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A Study of Monitoring and Operation for PEM Water Electrolysis and PEM Fuel Cell Through the Convergence of IoT in Smart Energy Campus Microgrid

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스마트에너지캠퍼스 마이크로그리드에서 사물인터넷 융합 PEM 전기분해와 PEM 연료전지 모니터링 및 운영 연구

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Abstract In this paper we are trying to explain the effect of temperature on polymer membrane exchange water electrolysis (PEMWE) and polymer membrane exchange fuel cell (PEMFC) simultaneously. A comprehensive studying approach is proposed and applied to a 50Watt PEM fuel cell system in the laboratory. The monitoring process is carried out through wireless LoRa node and gateway network concept. In this experiment, temperature sensor measure the temperature level of electrolyzer, fuel cell stack and H_2 storage tank and transmitted the measured value of data to the management control unit (MCU) through the individual node and gateway of each PEMWE and PEMFC. In MCU we can monitor the temperature and its effect on the performance of the fuel cell system and control it to keep the lower heating value to increase the efficiency of the fuel cell system. And we also proposed a mathematical model and operation algorithm for PEMWE and PEMFC. In this model, PEMWE gives higher efficiency at lower heating level where as PEMFC gives higher efficiency at higher heating value. In order to increase the performance of the fuel cell system, we are going to monitor, communicate and control the temperature and pressure of PEMWE and PEMFC by installing these systems in a building of university which is located in the southern part of Korea.

- Key Words : PEMWE, PEMFC, LoRa Node and LoRa gateway, temperature effect, IoT convergence

요 약 본 논문은 현재 진행 중인 대한민국 남부지역에 위치한 대학 내 스마트에너지캠퍼스 마이크로그리드에서 대학 내 빌딩에 설치될 수소전기분해 이용 연료전지 시스템 운용을 위한 선행 연구로써 고분자전해질막 전기분해(PEMWE)과 고분자전해질막 연료전지(PEMFC) 장치에서 동시에 온도변화 효과를 연구하고자 한다. 전반적으로 실험실에서 50W 고분자전해질막 연료전지(PEMFC)을 사용하여 수행하였다. 모니터링 프로세스는 무선 로라 노드와 게이트웨이 네트워크를 구성하여 실행하였다. 그리고 PEMWE와 PEMFC에 대한 수학적 모델링과 운전 알고리즘을 제안하였으며 제안한 모델에서 PEMWE는 낮은 발열 기준에서 효율이 더 높음을, 반면에 PEMFC는 높은 발열기준에서 효율이 더 높음을 을 알 수 있었다. 향후 대학 구내 빌딩에 설치될 실증시스템 성능을 높이기 위해 PEMWE와 PEMFC의 온도와 압력을 모니터링, 통신 및 제어 등 연구개발을 통하여 구현할 예정이다.

- 주제어 : 고분자전해질막 전기분해, 고분자전해질막 연료전지, 로라 노드와 게이트웨이, 온도 효과, 사물인터넷 융합

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1. Introduction

A fuel cell is an electrochemical energy conversion device that directly converts hydrogen and oxygen into electrical energy, heat and water. Some important features such as high power density, low operating temperature, safe construction and fast start-up, simple and low cost make those particularly suitable for home appliance, vehicles and transportation tools as well as large building, hospital, school and universities[1]. So the demand of fuel cell is increased rapidly. Fuel cell are being commercialized to provide electricity to buildings like hospital, school, houses to replace batteries in portable electronic devices, and as replacements for internal combustion engines in vehicles. PEM fuel cell are lighter smaller and more efficient than other types of fuel cell. They have high power density and can vary their output quickly to meet shifts in power demand. In smart energy campus microgrid system, we need to manage the electrolyzer and fuel cells by transferring their realtime data through IoT and sensor nodes to the power management system and energy management system. [2]

2. PEMWE (Polymer exchange Membrane Water Electrolysis)

PEMWE uses electricity, a catalyst and a proton exchange membrane to split water into molecules of hydrogen and oxygen. PWM water electrolysis process is just reverse of a PEM fuel cell process however the materials are typically different from PEM fuel cell. In PEMWE, water is input and hydrogen and oxygen are the outputs.

PEMWE use a polymer electrolyte membrane as ionic conductor. Water is oxidized at anode and produced oxygen and hydrogen at the cathode [3]. The electrolyte consists of thin solid ion-conducting membrane. The membrane transfers the H+ ion from the anode to cathode side and separates the hydrogen and oxygen gases. Due to the use of dense proton exchange membrane PEM water electrolysis system can produce relatively high and suitable pressure of hydrogen gas. So PEM water electrolyzer can be scaled up to address the large scale energy demand. The chemical reaction in PEMWE is as follows[4],

At anode

$$H_2O(l) \rightarrow \frac{1}{2}O_2(g) + 2H^+ + 2e^- \qquad (1)$$

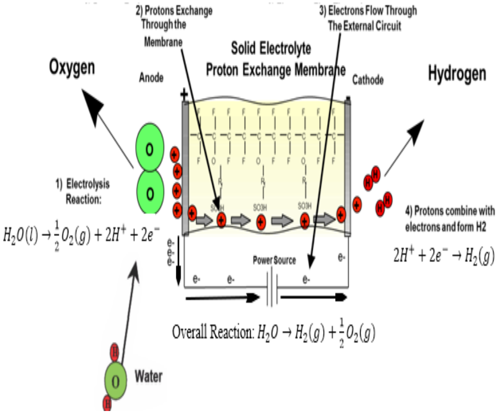
At Cathode:

$$2H^+ + 2e^- \rightarrow H_2(g) \qquad (2)$$

Overall Reaction:

$$H_2O(l) \rightarrow H_2(g) + \frac{1}{2}O_2(g) \qquad (3)$$

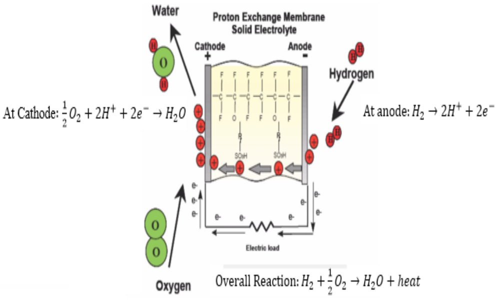
Components of PEM water electrolysis: Palladium or platinum at the cathode for the hydrogen evolution reaction and iridium or ruthenium oxides at the anode for the oxygen evolution reaction



[Fig. 1] PEM Water Electrolysis electron flow diagram with reaction [5]

3. PEMFC (Polymer Exchange Membrane Fuel Cell)

PEMFC is also called proton exchange membrane fuel cells (PEMFC) use a thin (50mm) proton conductive polymer membrane (such as perfluorosulfonated acid polymer) as the electrolyte. The catalyst is typically platinum supported on carbon with loadings of about 0.3㎎/㎠, or, if the hydrogen feed contains minute amounts of CO, Pt-Ru alloys are used. Operating temperature is typically between 40℃ and 80℃. PEM fuel cells are a serious candidate for automotive applications, but also for small-scale distributed stationary power generation, and for portable power applications as well.



[Fig. 2] PEMFC electron flow diagram [6]

In PEM fuel cell hydrogen side is negative and is called anode while the oxygen side is positive and is called cathode. The electrochemical reactions in PEM fuel cell occurs simultaneously on both anode and cathode sides of the membrane. The basic reactions in PEM fuel cell are:

At anode

$$H_2 \rightarrow 2H^+ + 2e^- \tag{4}$$

At Cathode

$$\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O \tag{5}$$

Overall Reaction

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O + Heat \tag{6}$$

The maximum amount of electrical energy generated in PEMWE and PEM fuel cell is resemble with Gibbs free energy $\triangle G$,

$$W_{el} = -\triangle G \tag{7}$$

The theoretical potential energy of fuel cell is given by, E,

$$E = -\frac{\triangle G}{nF} \tag{8}$$

Where n is number of electrons, F is the Faraday's constant (96,485 Column/electron-mole). At 25℃ and atmospheric pressure, the theoretical PEM fuel call potential is

$$E = -\frac{\triangle G}{nF} = \frac{237.340 Jmol^{-1}}{2 \times 96{,}485\, Asmol^{-1}} = 1.23\ Volts \tag{9}$$

By assuming the all Gibbs free energy can be converted into electrical energy then the maximum efficiency of fuel cell can be calculated by using Gibbs free energy equation, △G= -237.34 kJ/mol and by using high heating value of hydrogen(in liquid form) △H= -286.02 kJ/mol is 83% at 298.15K. But due to ohmic, activation and mass transportation losses, the practical efficiency of fuel cell will be 40%~60% only.

$$\eta_{HHV} = -\frac{\triangle G}{\triangle H} = \frac{\triangle G}{\triangle H_{HHV}} = \frac{237.34}{286.02} = 83\% \tag{10}$$

However, $\triangle H_{LVH}$ is used to express the fuel cell efficiency to compare it with internal combustion engine. Thus, the efficiency of fuel cell at low heating value of hydrogen gas (in vapour condition) can be calculated by using, △G= -228.74 kJ/mol, low heating value of hydrogen $\triangle H_{LHV}$ = -241.98 kJ/mol[7]. Then efficiency for LHV level becomes,

$$\eta_{LHV} = -\frac{\triangle G}{\triangle H} = \frac{\triangle G}{\triangle H_{LHV}} = \frac{228.74}{241.98} = 94.5\% \tag{11}$$

The equation (10) and (11) shows the relation between enthalpy and the efficiency of the fuel cell. The efficiency of the fuel cell is inversely proportional to the enthalpy (∆H) of the water electrolysis system. This means lower enthalpy value gives the higher efficiency of the system.

4. Mathematical Model

Due to the irreversible losses in thermodynamic potential (E), the actual potential (Vcell) is decreased. When current flow, the deviation from the thermodynamic potential occurs correspond to the electrical work performed by the cell. The deviation from the equilibrium value is called overpotential and is denoted by η. There are mainly three types o f potential loss in the fuel cell. These are active overpotential, ohmic overpotential and concentration potential.

i) Active Polarization Loss: It is also called active over potential loss. According to Sluggish electrode kinetics some voltage difference is required to get electrochemical reaction running properly. At higher the exchange current density, lower activation polarization losses occur. If anode polarization is neglected then it will be similar to Tafel Equation which becomes

$$\eta_{active} = \frac{RT}{\alpha F} ln(\frac{i}{i_0}) \tag{12}$$

ii) Ohmic Polarization Loss: In the fuel cell ohmic polarization loss occurs due to the electrical resistance losses such as resistance of imperfect electrodes and the resistance of the polymer electrolyte membrane to the ions.

$$\eta_{ohmic} = iR_i \tag{13}$$

iii) Concentration Polarization Loss (Mass transportation loss): Concentration losses is caused by the mass transfer limitations on the availability of the reactants near electrodes. Also if the reaction product accumulates near the electrode surface and obstructs the diffusion paths or dilutes the reactants then the mass transportation loss or concentration polarization loss occurs.

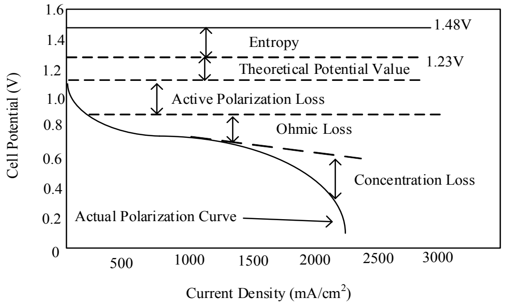
$$\eta_{concentration} = (\frac{RT}{nF}) \ln(\frac{i_L}{i_L - i}) \tag{14}$$

The active and concentration polarization can occur at both anode and cathode. Thus the actual cell voltage can be calculated by subtracting the different losses from the total voltage generated become

$$v_{cell} = E - \eta_{active} - \eta_{concentration} - \eta_{ohmic} \tag{15}$$

The actual polarization curve can be obtained from the following equation,

$$V_{cell} = E - \frac{RT}{\alpha F} ln(\frac{i}{i_0}) - \frac{RT}{\alpha F} ln(\frac{i_L}{i_L - i}) - iR_i \tag{16}$$



[Fig. 3] I-V Characteristic curve of PEM fuel cell for different losses [4]

Figure 3. shows the different polarization loss and the resulting actual polarization curve which is one of the important characteristic of fuel cell. It has greater impact on it's performance. The performance of fuel cell depends upon the different operating condition such as temperature, pressure, humidity, concentration of gases, flowrate. Generally, at 1 atmospheric pressure a fuel cell can produced 0.6A/㎠ at 0.6V [8]. It gives better performance at temperature 60℃ to 80℃.

The efficiency of fuel cell is defined as the ratio of output work rate to the product of the hydrogen consumption rate (m_{H_2}) and lower heating value of hydrogen gas ($LHV_{H_2} = 119.93KJ/g$) is given by [9]

$$\eta_{fc} = \frac{w_{gross}}{m_{H_2} \times LHV_{H_2}} \tag{17}$$

The output voltage of the stack for the given output current is determined by gross output power and is given by

$$W_{gross} = I \times V_{cell} \tag{18}$$

The output current is correlated with the hydrogen mass flow rate (MW_{H_2}) which is given by [9]

$$m_{H_2} = \frac{I\times MW_{H_2}}{2F} \tag{19}$$

Thus the thermodynamics efficiency of the fuel cell is given by

$$\eta_{FC} = \frac{2\times F\times V_{cell}}{MW_{H_2}\times LHV_{H_2}} \tag{20}$$

Similarly, the efficiency of fuel cell at lower heating alue of hydrogen gas is given by

$$\eta_{LHV_{H_2}} = \frac{V_{cell}}{1.254} \tag{21}$$

By solving equation (20) and (21) we get

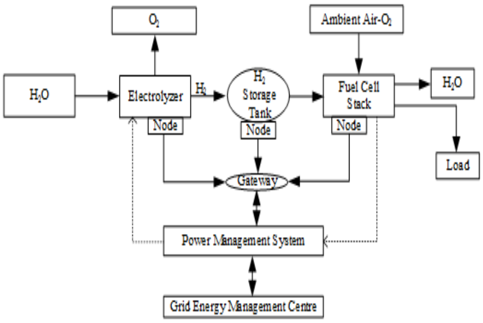
$$LHV_{H_2} = \frac{2.508\times F}{MW_{H_2}} \tag{22}$$

Equation (22) shows the inverse relation of lower heating value of hydrogen gas to the hydrogen gas flow rate. If we increases the hydrogen gas flow rate then lower heating value of hydrogen gas will be decreases, similarly if we decreases the flow rate of hydrogen gas then lower heating value of hydrogen increases.

If we putt the LHV value of equation (22) in the efficiency equation (11), we can get the efficiency of fuel cell. Higher value of enthalphy gives lower percentage of efficiency and lower value of enthalphy gives maximum efficiency. Thus we need enthalphy value should be as low as possible. Theoretically it will be large but practically efficiency of the fuel cell is always less than 60%.

5. Operation Algorithm for PEMWE

i) Input Water (H_2O) to Electrolyzer
ii) Split water into Hydrogen and Oxygen
iii) Generated Hydrogen is stored in storage tank
iv) Hydrogen goes to FC Stack
v) H_2 gas combine with air and electricity is generated in fuel cell stack
vi) Generated electricity goes to load
vii) Transmit the information by using sensor and LoRa node
viii) Collect the information of different part by using Cognitive Radio(CR) environment through base station
xi) Controlled the system from power management System
x) Handled by Campus Management

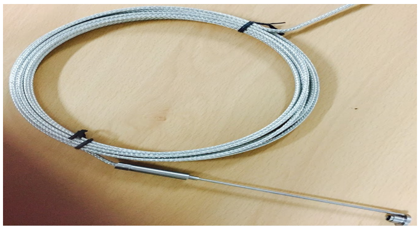


[Fig. 4] Block Diagram of PEM Water Electrolysis

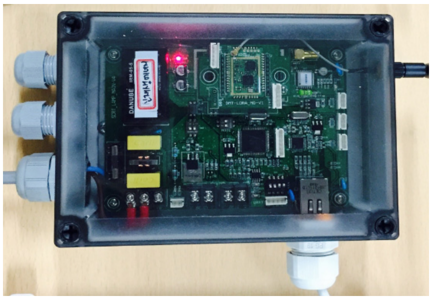
The block diagram of PEM Water Electrolysis of fuel cell is shown in figure 4. In this experiment, we used pure distilled water in electrolyzer, where hydrogen and oxygen is separated through electrolysis process. The produced oxygen goes to the environment and generated hydrogen is goes to the cylinder. There are different influencing parameters for the performance of the fuel cell, among them we are observe and monitor the effect of temperature on the system. Temperature of the system directly influence the voltage, current, power and efficiency of the fuel cell. As a result performance of the system will be changed [10, 11]. So in this experiment we studied about temperature effect and trying to monitor and control in real time and increased the performance of the system.

In this model each system of fuel cell are connected with gateway through node individually. Each node has individual sensor and A/D converter. A/D converter can convert measured value of analog data into digital data and node can send that data to the base station. We communicate to each part through base station and control from the power management Centre. The performance of PEMWE is highly influenced by different parameters. Among them temperature has significant effect on the PEMWE. So we can control the temperature of each part of PEMWE and increase the performance of our system.

Practically, we use 50 watt hydrogen fuel cell. Which can work below 50℃ only. Above this temperature, system will auto cutoff to prevent from the system from over heating. In figure below, we can see the different equipments which are used in PEMWE signal communication and control. In figure 5. we can see the temperature sensor which can sense the temperature of different part of PEMWE system and transmit to the base station.

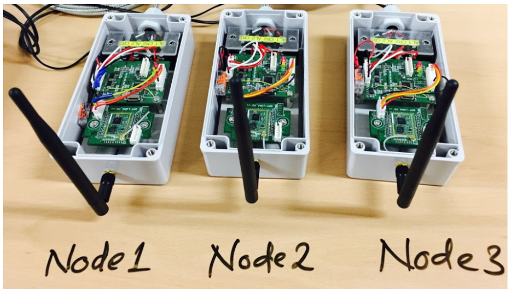


[Fig. 5] Temperature Sensor



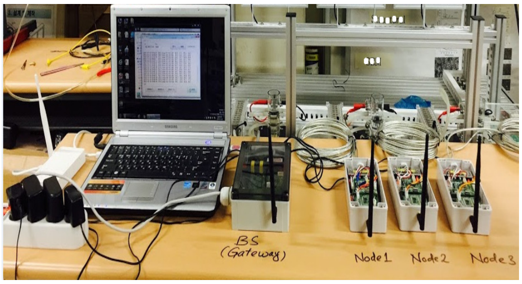
[Fig. 6] Base Station/Gateway

The base station is shown in figure 6. It is also served as a gateway to communicate the signal to the control center. For the real time monitoring, communication and control we can use both wire or wireless network Cognitive Radio environment[12].



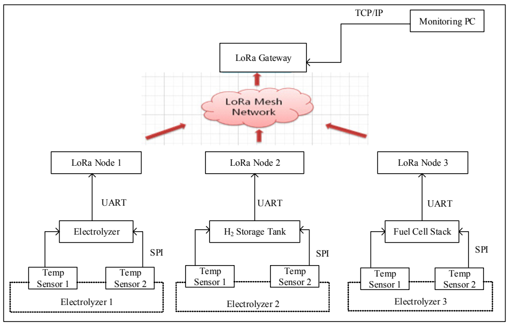
[Fig. 7] Nodes used in PEM Water Electrolysis

The Internet of Things (IoT) is an intelligent network that provides valuable information between the consumers, manufacturers and utility providers. The various things such as Radio-Frequency Identification (RFID), smart meters, sensors, actuators, and smart phones are able to interact and communicate with each other through unique addressing schemes, and cooperate with their neighbors to achieve common goals [13, 14]. When IoT technology is deployed in Smart Energy Campus Microgrid system, it forms an enormous smart network comprised of people and equipment, with various kinds of existing network technology, middleware technology, database technology etc. [15, 16]. To monitor, coordinate and synchronize the transmission and distribution of electrical power over large geographic areas we need better communication with system and power control center. So we need to implement LoRa technology based node. LoRa technology can communicate long range with low data rate and consume less power with both radio frequency (RF) and wired. Lora node and gateway technologies are known as Low-Power Wide Area Network radios, or LPWAN. It provides better sensitivity and can be demodulated over noise floor below -30㏈. It is more robust to jamming, noise and interference and can support variable data rates and multi-channel simultaneously. LoRa technology used unlicensed spectrum by using cognitive radio environment. LoRa networks can transmit up to 22 ㎞s when there is no obstruction, and up to 2 kilometers in obstructed environments. LoRa radios transmit at 0.30 to 50 Kbits per second at frequencies between 150 ㎒ and 1㎓ (usually between 850 ㎒ and 1 ㎓) [17].



[Fig. 8] Actual PEMWE Model used in experiment

The figure 9. shows the block diagram of LoRa networks having communication between the different part of PEMWE to the power management center by using wire and wireless technology. LoRa gateway is opportunist and can used unused frequency spectrum by using cognitive radio environment and increase the number of user and remove the frequency shortage problem caused by increasing number of mobile users and number of online applications.

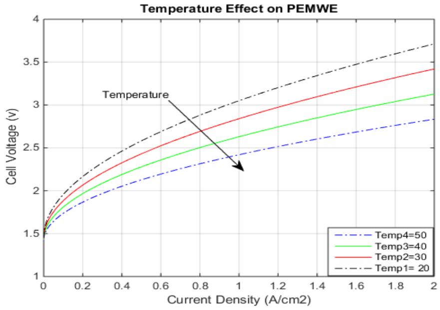


[Fig. 9] Connection between LoRa Nodes to different parts of PEMWE through gateway

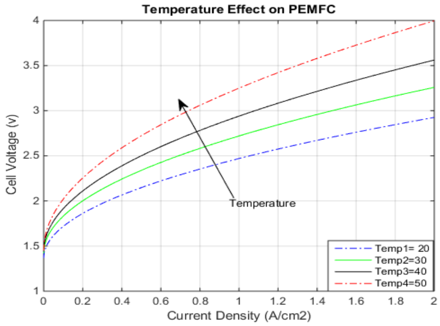
6. Simulation Results

By using experimental data and equation (10), (11) and (22) in MATLAB, we can plot the temperature effect. In this simulation we can see the voltage versus current density at different temperature. figure 10 shows that there is slightly gain in potential due to increase in temperature. In PEMWE we increased temperature from 20℃ to 50 ℃ at constant atmospheric pressure, as a result we found voltage is slightly increased from 1.11Volt to 1.36Volt. So PEMWE can produce higher voltage at lower temperature. Thus PEMWE has higher performance at lower temperature but at higher temperature it's performance is decreased due to high heating value. So it gives better performance in lower temperature.

Similarly in the figure 11, we increased the temperature from 20℃ to 50℃ at laboratory pressure, the performance of the system slightly increased as a result efficiency also increased. SO we conclude that at higher temperature PEMFC can gives higher performance.



[Fig. 10] Performance of PEMWE at different Temperature



[Fig. 11] Performance of PEMFC at different Temperature

7. Conclusion

Experimentally it was found that temperature of PEMFC and PEMWE has significant effect in it's performance. PEMWE has higher performance at lower temperature whereas just opposite PEMFC has higher performance at higher temperature and lower performance at lower temperature. In PEMWE, when the LHV is small it has low value of enthalpy (△H) as a result it gives higher efficiency but when the temperature increased enthalpy (△H) also increased then it gives lower efficiency with lower performance. Similarly in PEMFC, when the exchange current density increases with the increase in fuel cell temperature, which reduces the active losses. Also higher temperature increase the mass transfer within the fuel cells and result in a net decrease in cell resistance (Wang et al. 2003)[18]. The current is varying linearly with mass flow rate of hydrogen due to increase in rate of electrochemical reaction. Cathode temperature does not affect fuel cell performance but higher operating temperature at the anode results in increase the performance of the PEM fuel cell.

All the data from electrolysis system are transmitted to the power management center through LoRa node and gateway. So we can control certain parameters and can be increased the system performance. Due to the increased number of online application and mobile users smart energy campus will suffered from frequency shortage problem that cause system hang long time but by using cognitive radio environment in LoRa node and gate it will solve that problem. It uses the unlicensed frequency spectrum as a result number of user will be increased and our PEMWE system will give higher performance.

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