

Optimum hydrogen generation capacity and current density of the PEM-type water electrolyzer operated only during the off-peak period of electricity demand

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Abstract

A requirement for widespread adoption of fuel cell vehicles in the transportation sector will be ready availability of pure hydrogen at prices that result in operating costs comparable to, or less than, that of gasoline internal combustion engine vehicles. The existing electrical power grid could be used as the backbone of the hydrogen infrastructure system in combination with water electrolyzers. A water electrolyzer can contribute to the load leveling by changing operational current density in accordance with the change of electricity demand. The optimum hydrogen generation capacity and current density of the polymer electrolyte membrane (PEM)-type water electrolyzer operated only during the off-peak period of electricity demand in respect of both the shortest time required for start and the higher efficiency of water electrolysis are obtained as $500 \text{ Nm}^3 \text{ h}^{-1}$ and 30 kA m^{-2} , respectively. This PEM-type water electrolyzer could be used in the hydrogen refueling stations and energy storage systems constructed around hydrogen.

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Keywords: Water electrolyzer; Polymer electrolyte membrane; Fuel cell vehicles; Load leveling

1. Introduction

Load factor of power generation plants in Japan has decreased from 70% in 1967 to 55% in 2000. It is estimated that the increase of 1% in load factor can attain the reduction of 0.14 trillion yen per year in the expenses and 0.58 trillion yen in the investment for the building of new power generation plants [1]. The Federation of Electric Power Companies in Japan sets improvement of load factor as one of comprehensive measures for the reduction of carbon dioxide emission [2].

Because of the progress of performance in recent years, good compatibility with the environment, low cost in mass production, and fast refueling time, fuel cell vehicles are among the leading contenders in emerging markets for zero emissions vehicles (ZEVs) [3]. A requirement for widespread adoption of fuel cell vehicles in the transportation sector will be ready availability of pure hydrogen at

prices that result in operating costs comparable to, or less than, that of gasoline internal combustion engine vehicles. The possible fuel options are hydrogen, methanol and gasoline [4–7]. Compressed gaseous hydrogen is stored directly for the first option. The vehicle becomes simpler in design, more energy efficient and less costly compared with the last two options. High-temperature fuel processors onboard are required to convert the liquid fuel to hydrogen for the last two options. Hydrogen is not widely distributed to consumers today in Japan to refuel a large number of fuel cell vehicles like gasoline. Hydrogen infrastructure costs are unacceptably high in the case where construction of a large steam reforming plant and truck delivery system as a liquid to refueling stations or a wide hydrogen pipeline system to refueling stations is assumed.

It was shown that hydrogen could be delivered to the fuel cell vehicle at lower cost by small-scale water electrolyzers in mass production installed at the local fueling station or fleet operator's garage [6,7]. This fueling approach avoids the need for a large fleet of cryogenic liquid hydrogen trucks or a massive hydrogen pipeline system. The existing electrical power grid could be used as the backbone of the hydrogen infrastructure system. Hydrogen in quantities that matches

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Nomenclature

A	active surface area of MEA (m^2)
A_f	cross-sectional area of flow passage (m^2)
C_i	specific heat ($\text{J kg}^{-1} \text{K}^{-1}$)
De	equivalent diameter of flow passage (m)
F	Faraday constant
g	acceleration of gravity (m s^{-2})
h	heat transfer coefficient between the de-ionized water in compartment for the anode in the electrolysis module and surface of MEA ($\text{W m}^{-2} \text{K}^{-1}$)
h_b	heat transfer coefficient of nucleate boiling ($\text{W m}^{-2} \text{K}^{-1}$)
h_{tp}	heat transfer coefficient of two-phase flow ($\text{W m}^{-2} \text{K}^{-1}$)
h_w	heat transfer coefficient of water flow ($\text{W m}^{-2} \text{K}^{-1}$)
H	molar enthalpy (J mol^{-1})
i	current density (A m^{-2})
n	number of electrons conducted under the water electrolysis
p_{water}	partial pressure of water vapor (Pa)
P	total pressure in the water electrolyzer (Pa)
Pr_L	Prandtl number of de-ionized water (-)
Q_G	volumetric flow rate of gas in the two-phase flow ($\text{m}^3 \text{s}^{-1}$)
Q_L	volumetric flow rate of liquid in the two-phase flow ($\text{m}^3 \text{s}^{-1}$)
Q_{waste}	waste-energy (J mol^{-1})
Q_{gen}	energy loss of water electrolysis (W)
ΔT	temperature increase per unit time (K s^{-1})
T	electrolysis temperature ($^{\circ}\text{C}$)
T_m	surface temperature of MEA (K)
T_w	temperature of de-ionized water in compartment for the anode in the electrolysis module (K)
V_c	electrolysis cell voltage (V)
V_{tn}	thermoneutral voltage (V)
V_{HHV}	higher-heating-value voltage (V)
W_i	weight (kg)
W_L	amount of de-ionized water flowing in each compartment for the anode in the electrolysis module (kg s^{-1})
W_G	amount of oxygen flowing in compartment for the anode in the electrolysis module (kg s^{-1})
X_{tt}	Lockhart Martinelli parameter
Y	molar enthalpy of water at the electrolysis temperature (J mol^{-1})
<i>Greek letters</i>	
α	coefficient
Φ	mole number of water evaporated for each mole of the generated hydrogen

η	electrolysis energy efficiency
λ_L	thermal conductivity of de-ionized water ($\text{W m}^{-1} \text{K}^{-1}$)
μ_L	viscosity of de-ionized water ($\text{kg m}^{-1} \text{s}^{-1}$)
μ_G	viscosity of oxygen ($\text{kg m}^{-1} \text{s}^{-1}$)
ρ_L	density of de-ionized water (kg m^{-3})
ρ_G	density of oxygen (kg m^{-3})

the incremental growth of fuel cell vehicle sales could be produced where and when it is needed.

A water electrolyzer can contribute to the load leveling by changing operational current density in accordance with the change of electricity demand. A water electrolyzer is operated under the higher current density during the off-peak period of electricity demand. On the other hand, it is operated under the lower current density during the daytime and peak period of electricity demand. As the case may be, a water electrolyzer stops during these periods. In this operational way a water electrolyzer starts and stops once a day.

All electric power companies in Japan set up an electricity cost scheme classified with both seasons and periods of time in a day in order to promote the consumption of off-peak power and repress that of peak power as exemplified in reference [8]. The time in a weekday is divided into three periods. The electricity cost is set up most expensive when the electricity demand becomes highest as peak load. On the other hand the electricity cost is set up cheapest in the nighttime when the electricity demand becomes lowest as off-peak load. On Sunday the electricity cost is kept constant in a whole day and the same as that during the nighttime in the weekday.

A water electrolyzer must be operated under the higher temperature in order to increase the energy efficiency of water electrolysis. However, a water electrolyzer operated in the above-mentioned operational way starts from a low temperature. It is necessary to make the whole heat capacity of water electrolyzer as small as possible in order to attain to the rated temperature for water electrolysis in shorter time and to be operated as long as possible within the limited nighttime when the electricity cost is the cheapest.

Energy storage system constructed around hydrogen is the combination of water electrolyzer, fuel cell and hydrogen storage device. Using a water electrolyzer, electricity production in excess of demand is converted to hydrogen. Electricity demand in excess of production is met by converting hydrogen to electricity through a fuel cell. In this system the above-mentioned characteristics of water electrolyzer concerning heat capacity are required.

In this paper, we examine the optimum hydrogen generation capacity and current density of the polymer electrolyte membrane (PEM)-type water electrolyzer operated only during the off-peak period of electricity demand in respect of both the shortest time required for start and the higher efficiency of water electrolysis. This PEM-type water

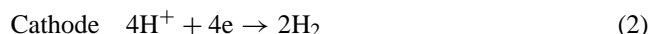
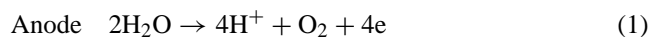
electrolyzer could be used in the hydrogen refueling stations and energy storage systems constructed around hydrogen.

2. PEM-type water electrolyzer

Water electrolyzers are divided broadly into two categories, namely, alkaline-type water electrolyzer and PEM-type water electrolyzer. PEMs work as electrolyte in the PEM-type water electrolyzer so that de-ionized water can be directly electrolyzed without the addition of strong electrolyte, such as potassium hydroxide. PEM-type water electrolyzer can operate over a wide range of temperature, pressure and current density compared with alkaline-type water electrolyzer. In this paper PEM-type water electrolyzer is adopted as the subject of investigation.

2.1. Electrolysis cell

Electrolysis cell is composed of separators, membrane electrode assembly (MEA), electric current collectors and gaskets as shown schematically in Fig. 1. MEA is an assembly of PEM and electrode catalysts. A solid sheet of perfluorocarbon sulphonate cation exchange membrane, such as Nafion manufactured by Du Pont is used as PEM. Platinum group metal catalyst is metallized on both surfaces of PEM as the electrode. De-ionized water is electrolyzed in accordance with the following equations.



Oxygen is generated in the anode. Charge carriers are protons which are generated at the anode and move through PEM by passing from one fixed sulphonic acid group to the adjacent one. Protons recombine electrochemically with electrons, which pass via the external circuit, to form the hydrogen in the cathode. Since PEM is a physical barrier separating the hydrogen from the oxygen, it is necessary that

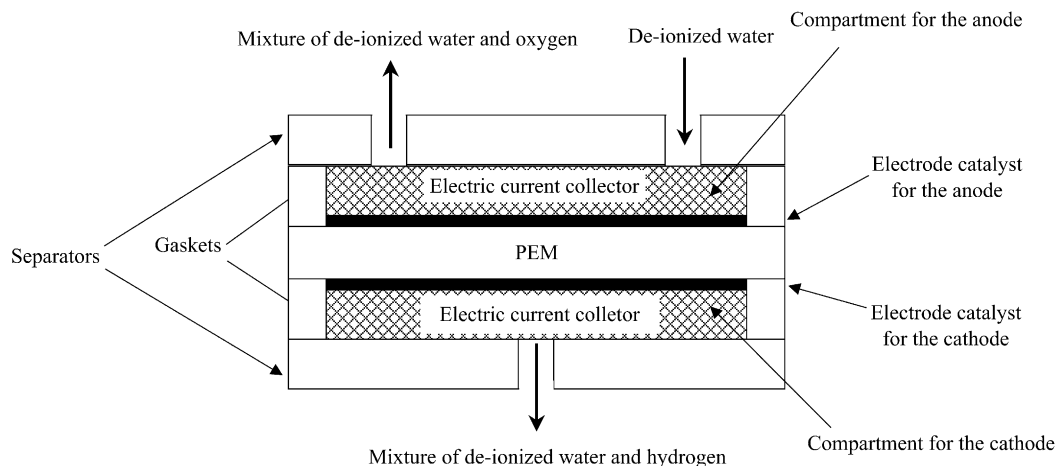


Fig. 1. Cross-sectional view of the electrolysis cell.

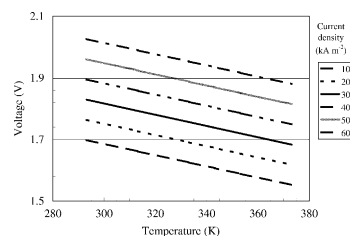


Fig. 2. Relations between the electrolysis temperature and electrolysis cell voltage using Nafion 112.

PEM must be free of defects and structurally strong enough to prevent the two gases from intermixing. For multiple cell arrangement as used in the large electrolyzers a bipolar current collector system is employed that requires separator sheets between cells. Namely, the above-mentioned parts are stacked in parallel and assembled to form the electrolysis module.

2.2. Electrolysis cell voltage

Overall electric energy consumption for water electrolysis is a major economic parameter for its success as a replacement for gasoline. The lower electrolysis cell voltage becomes, the more competitive cost of electrolytic hydrogen becomes. The electrochemical performances have been studied covering temperatures from ambient up to 373 K, current densities up to 60 kA m⁻² and polymer electrolyte membrane thickness from 50 μm (Nafion 112) to 180 μm (Nafion 117). The electrolysis cell voltage becomes lower when the electrolysis temperature becomes higher because of the activation of electrolysis catalyst metallized on the surfaces of PEM as shown in Fig. 2. Considering the decrease of mechanical strength caused by the swelling of PEM and the decrease of energy efficiency caused by the increase of gas permeation through PEM, the operational temperature of PEM-type water electrolyzer was determined as 353 K.

Relations between the current density and the electrolysis cell voltage at the water electrolysis temperature of 353 K

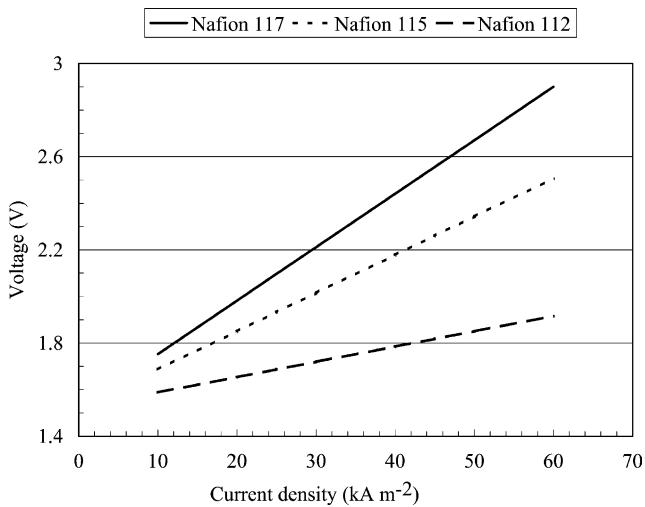


Fig. 3. Relations between the current density and electrolysis cell voltage at the electrolysis temperature of 353 K.

are shown in Fig. 3. The electrolysis cell voltage becomes lower when polymer electrolyte membrane becomes thinner because of the decrease of ohmic loss. In order to decrease the electrical power consumption for water electrolysis the thickness of PEM was determined as 50 μm (Nafion 112).

2.3. Flow diagram of the PEM-type water electrolyzer

PEM-type water electrolyzer is composed of electrolysis module, tank for oxygen separation, tank for hydrogen separation, circulation loop for the de-ionized water, de-humidifier, electrical power rectifier and control panel as

shown in Fig. 4. Inlet of compartment for the anode in the electrolysis module is connected to the circulation loop for the de-ionized water. Outlet of compartment for the anode in the electrolysis module is connected to the tank for oxygen separation. Compartment for the cathode in the electrolysis module is connected by piping to the tank for hydrogen separation. There are some molecules of H_2O transported with each proton from the anode to the cathode [9,10]. So the hydrogen contains some de-ionized water, which is separated in the tank for hydrogen separation.

An excess of de-ionized water is supplied to compartment for the anode in the electrolysis module by circulation pump. De-ionized water of 803.6 g is consumed to generate hydrogen of 1 Nm^3 . The remaining de-ionized water functions to cool the surface of MEAs. Temperature of de-ionized water in compartment for the anode of electrolysis module rises due to the heat generation at the surface of MEAs. Heat exchanger in the circulation loop for the de-ionized water removes this heat and keeps the rated temperature of de-ionized water for the electrolysis.

2.4. Hydrogen generation capacity

Scenarios for introduction of fuel cell vehicles are discussed in the research and development of international clean energy network using hydrogen (WE-NET) [11]. In these scenarios it is forecasted that 692 refueling stations for fuel cell vehicles will be built in Japan by 2020 of which on-site hydrogen generation capacity will be 500 $\text{Nm}^3 \text{h}^{-1}$. With reference to this capacity PEM-type water electrolyzer of which hydrogen generation capacity is twice as large as 500 $\text{Nm}^3 \text{h}^{-1}$ is considered in this paper.

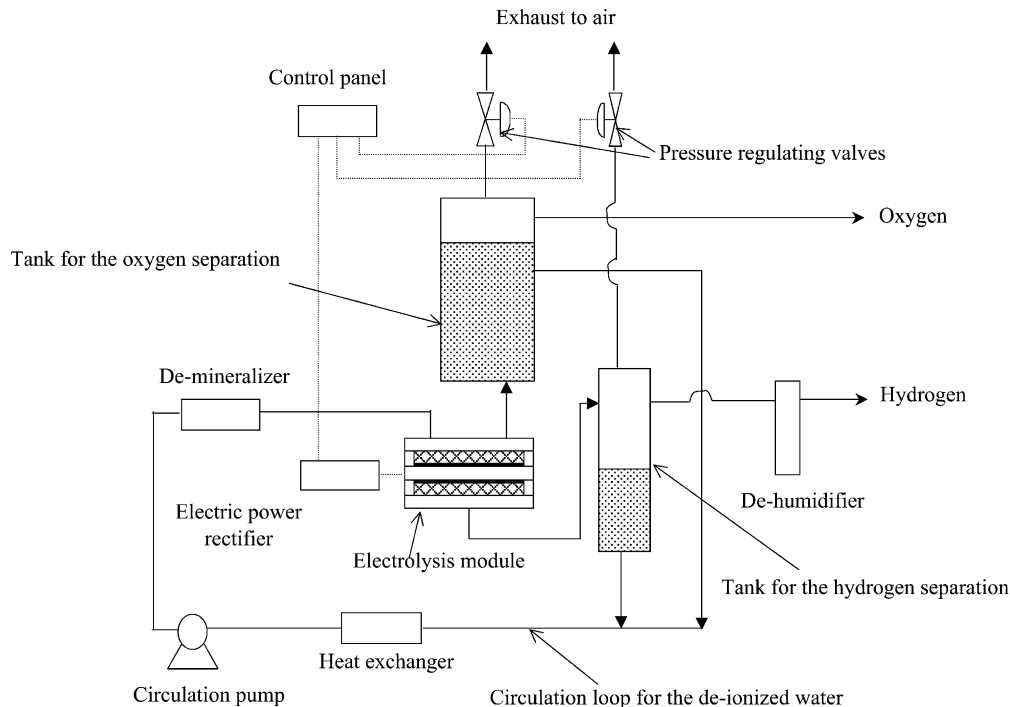


Fig. 4. Flow diagram of the PEM-type water electrolyzer.

A single function is frequently performed by multiple units. For example a plant's steam requirements may be generated in several boilers rather than in a large one. This may be done for one or more of the following reasons. Supplying all the demand from a single unit would require one so large that it would be impractical to build it. The operating range of certain equipment in the process may be so narrow that fluctuations in demand could be handled more efficiently by taking several units on and the remaining units off rather than by trying to adjust the output from a single unit. Production would not have to be curtailed when equipment failed or had to be shut down for maintenance if multiple units were available. In accordance to those reasons hydrogen generation capacity of $1000 \text{ Nm}^3 \text{ h}^{-1}$ is divided into those of several units as follows.

- Case 1: $100 \text{ Nm}^3 \text{ h}^{-1} \times 10$ units.
- Case 2: $200 \text{ Nm}^3 \text{ h}^{-1} \times 5$ units.
- Case 3: $500 \text{ Nm}^3 \text{ h}^{-1} \times 2$ units.
- Case 4: $1000 \text{ Nm}^3 \text{ h}^{-1} \times 1$ unit.

3. Heat transfer at the surface of MEA

De-ionized water supplied to compartment for the anode in the electrolysis module is used as a coolant for MEA. In the case where amount of supplied de-ionized water is insufficient, surface temperature of MEA becomes higher and MEA is damaged. In the worst case MEA is broken. On the other hand in the case where amount of supplied de-ionized water is excessive, electrical power consumption by the circulation pump and sizes of constituent parts, such as tanks and piping increase. As a result heat capacity of constituent parts increases and it takes more time for the PEM-type water electrolyzer to attain to the rating operational temperature. There is a trade-off problem between the surface temperature of MEA and amount of the water supplied to compartment for the anode in the electrolysis module. Heat transfer at the surface of MEA and temperature change of the PEM-type water electrolyzer can be described as follows.

3.1. Energy loss at the surface of MEA

LeRoy and Bowen [12], LeRoy [13] discussed the energy conversion of a real water electrolyzer as follows. In a real water electrolyzer which is operating with an electrolysis cell voltage V_c , it is convenient to think of a black box into which water at 293 K and at 0.10133 MPa is fed together with energy in the amount nFV_c and out of which comes wet hydrogen and wet oxygen together with waste energy in the form of radiation, convection and conduction. These waste-energy terms can be grouped together and defined as Q_{waste} . As the energy must be conserved,

$$nFV_c = nFV_{\text{tn}} + Q_{\text{waste}} = H(\text{wet hydrogen})_{T,P} + H(\text{wet oxygen})_{T,P} - H(\text{feed water})_{293 \text{ K}, 0.10133 \text{ MPa}} + Q_{\text{waste}} \quad (3)$$

$$nFV_{\text{tn}} = nFV_{\text{HHV}} + \Phi Y \quad (4)$$

$$V_{\text{HHV}} = 1.4756 + 2.252 \times 10^{-4}T + 1.52 \times 10^{-8}T^2 \quad (5)$$

$$\Phi = \frac{1.5 p_{\text{water}}}{(P - p_{\text{water}})} \quad (6)$$

$$Y = 42960 + 40.762T - 0.06682T^2 \quad (7)$$

Useful output from the expenditure of nFV_c is usually considered to be equivalent to the higher-heating-value (HHV) of the generated hydrogen, represented by the term nFV_{HHV} . It is customary to define the electrolysis energy efficiency η of an electrolyzer using this V_{HHV} where as

$$\eta = \frac{V_{\text{HHV}}}{V_c} \quad (8)$$

This definition of energy efficiency has become widely accepted.

Thermoneutral voltage V_{tn} is the voltage at which a perfectly insulated electrolyzer would operate if there were not net heat input and output. Thus thermoneutral voltage is equal to the sum of higher-heating-value voltage and a voltage corresponding to the energy required for saturation of the hydrogen and oxygen with water vapor. Value of the thermoneutral voltage is a thermodynamic quantity and a single-valued function of the operating conditions, such as electrolysis temperature and total pressure. Consequences of the combined kinetic and thermodynamic constraints for the operation of practical electrolyzers are shown in Fig. 5. Solid curve illustrates a typical dependence of electrolysis cell voltage in the PEM-type electrolyzer operating at the pressure of 1 MPa. This curve shifts to higher voltage in the case where the electrolysis cell is operated at higher current density. Conversely, it moves to lower voltage in the case where current density is decreased. Dotted curve illustrates the thermoneutral voltage at the pressure of 1 MPa. Chain curve illustrates the higher-heating-value voltage. At lower electrolysis temperatures the electrolysis cell must be

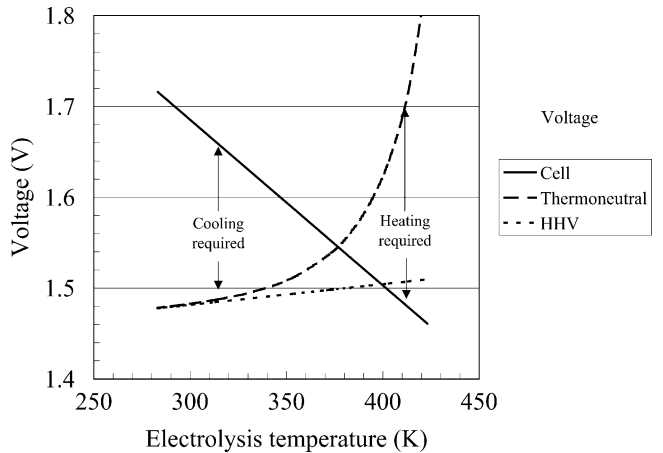


Fig. 5. Thermal balance as a function of electrolysis temperature at the total pressure of 1 MPa.

cooled, while a net heat input is necessary at higher electrolysis temperature.

Usually heat generated at economical current density levels exceeds the heat required to maintain the temperature of the electrolyzer and cooling must be used in the electrolyzer. This energy loss is caused by the electrode overvoltage and ohmic loss. Product of the number of electrons conducted under the water electrolysis, Faraday constant and the difference between the electrolysis cell voltage and the thermoneutral voltage is changed to the energy loss. Thus, energy loss at the surface of MEA is as follows.

$$Q_{\text{gen}} = (V_c - V_{\text{tn}})iA \quad (9)$$

3.2. Heat transfer coefficient at the surface of MEA

De-ionized water in compartment for the anode in the electrolysis module contains the oxygen. This means that the fluid in compartment for the anode in the electrolysis module is two-phase flow. Quality is equal to weight fraction of oxygen flow rate in the two-phase flow. Flow regimes of the two-phase flow are identified with quality, such as bubble flow, slug flow and annular flow. Heat transfer coefficient of the forced convective two-phase flow accompanied with boiling in the flow regimes, such as bubble flow, slug flow and annular flow is given as follows [14].

$$h = \alpha h_b + h_{\text{tp}} \quad (10)$$

α is a coefficient indicating the contribution of nucleate boiling. As oxygen is generated by electrolysis, α can be considered as zero. Schrock and Grossman proposed the heat transfer coefficient of forced convective two-phase flow for the vertical upward flow as follows [15].

$$h_{\text{tp}} = \frac{2.5h_w}{X_{\text{tt}}^{0.75}} \quad (11)$$

$$X_{\text{tt}} = \left(\frac{W_L}{W_G} \right)^{0.9} \left(\frac{\rho_G}{\rho_L} \right)^{0.5} \left(\frac{\mu_L}{\mu_G} \right)^{0.1} \quad (12)$$

$$h_w = 0.023\lambda_L \left(\frac{W_L D_e}{A_f \mu_L} \right)^{0.8} \frac{\text{Pr}_L^{0.4}}{D_e} \quad (13)$$

3.3. Surface temperature of MEA

Energy loss generated at the surface of MEA must be cooled with the heat transfer between the surface of MEA and the de-ionized water supplied to compartment for the anode in the electrolysis module. Surface temperature of MEA is given as follows.

$$T_m = T_w + \frac{Q_{\text{gen}}}{hA} \quad (14)$$

3.4. Temperature increase of the PEM-type water electrolyzer

In the case where heat exchanger in the circulation loop for the de-ionized water does not remove the heat generated

at the surface of MEA until the PEM-type water electrolyzer attains to the rated operational temperature from the start of operation, temperature increase of water electrolyzer per unit time is calculated as follows.

$$\Delta T = \frac{Q_{\text{gen}}}{\Sigma(W_i C_i)} \quad (15)$$

4. Results and discussion

An active area of vertical MEA for electrolysis is set as 0.25 m in length and 1 m in height. Width and length of flow passage for the mixture of de-ionized water and oxygen in compartment for the anode in the electrolysis module is set as 1 mm and 0.25 m, respectively. The PEM-type water electrolyzer is operated under the pressure of 1 MPa. All constituent parts of the PEM-type water electrolyzer are insulated with the glass fiber having a thickness of 40 mm to prevent heat from releasing. Ambient temperature is set as 278 K. Operation of the PEM-type water electrolyzer starts from 293 K.

4.1. Surface temperature of MEA

Surface temperature of MEA changes along the flow passage for the mixture of de-ionized water and oxygen in compartment for the anode in the electrolysis module from the inlet to exit. Surface temperature of MEA becomes maximum at the exit. In the case where inlet temperature of de-ionized water supplied to compartment for the anode in the electrolysis module is 353 K, dependences of the maximum surface temperature of MEA on the amount of de-ionized water supplied to compartment for the anode in the electrolysis module per unit area of MEA are shown in Fig. 6.

Surface temperature of MEA is almost constant in the range of $1 \text{ kg m}^{-2} \text{ s}^{-1}$ or more at each current density. At the current density of 10 kA m^{-2} surface temperature of MEA is almost constant also below $1 \text{ kg m}^{-2} \text{ s}^{-1}$. The higher current density becomes except the current density of 10 kA m^{-2} in the range of less than $1 \text{ kg m}^{-2} \text{ s}^{-1}$, the more drastically surface temperature of MEA becomes higher. Thermal decomposition temperature of Nafion in H^+ form was measured as 558 K [16]. With reference to this thermal decomposition temperature the rated amounts of de-ionized water supplied to compartment for the anode in the electrolysis module were determined in order not for the surface temperature of MEA to exceed the temperature of 373 K as shown in Table 1.

4.2. Flow regime in compartment for the anode in the electrolysis module

Flow regimes in compartment for the anode in the electrolysis module on the flow regime map identified by Griffith and Wallis [17] in a vertical upward flow are shown in

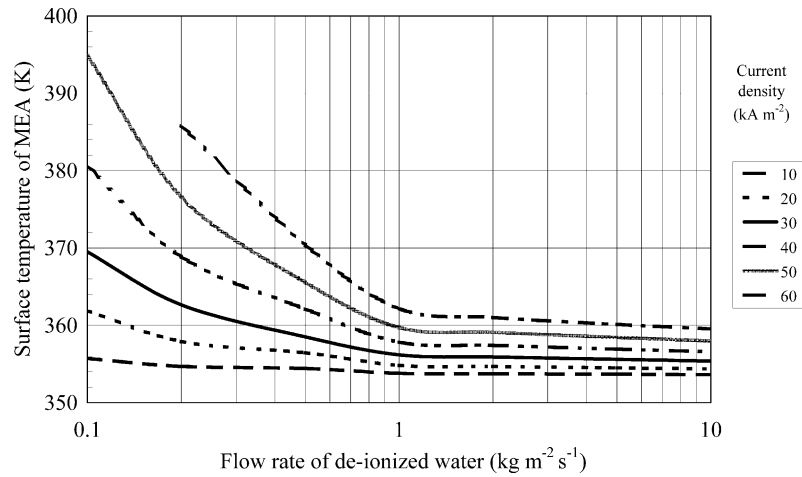


Fig. 6. Dependences of the maximum surface temperature of MEA on the amount of de-ionized water supplied to compartment for the anode in the electrolysis module per unit area of MEA.

Table 1
Rated amounts of de-ionized water supplied to compartment for the anode in the electrolysis module per unit area of MEA

Current density (kA m ⁻²)	Rated amounts of de-ionized water supplied to compartment for the anode in the electrolysis module per unit area of MEA (kg m ⁻² s ⁻¹)
10	0.1
20	0.1
30	0.1
40	0.2
50	0.3
60	0.5

Fig. 7 in the case where the PEM-type water electrolyzer is operated under the rated amounts of de-ionized water supplied to compartment for the anode in the electrolysis module as shown in Table 1. The higher current density becomes, the nearer flow regimes in compartment for the anode in the electrolysis module get from the slug flow to the annular flow. The surface of MEAs does not become dry in the flow regimes of slug flow and annular flow. Thus MEA is not damaged.

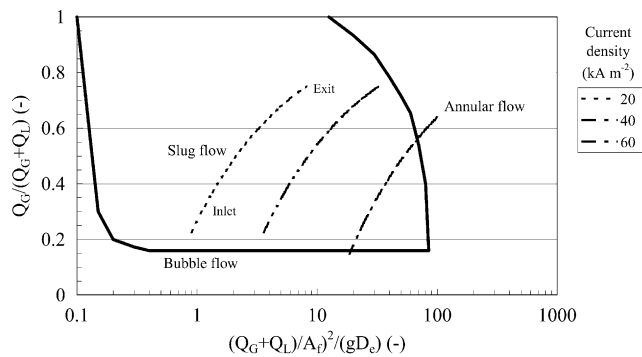


Fig. 7. Flow regimes in compartment for the anode in the electrolysis module.

4.3. Heat capacity of the PEM-type water electrolyzer

Separation becomes more difficult when the gas is dispersed in the form of bubbles of only a few micrometers in size [18]. An example is the evolution of gas from a liquid in which it has dissolved and released through chemical reaction, such as electrolysis. Coalescence of the dispersed phase can be helpful in such circumstances. This method by insertion of meshes into the tanks was applied for oxygen separation and hydrogen separation in this paper. Setting the time that the de-ionized water stays in the tanks for oxygen separation and hydrogen separation as 90 s, inner diameters of tanks were determined. Using the water velocity of 0.5 m s⁻¹ in the piping, inner diameters of piping were determined.

Materials forming heat capacity of the PEM-type water electrolyzer are divided broadly into four categories, namely de-ionized water, stainless steel (SUS 316), titanium and plastics. For example breakdown of weight and heat capacity for the PEM-type water electrolyzer of 500 Nm³ h⁻¹ in hydrogen generation capacity and 30 kA m⁻² in rated current density is shown in Fig. 8. Heat capacity of the PEM-electrolyzer is determined by de-ionized water and stainless steel of which sum occupies 86% of total heat capacity. Proportions of weight and heat capacity for the PEM-type water electrolyzer of other hydrogen generation capacities and rated current densities are almost similar.

Heat capacities of de-ionized water and stainless steel and energy loss of water electrolysis as a function of current density for the PEM-type water electrolyzer of 500 Nm³ h⁻¹ in hydrogen generation capacity are shown in Fig. 9. Heat capacity of de-ionized water has a minimum value at the current density of 30 kA m⁻². Heat capacity of stainless steel for tanks, piping and constituent parts of circulation loops for de-ionized water has a minimum value at the current density of 30 kA m⁻². On the other hand heat capacity of stainless steel for constituent parts of electrolysis module decreases

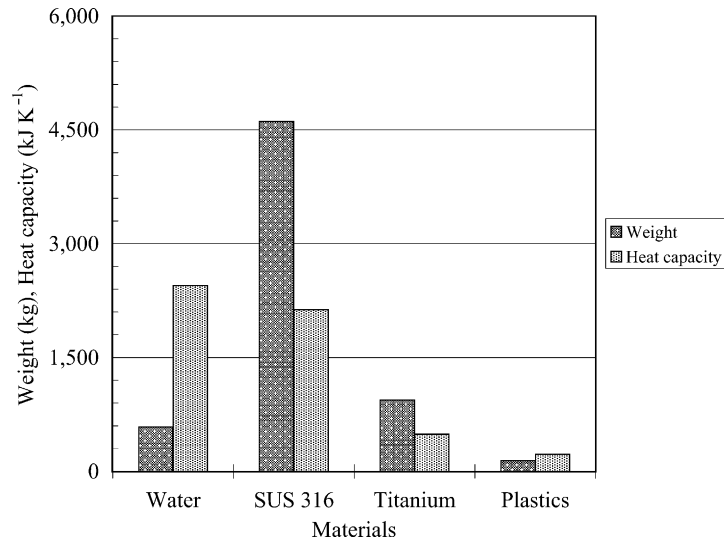


Fig. 8. Breakdown of weight and heat capacity for the PEM-type water electrolyzer of 500 Nm³ h⁻¹ in hydrogen generation capacity and 30 kA m⁻² in rated current density.

with the increase of current density. As a result total heat capacity of stainless steel decreases with the increase of current density in the range from 10 to 30 kA m⁻² and keeps almost constant in the range of 30 kA m⁻² or more. Consequently, total sum of heat capacity of de-ionized water and stainless steel has a minimum value at the current density of 30 kA m⁻². Energy loss of water electrolysis, namely heat generated at the surface of MEA increases with the increase of current density.

4.4. Change of temperature in the PEM-type water electrolyzer

Temperatures of the PEM-type water electrolyzer of 500 Nm³ h⁻¹ in hydrogen generation capacity as a function

of time from the start of operation are shown in Fig. 10. Time required to attain to the water electrolysis temperature of 353 K as a function of current density for each hydrogen generation capacity is shown in Fig. 11. Time required to attain to the water electrolysis temperature of 353 K becomes shorter with the increase of current density in the range from 10 to 30 kA m⁻² and keeps almost constant in the range of 30 kA m⁻² or more in accordance with both the total sum of heat capacity of de-ionized water and stainless steel and energy loss of the water electrolysis as a function of current density as shown in Fig. 9. Time required to attain to the water electrolysis temperature of 353 K for the PEM-type water electrolyzer of 500 Nm³ h⁻¹ in hydrogen generation capacity at the current density of 30 kA m⁻² is the shortest.

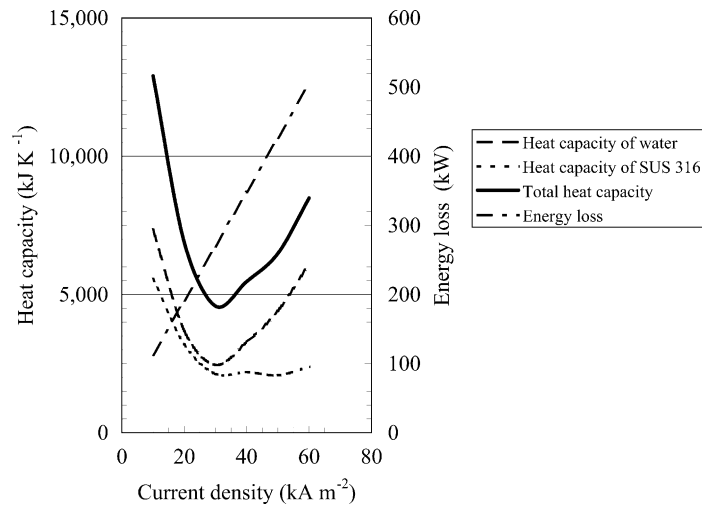


Fig. 9. Heat capacities and energy loss of the water electrolysis as a function of current density for the PEM-type water electrolyzer of 500 Nm³ h⁻¹ in hydrogen generation capacity.

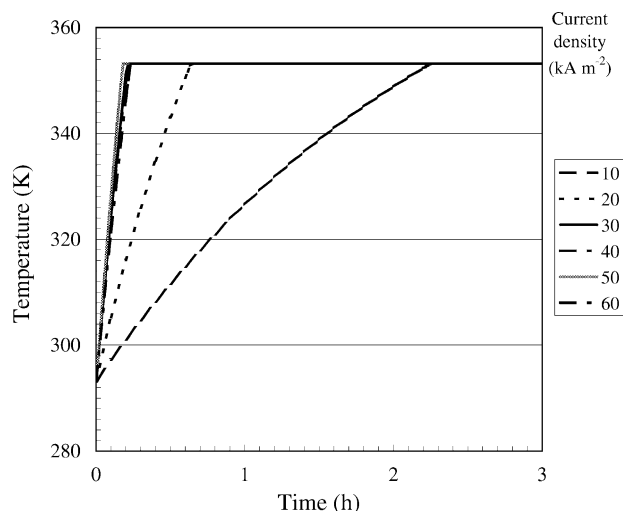


Fig. 10. Temperature of the PEM-type water electrolyzer of $500 \text{ Nm}^3 \text{ h}^{-1}$ in hydrogen generation capacity as a function of time from the start of operation.

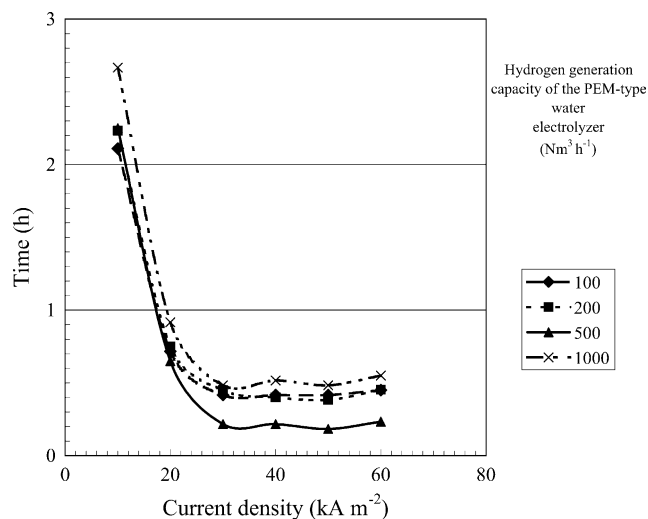


Fig. 11. Time required to attain to the water electrolysis temperature of 353 K as a function of current density.

The optimum hydrogen generation capacity and operational current density of the PEM-type water electrolyzer operated only during the off-peak period of electricity demand in respect of both the shortest time required for start and the

higher efficiency of water electrolysis are $500 \text{ Nm}^3 \text{ h}^{-1}$ and 30 kA m^{-2} , respectively.

5. Conclusions

The optimum hydrogen generation capacity and operational current density of the PEM-type water electrolyzer operated only during the off-peak period of electricity demand in respect of both the shortest time required for start and the higher efficiency of water electrolysis are obtained as $500 \text{ Nm}^3 \text{ h}^{-1}$ and 30 kA m^{-2} , respectively. It is necessary to establish both a reliability and competitiveness in cost in order to realize the PEM-type water electrolyzer under the high current density of 30 kA m^{-2} .

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