. They showed that the voltage predicted by the calibrated model has a good agreement with experimental data for constant-current operations. Also, they expressed the nitrogen accumulation in the anode as a function of operating current density and programmed it into the controller for anode purge management. They stated that the Current-integration method is a simple purge strategy; while nitrogen accumulation cannot be estimated.

Belvedere et al. [16] investigated the flooding phenomenon of a PEM fuel cell according to performance degradation. They analyzed the purge process at the anode side of the PEM and the purge operation that allows recovering the instantaneous fuel cell voltage drop. They tested the purge process at five different fuel cell power set points. They examined a new purge programming logic, characterized by variable flooding. They reported that by using this new logic the fuel cell efficiency increases significantly, especially at part-load, resulting in less input fuel. In addition, they concluded that the optimized purge process increases the fuel utilization factor.

Jenn et al. [17] experimentally investigated the effects of different hydrogen supply schemes on the efficiency of a PEM fuel cell system. The electrochemical performance of the flow-through mode was determined using a commercial test station that served as the benchmark for the fuel cell generator designs using the various hydrogen delivery schemes. They used Self-designed experimental setups and smart control strategies to examine the performance of the fuel cell generator in both dead-end and recirculation modes. They reported that transient measurements of the flow and electrochemical characteristics of conditional anode purging stabilizes the stack voltage for constant stack currents in the dead-end mode. They presented that the anodic stoichiometric ratio ranged between 1.3 and 1.6 under periodic step loading from 350 W to 700 W in the recirculation mode, which is comparable to that of the flow-through mode operated using the commercial test station. Their system efficiency was between 22% and 38%, whereas the stack efficiency remained constant at approximately 54±2% for the recirculation mode. As well, for stack powers less than 1.2 kW, both the dead-end and recirculation modes have roughly the same stack and system efficiencies.

Devrim et al. [18] designed and fabricated a 500 W air-cooled PEMFC stack. The stack was designed ssing electrochemical data extracted at 0.60 V and i=0.5 A/cm^2 from performance tests of a single cell. Twenty-four cells were assembled in the stack with external fixing plates. They achieved a maximum power of 647 W from the stack. They reported the PEMFC stack was stable during a 7 days test.

The operating parameters have a great effect on purge characteristics. Yang et al. [19] investigated the effects of different operating parameter on performance of PEMFC work under galvanostatic mode. They used the voltage base method for purge interval. The outlet valve was opened when the voltage reduced 0.1 V. They recorded local current densities to analyze the detailed of local characteristics. Their results showed that mean purge intervals reduced with increasing cathode inlet humidity and current density.

In-Su Han et al. [20] proposed a new design for a polymer electrolyte membrane (PEM) fuel-cell stack that can achieve higher fuel utilization. The basic concept of their proposed design was to divide the anodic cells of a stack into several blocks by inserting compartments between the cells, thereby constructing a multistage anode with a single-stage cathode in a single stack. They designed a 15 kW-class PEM fuel cell stack, fabricated, and tested it to investigate the effectiveness of the proposed design. The experimental results indicated that the amount of purge gas is significantly reduced; and consequently, a higher fuel utilization of more than 99.6% is achieved. Additionally, they reported that the output voltage of the stack fluctuates much less than that of conventional fuel cells owing to the multistage anode designs. Also, recently In-Su Han et al. [21] developed a cascade-type PEM fuel cell stack and cell components for the propulsion of an underwater vehicle. The stack was designed and fabricated to meet some design requirements such as: air independent operation with hydrogen and pure oxygen, high hydrogen and oxygen utilizations, low hydrogen and oxygen consumptions, a high ramp-up rate, and a long lifetime. They tested and analyzed the basic, load-following, and long-term performances of the cascade-type stack. They obtained a high stack efficiency of more than 65% at the rated power because of a higher average cell voltage and higher operating pressure.

Many researchers have investigated the performance and design of dead-end stacks, but none of them concentrated on the cascade type of a PEMFC stack with an internal manifold which dramatically decreases the weight, size and volume of the stack.

In this study, a novel cascade type dead-end PEMFC stack with an internal manifold was designed, fabricated and tested for the first time. In addition, using an innovative implementation led to the division of anodic and cathodic cells of the stack into two stages to achieve higher stoichiometry for the first stage while the stoichiometry of the stack was one. After activation of the stack the basic performances, such as the polarization curve, power generation, hydrogen and oxygen utilizations, and hydrogen and oxygen consumptions, were evaluated meticulously. The effect of purge time on the performance of the stack at time base approach was investigated. Using the newly applied design, high hydrogen and oxygen utilizations, low hydrogen and oxygen consumptions, a high performance and low volume and weight of stack would be achieved.

2.New stack design

Fig. 1 shows the schematic depiction of the proposed design for a PEM fuel-cell stack without any hydrogen and oxygen recirculation devices. Liquid separators were used to remove liquid water from the hydrogen and oxygen exiting in each stage. The fabricated 1000W PEM fuel cell stack and the test station equipped with cell voltage monitoring cables are depicted in Fig. 2. The total number of cells is

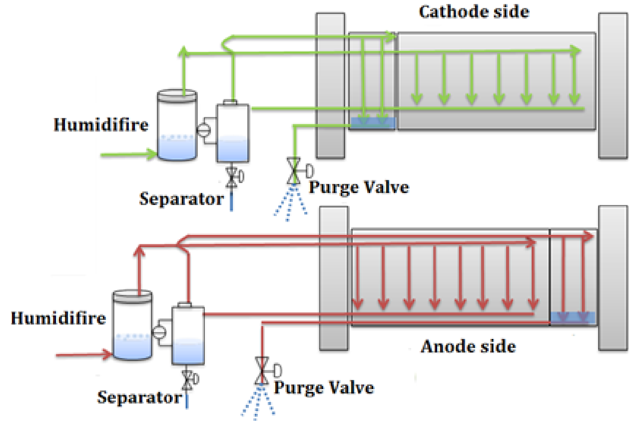


Fig. 1. Schematic of the proposed PEM fuel-cell stack design.

14. The first 12 cells are included in the first stage of hydrogen while the others are considered for the second stage. The second 12 cells are included in the first stage of oxygen. The stoichiometry values for the first and second stages are 1.17 and approximately 1, respectively. Furthermore, the geometry of the anode and cathode flow field is depicted in Fig. 3.

3. Test bench

The process flow diagram (PFD) of the test bench is presented in Fig. 4. An in-house fuel cell test station was used to test the stack. Hydrogen and oxygen are fed into the humidifiers and separators before entering the stack. Two solenoid valves are used after the gas tank to allow the choice of which gas is entering the stack: reactant gas or nitrogen. The inlet pressures of hydrogen and oxygen are controlled using forward pressure regulators. The residual gases from the stack are intermittently discharged into the surrounding environment by opening the purge valves under certain conditions: the anode purge valve opens for a short period whenever the voltage of the anode monitoring cell drops by a specified amount below the average cell voltage of the stack, and similarly, the cathode purge valve opens whenever the voltage of the cathode monitoring cell drops by a specified amount below the average

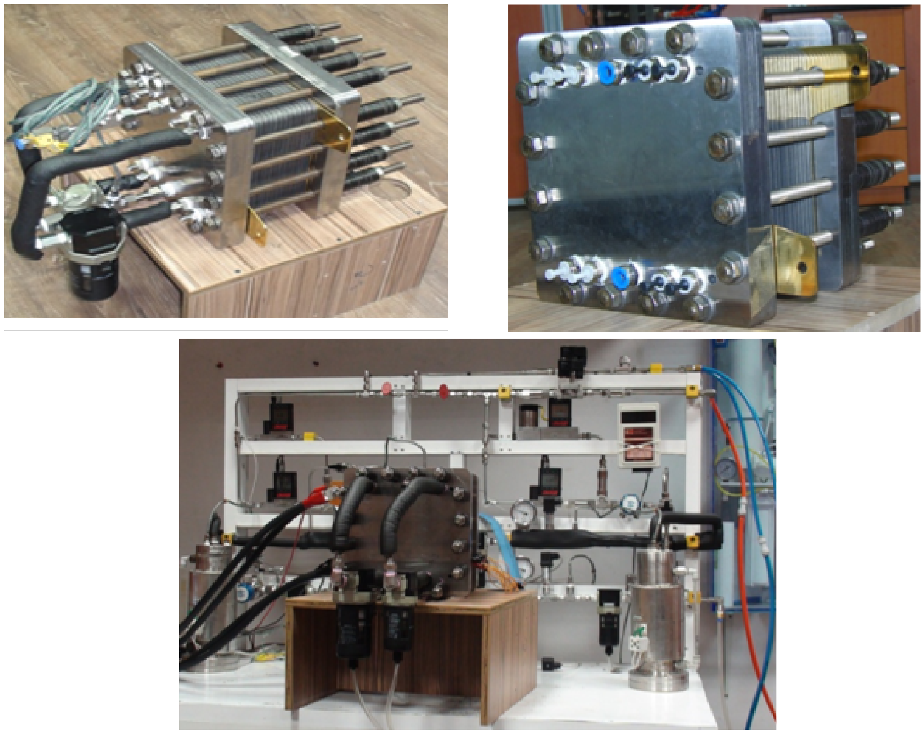


Fig. 2. 1000 W dead-end stack with liquid separators, cell voltage monitoring cables, and an in-house test system.

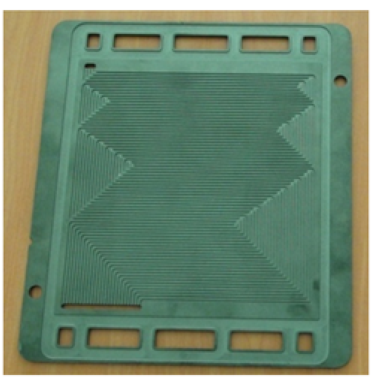


Fig. 3. Geometry of anode and cathode flow field.

cell voltage. The purge-gas flow rates are measured using mass flow indicators installed at the anode and cathode outlets of the stack. The inlet and outlet temperatures of the cooling water are regulated by a PID controller by setting the fan speed and changing the heat transfer rate in the radiator. LabView software is used for controlling and monitoringthe test station. A schematic of the LabView software is shown in Fig. 5.

The component of the test setup including types of sensors is presented in Table 1.

Furthermore, the test inputs (operating condition), sampling rate, measurement range and uncertainty are presented in Table 2.

4. Activation Process of MEA

One of the main components of PEM Fuel Cells is the membrane-electrode assembly (MEA). Their best performance is achieved when they are activated properly. To this end, a fuel cell is operated at an elevated temperature and pressure for a couple of hours. The performances of the resulting MEAs improve dramatically after this procedure. The activation process increases the number of accessible active sites in the catalyst layer thus leading to enhanced catalyst utilization and better fuel cell performances. In the present investigation, the stack is initially conditioned according to PaxiTech company activation procedure mentioned in Table 3, and then the PEMFC performance is measured.

Based on the obtained result two and a half hours are needed to complete the conditioning procedure. The

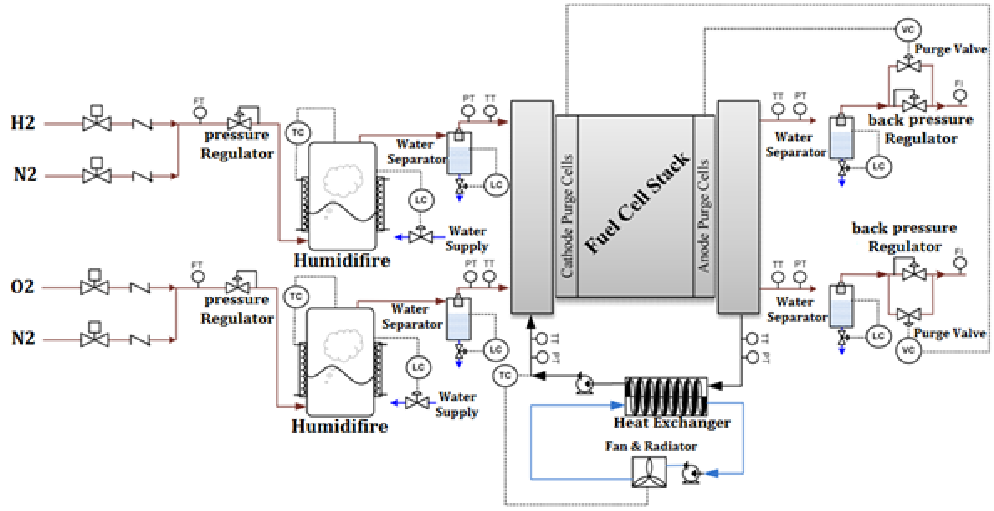


Fig. 4. Process flow diagram of applied test bench.

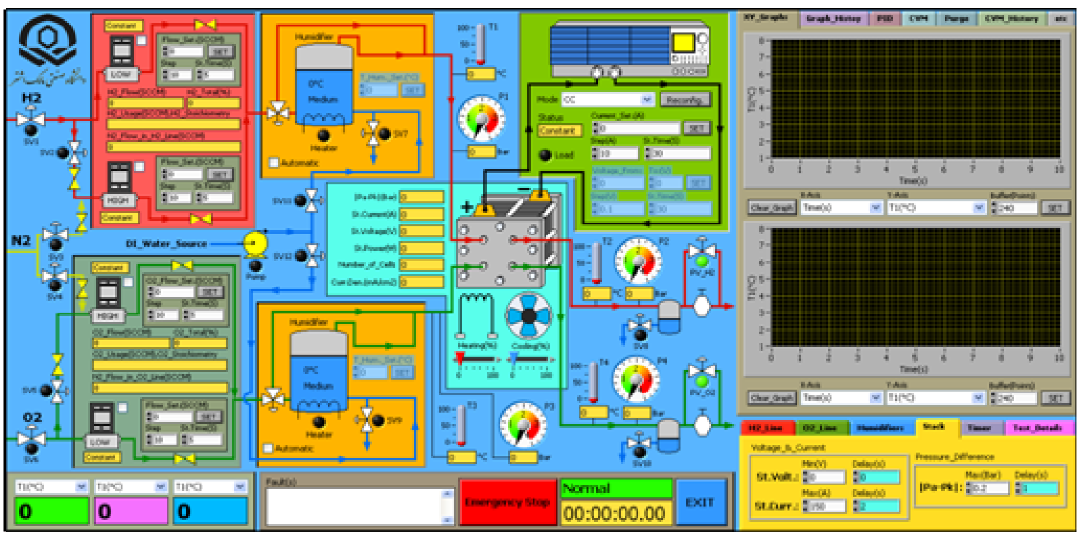


Fig. 5. LabView software for controlling and monitoring of test station.

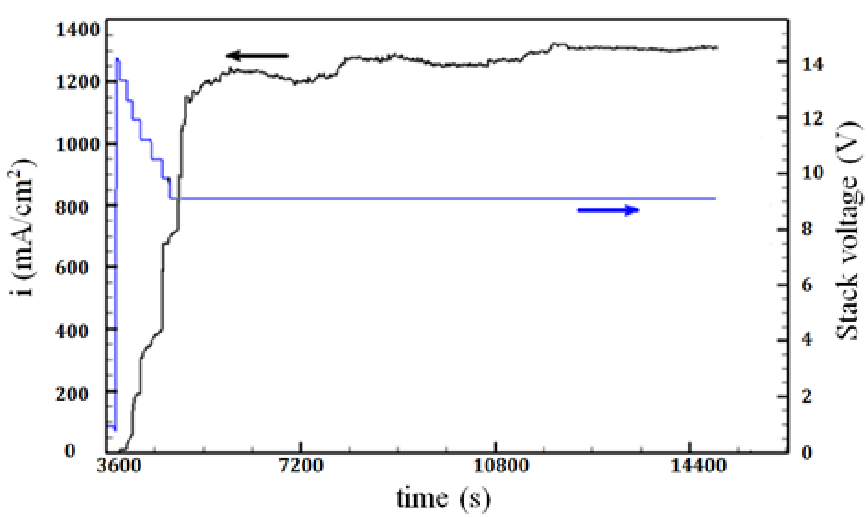


Fig.6. Variation of voltage and current with time in the activation process (Inlet humid of H2 =0%, inlet humid of O2>80%) a) PaxiTech company and b) present work.

Table 1. Components of the Test Setup

Description	Type
Stack temperature	PT100
Coolant mass flow rate	Rotameter
Gas mass flow rate	Alicat Mass Flow Controller
Gas pressure at outlet port	BD sensor pressure transmitter
Gas temperature at fuel inlet	PT100
Gas temperature at oxidant inlet	PT100
Stack current	DC Shunt, Zigler, 500A/75mV
Fuel flow	Alicat Mass Flow Controller
Oxidant flow	Alicat Mass Flow Controller
Stack voltage	MWT4 Autonics
Individual cell voltages	Analogue Input, DAQ
Gas temperature at fuel outlet	PT100
Gas temperature at oxidant outlet	PT100
Stack coolant inlet temperature	PT100
Stack coolant out temperature	PT100
Coolant inlet-outlet temperature difference	Calculated
Pressure drop in fuel flow path	DPT (differential pressure transducer)
	BD sensor pressure transmitter
Pressure drop in oxidant flow path	BD sensor pressure transmitter
Pressure drop in coolant flow path	BD sensor pressure transmitter

Table 2. The Test Parameter Measurement Range and Uncertainty

Input Measurement	Range/Value	uncertainty	Sample rate
i	0.01- 1.2 A/cm^2	± 0.025 A/cm^2	
X_{fuel}	99.999 % H_2	± 0.005 %	
X_{O2}	99.995 % O_2	-	
p_{O2}	0-200 kPa	0.35 kPa	
p_{H2}	0-200 kPa	0.35 kPa	
Q_{fuel}	0-35 Nlpm	7.4 Nl/min	
Q_{ox}	0-20 Nlpm	43.3Nl/min	
St_{H2}	1-1.2	-	
St_{O2}	1-1.5		
RH_{O2}	95 % >	± 2 %	1 Hz
RH_{H2}	95 % >		
$T_{dew\ O2}$	58.9°C	± 2°C	
$T_{dew\ H2}$	58.9°C		
T_{stack}	70°C		
$T_{cool,\ in}$			
$T_{fuel,\ in}$	70°C		
$T_{ox,\ in}$			
Qcool	0-35 lpm	± 1 lpm	

Table 3. Parameters for Activation Procedure according to PaxiTech Company

	Temperature (°C)	Pressure (bar)	Stoichiometry	Gas Flow Rate (lpm)
Hydrogen	Dry	2	1.2	39
Fuel Cell	70			
Oxygen	53	2	1.5	24

diagram of current density at a constant voltage (V) is depicted in Fig. 6 to investigate its variation. The activation process is assumed complete when the current density variation is almost zero. As can be seen, the stack current density remains constant after 3h meaning the activation process is complete. The achieved result is verified by a comparison with the PaxiTech company activation procedure.

5. Result and discussion

After preconditioning, polarization curves for dead-end and open-end modes have been achieved and compared to each other. The operating conditions presented in Table 4, were applied to the stack during all the tests. Cell numbers 13 and 14 are considered as the hydrogen purge cells while the ones for oxygen are 1 and 2. In order to prevent a sudden decrease in voltage due to flooding, the purge cells for hydrogen and oxygen are assumed different.

A comparison made between the results obtained by dead-end and open-end conditions is shown in Fig. 7. It can be seen that for the proposed design, the dead-end mode has the same performance as the open-end one. In other words, for very low hydrogen and oxygen purges in the dead-end mode (0.7% for H_2 and 1.5% for O_2), its efficiency is higher than the open-end mode.

The effect of pressure on PEMFC performance is depicted in Fig. 8. With increasing pressure the gas diffusion on GDL and catalyst layer will increase and as a result the enhances performance .

In this study, two criteria are considered for purge procedures (i) time base and (ii) voltage base. Variation of voltage at stack and purge cells during different purge procedures are illustrated in Fig. 9. As can be observed, it is divided into four different parts. The first part is a time base purge at both anode and cathode sides and the second part is a voltage base purge at the anode side. The third and fourth parts are voltage base purges at the cathode side and a voltage base purge at both anode and cathode sides, respectively. Cell number 13 and 14 are purge cells for the anode side and cell number 1and 2 are for the cathode side. As can be seen, the cells voltages increase (decrease) when the purge valve opens (closes). The achieved results show that the stack voltage is more dependent on the purge of the cathode side than the anode side. In the time base mode, the stack voltage cannot be controlled properly; therefore, it is required to test the system at different times to determine the best time period for closing and purging the solenoid valve. It was also found that for the proposed stack, the optimum times for opening and closing the purge valve are 60 ms and 100s for cathodic cells and 60 ms and 200s for anodic cells.

Fluctuation of voltage in the hydrogen purge cells is shown in Fig. 10a. When flooding is negligible (i.e. low current density), the time base procedure should be applied while at high current density the voltage base should be considered. The results show that according to the applied design, the outlet solenoid valve can be closed without any significant decrease in cell output voltage. It is assumed that when the purge cell's voltage decreases 0.05 volt compared to the average voltage of cells the purge valve operates. However, owing to its time constant, a 0.1 volt drop in voltage is seen. As well, a difference between the voltages of purge cells can be observed that is related to the nonuniformity of gas distribution. As shown in Fig. 10, the stack voltage shows very small variations, while the purge cells voltages fluctuate significantly. These large fluctuations are mainly caused by the pressure oscillation or change in the 2^{nd} stage arising from the periodic opening of the purge valve.

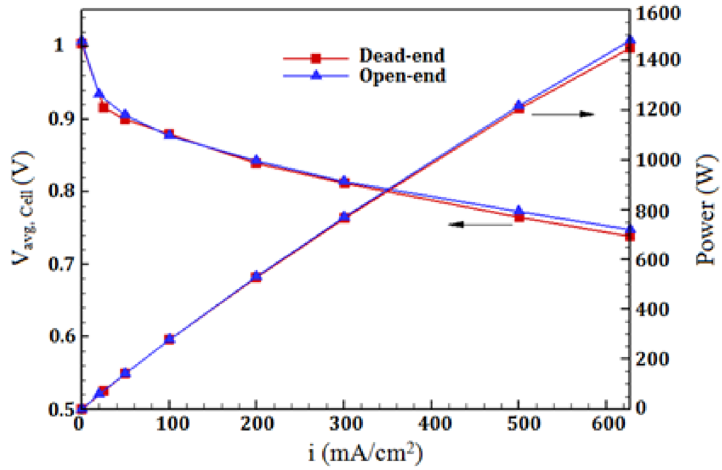


Fig. 7. Polarization curves of dead-end and open-end mode (st at open-end mode (H_2=1.2, O_2=1.5) and at dead-end mode (H_2=1.007, O_2=1.015), P=1 bar).

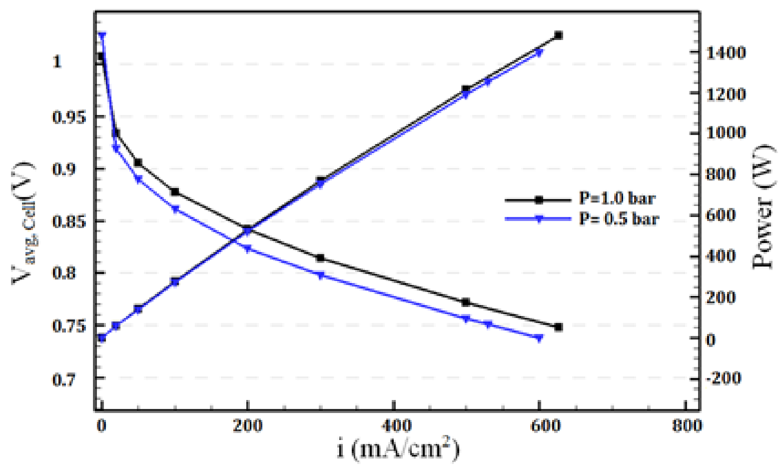
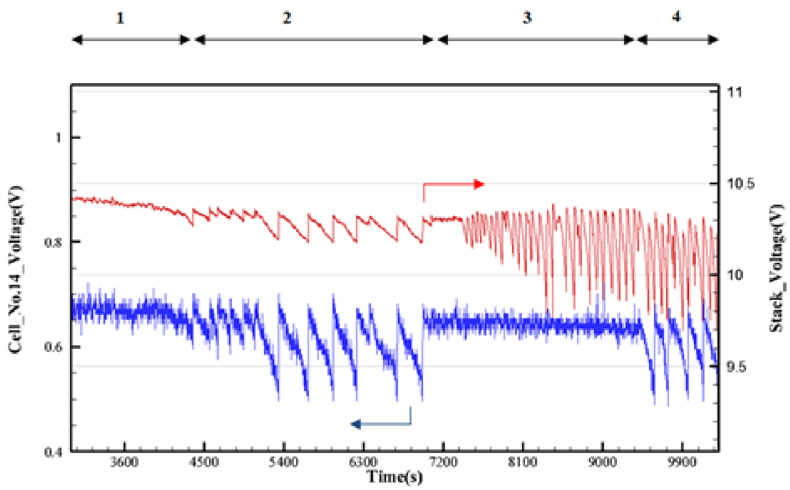


Fig. 8. Polarization curves of the dead-end mode (T= 70'C).

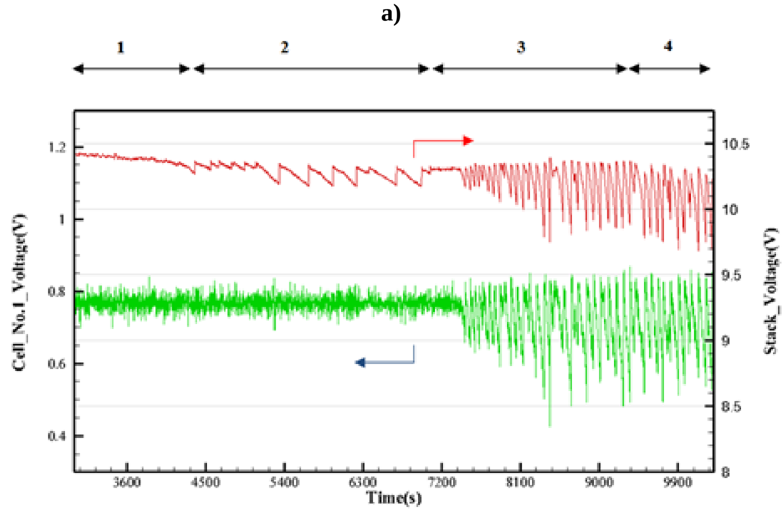
Table 4. Operating Conditions of the Stack

Operating variables	Operating conditions
Gas inlet temperature	70 °C (hydrogen)/70 °C (oxygen)
Gas inlet gage pressure	1 bar (hydrogen)/1 bar (oxygen)
Relative humidity of inlet gases	>80% (hydrogen)/>80% (oxygen)
Gas purity	99.999% (hydrogen)/99.95% (oxygen)
Cooling water temperature	70 °C (inlet)/≤75 °C (outlet)
Purge-valve opening time	60 ms (hydrogen)/60 ms (oxygen)
Purge-valve opening condition according to voltage base approach	$0.05V \leq (V_{avg} - V_{H2,mon})$ for anode, $0.05\ V \leq (V_{avg} - V_{O2,mon})$for cathode
Purge-valve closing condition according to time base approach	200s for anode and 100s for cathode

The vacillation of voltage in the oxygen purge cells is shown in Fig 9b. The same result can be seen but the fluctuation of voltage is higher than the hydrogen side. This can be explained by the formation and accumulation of water at the cathode sides and accumulation of impurities in the purge cells. This is conducted to decreasing the purge interval for water removal from the channels. It was found that both cathode purge cells show the same behavior, which is a sign of uniform gas distribution between cells. In addition, it is understood that when the time period for closing te hsolenoid valve increases due to water and impurities accumulation, the reduction of purge cells voltages increases.



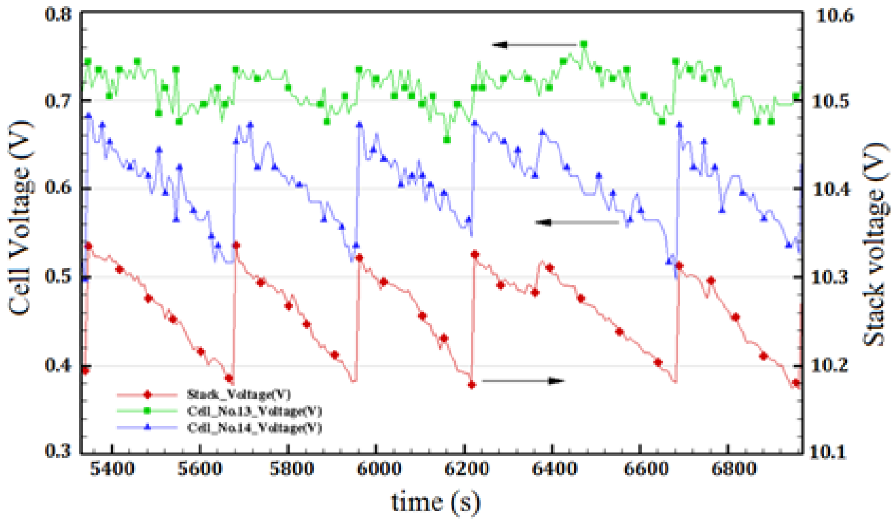
a)



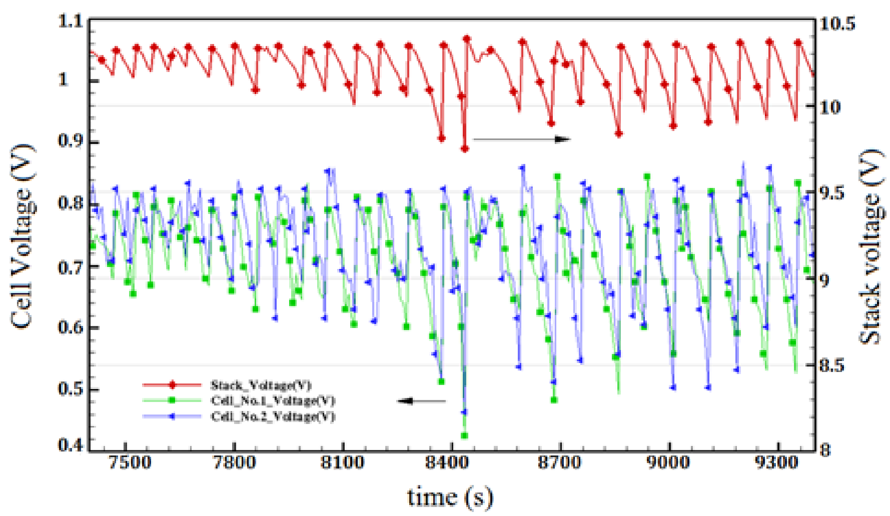
b)

Fig. 9. Variation of stack Voltage and purge cells a) cathode and b) anode with time in the dead-end mode (st (H_2=1.007, O2=1.015) (1- anode and cathode: open-end, 2- anode: dead-end, cathode: open-end, 3- anode: open-end, cathode: dead-end, 4- anode and cathode: dead-end).

The voltage of cells and average voltage of any step for both dead-end and open-end mode are depicted in Fig. 11. The figures show the same performances in a cascade type PEMFC for different operating modes due to their similar polarization curves. Therefore, it can be deduced that the proposed cascade type fuel cell improves the utilization of fuel and oxidant. In addition, the performances of the stack at dead-end and open-end modes are the same, confirming the ability of the cascade type PEMFC. As it can be seen from Fig. 10, the voltage level of the 2nd step of oxygen (the first 12 cells) is higher than the 1st step of oxygen and the 2nd step of hydrogen (the last 12 cells). This behavior can be explained by the gas flow distribution between cells. As shown in Fig. 1, a U type model is used for flow distribution in the 2nd step of the O_2 manifold. For a U type configuration the flow rate at terminal cells is less than the initial ones [22]. The low level of terminal cells voltage, especially 12, 13 and 14, is related to the lesser flow rate as well as inappropriate water management leading to the reduction of the electrocatalyst active area. This behavior is not seen in the first 12 cells due to hydrogen's lower viscosity and its other properties. The comparison made between the averaged voltage



a)



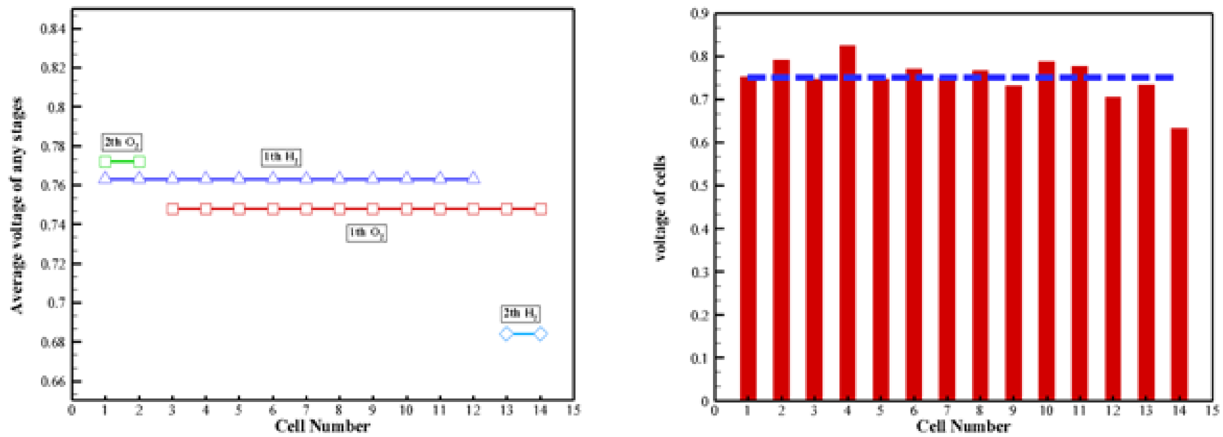
b)

Fig. 10. Variation of stack and purge cells voltage in the voltage base purge process a) Hydrogen and b) Oxygen (st (H_2=1.007, O_2=1.015)).

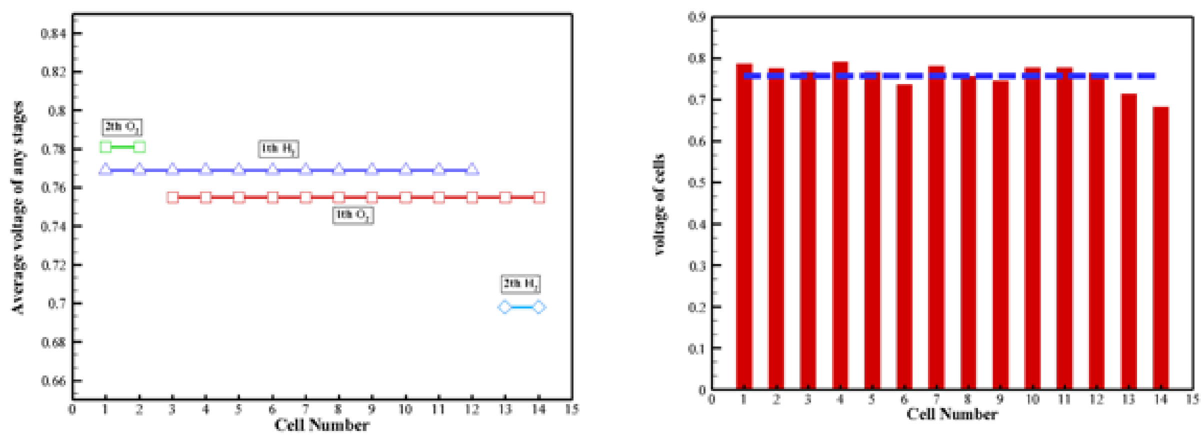
of different stages for open-end and dead-end modes shows that their behavior are the same. Since a higher stichiometry is considered for the open-end mode, the misdistribution of reactant gases reduces, resulting in a uniform voltage between cells (as can be seen in Fig. 11).Fig. 12 shows the hydrogen and oxygen utilizations as functions of the power output. The purge-gas flow rates are measured using mass flow indicators installed at the anode and cathode outlets of the stack. Utilization factor indicates the percent of reactants usage and can be given by:

$$\text{Utilization factor}\left(U_f\right)\% = \frac{\text{used reactant}}{\text{inlet reactant}} \times 100 \qquad (1)$$

The performance of PEMFC will be enhanced with the increase of the U_f base on Eq. 1, and as a result the capital cost will be decreased. As it can be seen, when the PEMFC output power increases, the U_f of oxygen decreases. Due to the cascade structure of the stack, when the drawn power from the stack rises, the amount of produced and accumulated water at the terminal stage of the cathode grows leading



a) Dead-end



b) Open-end

Fig. 11. Cells voltage and averaged voltage of any step for both dead-end and open-end modes.

to a bigger drop in voltage. Therefore, the purge valve needs to be opened with higher frequency resulting in a reduced U_f. At high current density, the amount of produced water at the cathode purge stage is dominant on water transfer from MEA due to the back diffusion mechanism, and it increases for bigger output power. Therefore, when the terminal stage operates at dead-end mode for water and impurities removal a short purge interval is needed. Furthermore based on test results, the utilization factor of hydrogen is increased with increasing power.

The major part of water created in the final stage of the anode is due to the existence of humidity in the hydrogen and the transfer of water from the cathode side to the anode side with back diffusion. Due to the electrosmotic drag and increasing of power, water transfer from the anode side to the cathode side increases, and subsequently water accumulation decreases. Finally, by increasing the purge interval the utilization of hydrogen will be increased.

5.Conclusion

In this study a cascade type dead-end PEMFC stack with internal manifold is designed, fabricated and tested. Both anode and cathode sides were kept in

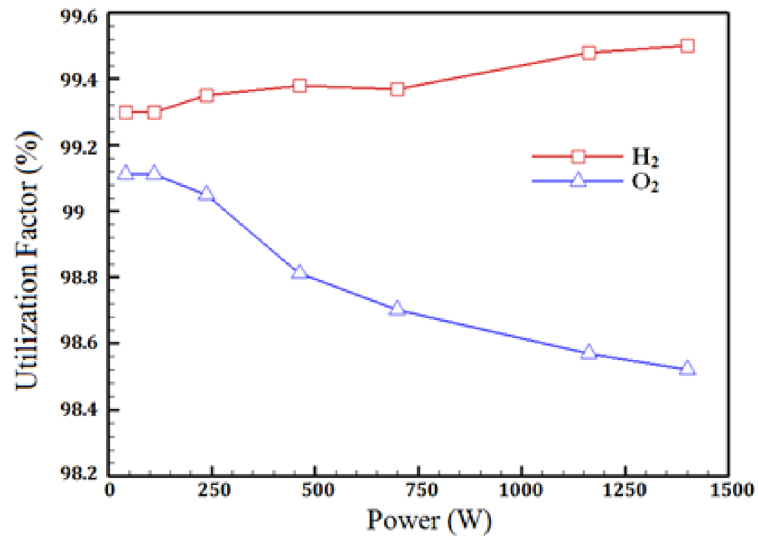


Fig.12. Utilization factor of reactant gases for different output powers.

dead-end mode. In addition, using an innovative implementation led to the division of anodic and cathodic cells of the stack into two stages to achieve higher stoichiometry for the first stage while the stoichiometry of the stack was one. This approach leads to a better handling of the flooding problem. The effect of purge time on the performance of the stack is investigated. For the designed PEM fuel cell, the performance (Polarization curve) of the dead-end PEMFC is the same as the open-end one. However, the efficiency of the dead-end PEMFC is higher than the open-end one due to the very low hydrogen and oxygen purges. As well, the fluctuations of voltage and pressure drop decreased as compared with a conventional dead-end stack. It is also understood that the fluctuation of voltage in the cathode purge cells is higher than the hydrogen ones, which can be explained by the formation and accumulation of more water at the cathode sides. This is conducted to(unclear? Did you mean “resulted in a”) decreasing purge interval for water removal. By using the proposed design, high hydrogen and oxygen utilizations, low hydrogen and oxygen consumptions, a high performance and low volume and weight of stack is achieved. It is confirmed that the cascade-type stack is superior to the single stage dead-end stack with an external manifold in terms of hydrogen and oxygen utilizations, weight, size and stack efficiency. In a forthcoming paper the humidifying section will be integrated with a PEMFC stack to reduce the system’s volume and size and decrease the number of controlling devices.

Nomenclature

GDL	Gas diffusion layer
F	Faraday’s constant(96,485 C /mol)
H_2	Hydrogen
I	Current (A)
i	Current density (mA/cm^2)
MEA	Membrane electrode assembly
p	pressure (Kpa)
P	Power (W)
PEMFC	Polymer electrolyte membrane fuel cell
Q	Flow rate (Nlpm)
RH	Relative humidity
SLPM	Standard liter per minute
St	Stichiometry
T	Temperature (K)
Uf	Utilization factor
v	Voltage

W	Watt
XO_2	Oxygen content in oxidant gas (molar fraction)
XH_2	Hydrogen content in fuel gas (molar fraction)

Subscrips

avg	Averaged
mon	Monitored

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