Impact of Heat Transfer Media on Performance of Solar-Hydrogen Power Generation

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Abstract

Solar-hydrogen system has great potential for contributing to sustainable and clean energy supply. The aim of this study is to clarify the impact of heat transfer media in solar collector such as methane, ammonium, hydrogen, air and water on the performance of solar-hydrogen system. After estimating the highest temperature attainable by each heat transfer media, the amount of thermal energy that could be saved in the production of hydrogen or preheat for power generation by fuel cell was calculated. The power generation performance of fuel cell using each heat transfer media was also investigated. As a result, it has been revealed that the temperature changes of methane, ammonium and air follow the horizontal solar radiation intensity irrespective of seasons, and their highest temperatures are almost the same among them. The temperature response of hydrogen is slower than methane, ammonium and air. This study defines the ratio of saving thermal energy which indicates the effect of solar thermal utilization for production of hydrogen or preheat for power generation by fuel cell without using utility gas. It has been found that the biggest thermal energy saving is obtained when hydrogen and air are used as the heat transfer media. The power generated by PEFC system per effective area of evacuated tube collector in the case of using methane or ammonium is 3.309×10^{-2} kWh/m² and 2.076×10^{-2} kWh/m², respectively, while it is 2.466×10^{-2} kWh in the case of using hydrogen and air.

Keywords

Solar Collector, Heat Transfer Media, Heat Transfer, Solar-Hydrogen System, Fuel Cell

1. Introduction

Renewable energy such as solar thermal energy has great potential to contribute

for sustainable and clean energy supply.

Utilization of solar thermal energy for hydrogen production is also promising technology. Hydrogen can be used for power generation in fuel cells which discharge only water. Therefore, the solar thermal hydrogen system is a clean and sustainable energy supply system. Many researches on such a solar-hydrogen system were reported recently. Water splitting cycle using terbium oxide [1], ceria zirconia solid solution [2], zinc oxide-zinc sulfate [3] and samarium and erbium oxide [4] with solar thermal energy were evaluated by means of solar-to-fuel conversion efficiency. These researches focused on water splitting technology and thermodynamic characteristics of each material for water splitting. The solar thermal energy is used for the thermochemical reaction. Therefore, it is necessary to find the water splitting cycle operated with lower heat input. The system consisting of water electrolysis with solar thermal energy was investigated from the viewpoint of energy and exergy efficiency [5] [6] [7]. M The evaluation of energy and exergy efficiency is important to develop these technologies since the effective utilization of solar thermal energy is needed. In addition, catalytic steam reforming using solar thermal energy for biogas [8], propane [9] and methanol [10]-[15] attracted attention recently. In these researches, the catalytic reaction is carried out by endothermic reaction, resulting that solar thermal energy is used for the reaction. The performance of catalytic steam reforming technology is influenced by the catalyst and reactor design. Furthermore, the operation temperature is influenced by the type of fuel such as biogas, propane and methanol. Therefore, the optimization of catalyst type, reactor size and operation temperature is very important. The researches [10]-[15] were evaluated by means of methanol conversion or temperature distribution in the reactor, which were conducted for reactor development. Since energy management is also important, the effective procedure to collect solar thermal should be developed. In these solar-hydrogen systems, various solar collectors are used. There are many types of solar collector, *i.e.*, parabolic dish, parabolic trough, flat plate and evaluated tube collectors and so on, for utilization of solar thermal energy. Exergy analysis of many types of solar thermal collectors and processes was reported [16]. Heat transfer analysis by numerical model for novel all-glass evacuated tube solar collector manifold header with an inserted tube [17], evacuated tube solar air collector [18], façade integrated solar concentrator [19], metal corrugated packing solar air collector [20] and flat plate solar air collector [21] was conducted to clarify the heat transfer mechanism and the outlet temperature of solar collector. The system integrated with phase change material [22] [23] and adoption of nanofluids into water as heat transfer fluids [24] [25] [26] [27] [28] were adopted to promote the thermal performance of solar collector.

Although the research on solar-hydrogen system using solar collector has been reported well, there is few research to investigate the effect of heat transfer media used in the solar collector on the system performance. In this paper, such effects with methane, ammonium, hydrogen, air and water as the heat transfer

media were investigated using the meteorological data of the project "PV300" (period from August, 2013 to July, 2014 [29]). The evacuated tube collector was considered as the solar collector in this study. After estimating the highest temperature could be attained by each heat transfer media, the amount of saving thermal energy to produce hydrogen was calculated for methane and ammonium. In addition, the amount of saving thermal energy to preheat for power generation by fuel cell was also calculated for hydrogen and air. Water was investigated as a reference media. This study defines the ratio of saving thermal energy (R) which indicates the effect of solar thermal utilization for production of hydrogen or preheat for power generation by fuel cell without using utility gas. Finally, the power generation performance of fuel cell using each heat transfer media was also investigated.

2. Analysis and Assessment

2.1. Heat Transfer Model of Solar Collector

In this study, the commercial evacuated tube collector SOLARIS CPC1518 produced by Terada Tekkosyo [30] has been considered. **Figure 1** and **Table 1** show schematic drawing and specification, respectively. This evacuated tube collector is suitable for gases and liquids as heat transfermedia.

The temperature of heat transfer media in the evacuated tube collector is calculated by the following equation:

$$Q(t+dt) = I(t+dt) \times A = c_i G_i \{T_i(t+dt) - T_i(t)\} + Q_{loss}(t+dt) \tag{1}$$

where Q is thermal heat by solar irradiation (kJ), I is horizontal solar radiation referred by PV300 [29] (kJ/m^2), A is effective area of evacuated tube collector (m^2), c_i is specific heat of heat transfermedia in evacuated tube collector

Figure 1. Schematic drawing of SOLARIS CPC1518.

Table 1. Specification of SOLARIS CPC1518.

Number of glass tube	18
Size	2.08 m × 1.64 m × 0.1 m
Effective area	3.0 m^2
Volume	2.4 × 10^{-3} m^3
Weight	54 kg
Size of each glass tube	47 mm (O.D.), 33 mm (I.D.), 1500 mm (L.)

(kJ/(kg·K)), G_i is total mass of heat transfermedia fulfilling evacuated tube collector(kg), T_i is temperature of heat transfer media in evacuated tube collector (K) and Q_{loss} is heat loss due to thermal convection and radiation (kJ). It is assumed that $T_i(0) = 293$ K when $t = 0$ s·dt is time interval of 10 s·Q_{loss} is calculated by the following equation:

$$Q_{loss}(t+dt) = hA\{T_i(t+dt) - T_{air}(t+dt)\}dt$$
$$+ A\sigma\varepsilon F_{c\rightarrow air}\left[\{T_i(t+dt)\}^4 - \{T_{air}(t+dt)\}^4\right]dt \tag{2}$$

Where h is heat transfer coefficient (W/(m^2·K), T_{air} is ambient air temperature referred by PV300 [29] (K), σ is Stefan-Boltzmann constant (= 5.670×10^{-11}) (kW/(m^2·K^4)), ε is the emissivity of glass from 293 K to 373 K (= 0.92) [31] (-) and $F_{c\rightarrow air}$ is the shape factor from evacuated tube collector to ambient air (= 1) (-). h is calculated by the following empirical equation on forced thermal convection for laminar flow over flat plate [32]:

$$Nu = \frac{hl}{k_{air}} = 0.664\,\mathrm{Re}^{1/2}\,\mathrm{Pr}^{1/3}, \left(0 < \mathrm{Re} \le 5\times10^5\right) \tag{3}$$

$$\mathrm{Re} = \frac{puD}{\mu} \tag{4}$$

where l is length of evacuated glass tube (= 1.5) (m), k_{air} is thermal conductivity of air (W/(m·K)), ρ is density of air (kg/m^3), u is velocity of air surrounding evacuated tube collector referred by PV 300 [29] (m/s), D is outside diameter of evacuated glass tube (= 0.037) (m) and μ is viscosity of air (Pa·s). k_{air}, ρ, μ and Prare assumed to be 2.57×10^{-2} W/(m·K), 1.166 kg/m^3, 1.822×10^{-5} Pa·s and 0.717, respectively, which are values at 293 K [33]. In this study, the highest u is 5.5 m/s, resulting that the maximum Re is 12,608.

In this study, the following assumptions were made:

1) The natural convection of heat transfer media in evacuated glass tube is neglected. Since the temperature rise of heat transfer media is not high, the driving force of natural convection, which is density change of heat transfer media, is thought to be small.

2) There is no temperature distribution of heat transfer media in evacuated glass tube. Since the volume of evacuated glass tube is small which is 2.4 × 10^{-3} m^3, it is thought that the temperature distribution of heat transfer media in evacuated glass tube is small.

3) There is no temperature distribution in evacuated glass tube. Since the thickness of evacuated glass tube is small which is 7 mm, it can be thought that the temperature distribution in evacuated glass tube is small.

4) The temperature of evacuated glass tube is the same as the temperature of heat transfer media. As mentioned above, the thickness of evacuated glass tube is small which is 7 mm. Therefore, it can be thought that the temperature of evacuated glass tube equals to the temperature of heat transfer media in evacuated glass tube.

4) The physical properties of heat transfer media are constant, which keep the values at 293 K. Though the physical properties of heat transfer media, *i.e.*, specific heat, considered in this study is changed with temperature, it is small. For example, the specific heats of air at 293 K and 353 K are 1.005 kJ/(kg·K) and 1.010 kJ/(kg·K), respectively [33]. Therefore, it can be thought that the physical properties of heat transfer media keep constant.

5) The pump energy loss for transporting heat transfer media is ignored. If the total energy balance and efficiency in the whole system are evaluated, the pump energy loss for transporting heat transfer media should be considered. However, the aim of this study is to evaluate the ratio of saving thermal energy which indicates the effect of solar thermal utilization for production of hydrogen or preheat for power generation by fuel cell without using utility gas. Then, this study focuses on temperature and required thermal energy of heat transfer media in evacuated glass tube, reactor and preheater for evaluation of saving thermal energy. The consideration of pump energy loss for transporting heat transfer media is the future work in this study.

The initial calculation parameters of numerical calculation are set as follows:

1) T_i is 293 K.

2) T_{air} is 293 K.

3) C_i at 293 K is used.

4) The physical properties of air surrounding evacuated glass tube at 293 K are used.

Table 2 lists the specific heat of heat transfer media and mass of heat transfer media fulfilling the whole evacuated tube collector.

## 2.2. Estimation Procedure of Saving Thermal Energy

In this study, two cases are considered for solar-hydrogen system which are shown in Figure 2.

As to the first case, methane or ammonium is used as heat transfer media. After preheated in the evacuated tube collector, methane reacting with water (*i.e.*, steam) in the reactor which is reformed into hydrogen, and ammonium is decomposed into hydrogen and nitrogen. Methane reacts with steam at temperature between 873 K and 1273 K, in the presence of a catalyst; e.g., nickel [34] [35] [36]. Therefore, this study considers the methane reforming reactor operated at 1073 K which is kept by a gas combustor. Since the methane is preheated

Table 2. Specific heat of heat transfer media and mass of heat transfer media fulfilling the whole evacuated tube collector.

Heat transfer media	Specific heat c_i (kJ/(kg·K))	Mass of heat transfer media fulfilling the whole evacuated tube collector (kg)
Methane	2.206	1.558×10^{-2}
Ammonium	2.200	1.487×10^{-2}
Hydrogen	14.34	1.882×10^{-3}
Air	1.006	2.769×10^{-2}
Water	4.182	23.71

Case 1 (methane, ammonium)
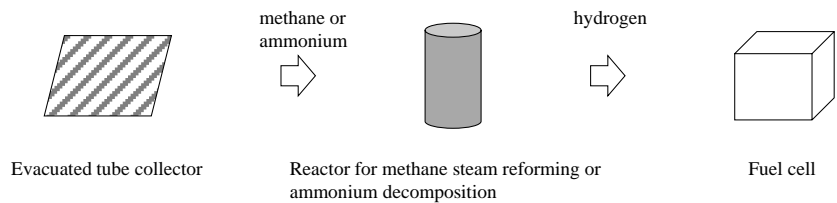
Case 2 (hydrogen, air)
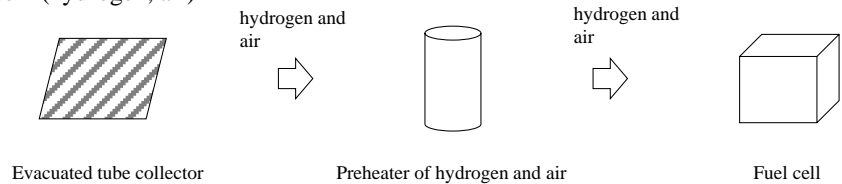
Figure 2. System flow.

by solar thermal energy, the utility gas can be saved. The amount of heat needed from the utility gas is calculated by the following equation:

$$Q' = c_i G_i \left(T_r - T_i' \right) \tag{5}$$

where Q' is the amount of heat needed from room temperature or temperature preheated by evacuated tube collector to the reforming temperature (kJ), T_r is reforming temperature (K) and T_i' is room temperature or temperature of heat transfer media preheated by evacuated tube collector (K). If the Q' is divided by the lower heating value of methane which is the main component of utility gas of 50.01 MJ/kg, the amount of utility gas needed for attaining the reforming temperature is derived.

In the case of ammonium, the ammonium is decomposed into hydrogen and nitrogen fully at the temperature over 923 K [37]. Therefore, this study considers the ammonium decomposition reactor operated at 923 K which is kept by the combustion of utility gas. The amount of utility gas needed for attaining the de-composition temperature is calculated by Equation (5) and the lower heating value of the utility gas of 50.01MJ/kg.

In the second case, hydrogen and air are used as heat transfer media. After heated in the evacuated tube collector, hydrogen and air are provided for fuel

cell. In this study, polymer electrolyte fuel cell (PEFC) was considered as typical fuel cell system. Generally, PEFC is operated at 353 K [38]. Therefore, this study considers the PEFC system operated at 353 K which is normally maintained by the hydrogen and air heated by the combustion of utility gas. Since hydrogen and air are preheated by solar thermal energy in our case, the utility gas can be saved. The amount of heat needed from the utility gas is calculated by the following equation:

$$Q'' = c_i G_i \left(T_f - T_i' \right) \tag{6}$$

where Q'' is the amount of heat needed from room temperature or temperature preheated by evacuated tube collector to operation temperature of PEFC system (kJ) and T_f is operation temperature of PEFC system (= 353) (K). If the Q'' is divided by the lower heating value of the utility gas of 50.01 MJ/kg, the amount of utility gas needed for attaining the operation temperature of PEFC system is derived.

2.3. Estimation Procedure of Power Generation by Fuel Cell

It has been assumed that the H_2 would be used to generate power through PEFC system. H_2 is converted into electricity in fuel cell following the reaction below:

$$H_2 + 1/2 O_2 = H_2O + \eta_f H \tag{7}$$

where η_f is power generation efficiency of latest PEFC stationary system based on lower heating value (= 0.39) [39], H is lower heating value of H_2 (= 242) (kJ/mol). It is assumed that the energy loss for operating pump to preserve and provide gases is ignored.

3. Results and Discussion

3.1. Impact of Heat Transfer Media on the Temperature out of Solar Collector

As described in earlier section, this study has investigated the performance of evacuated tube collector with various heat transfer media using the meteorological data base of PV300 [29] including air temperature, solar intensity and wind speed at 10 sec intervals. January, April, July and October were selected as the months which are representative of four seasons, respectively. Temperature change of heat transfer media in the evacuated tube collector with time was estimated for the standard day in the month with the mean amount of horizontal solar radiation of the month using the meteorological data base of PV300 [29].

Figures 3-6 show temperature change of heat transfer media in evacuated tube collector in daytime for January, April, July and October, respectively. Horizontal solar radiation intensity is also shown in these figures. Table 3 lists the highest temperature for each heat transfer media shown in Figures 3-6.

According to Figures 3-6, temperature changes of methane, ammonium and air follow the horizontal solar radiation intensity irrespective of seasons, and their highest temperatures are almost the same. The temperature change of
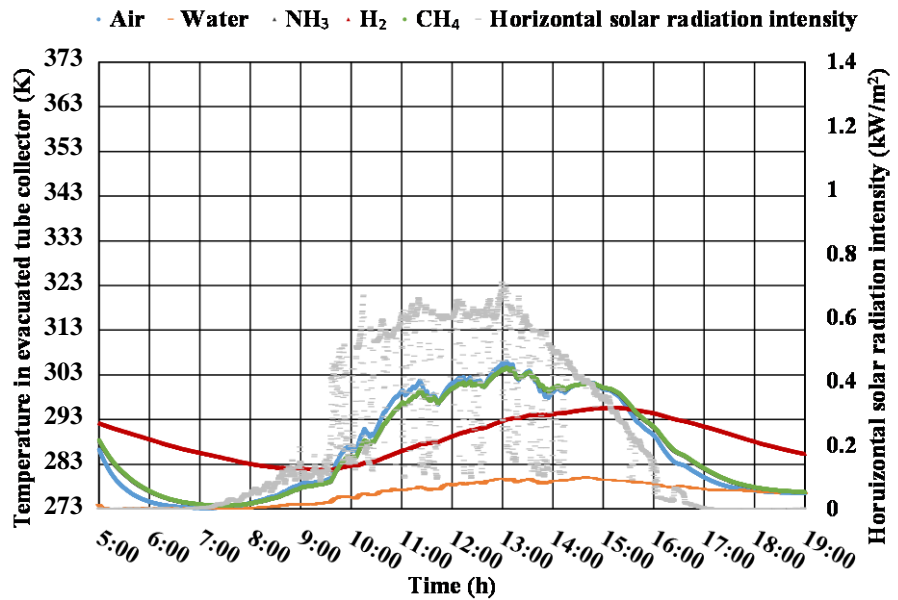
Figure 3. Temperature change of heat transfer media in evacuated tube collector in daytime for January.
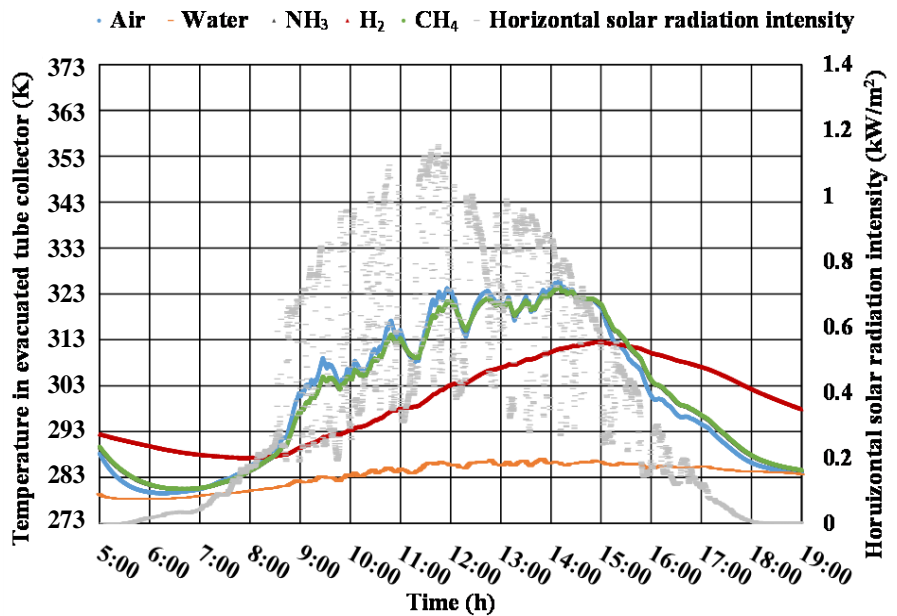

Figure 4. Temperature change of heat transfer media in evacuated tube collector in daytime for April.

methane, air and ammonium are influenced by the change in horizontal solar radiation intensity with time strongly since the specific heats of them are small. The temperature change and the maximum temperature in the evacuated tube collector for water are smaller compared to the other heat transfer media irrespective of seasons. Since the mass and specific heat of water inside the evacuated tube collector is larger than the other heat transfer media, the temperature of water changes slower with time and does not rise so high. In addition, the
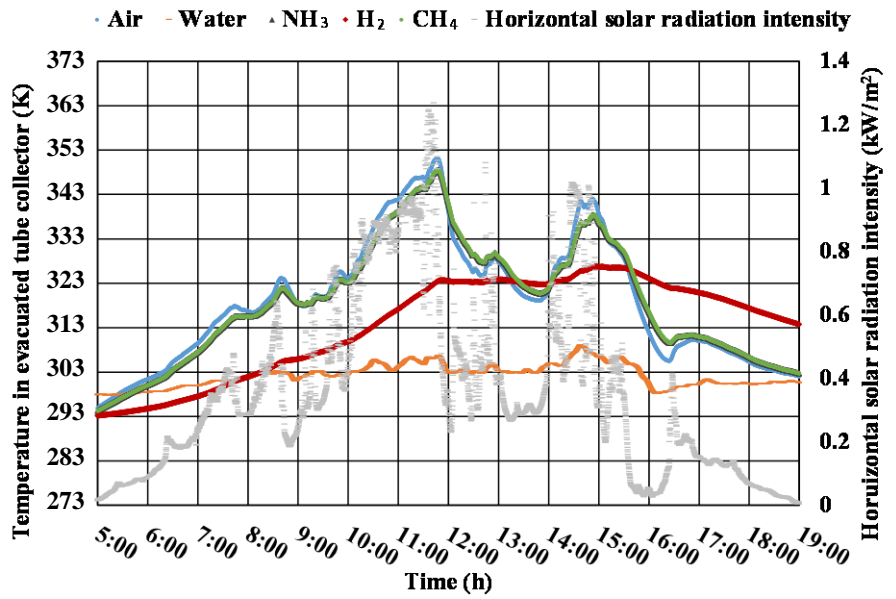
Figure 5. Temperature change of heat transfer media in evacuated tube collector in daytime for July.
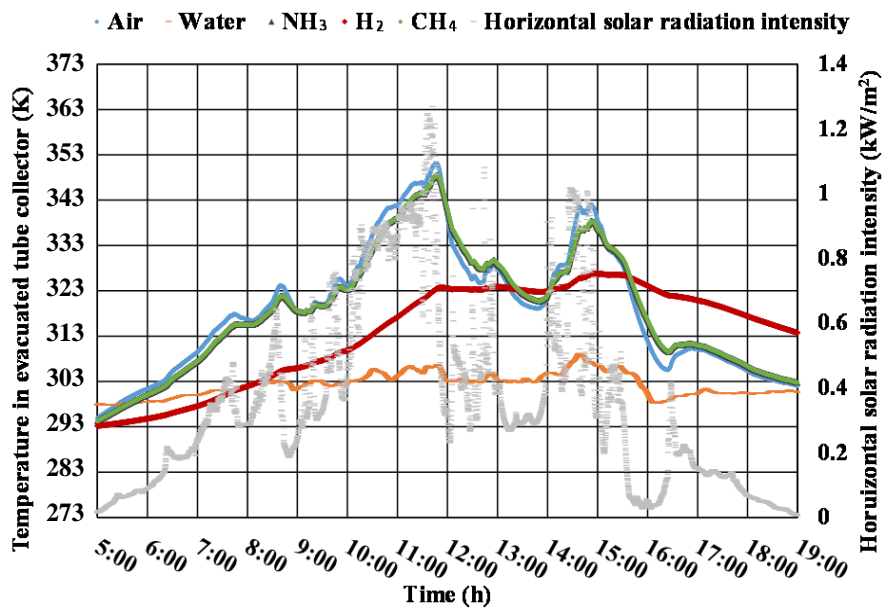
Figure 6. Temperature change of heat transfer media in evacuated tube collector in daytime for October.

Table 3. The highest temperature for each heat transfer media shown in **Figures 3-6**.

	January	April	July	October
Methane (K)	306	325	348	320
Ammonium (K)	306	325	348	320
Hydrogen (K)	297	313	327	311
Air (K)	307	326	351	321
Water (K)	301	287	308	298

temperature rise and drop of hydrogen are slower than methane, ammonium and air. Since the specific heat of hydrogen is larger than the other heat transfer media, the temperature response of hydrogen is slower.

3.2. Evaluation of Saving Thermal Energy and Power Generation by Fuel Cell

In the case of using methane or ammonium as heat transfer media, Q', the thermal energy from utility gas required, was calculated by Equation (5). When methane is heated from the room temperature of 293 K to the reforming temperature of 1073 K per the mass of methane in an evacuated tube collector, Q' is 26.81 kJ, which is equivalent to the needed utility gas indicated by M of 5.361×10^{-4} kg. On the other hand, when ammonium is heated from the room temperature of 293 K to the decomposition temperature of 923 Kper the mass of ammonium in an evacuated tube collector, Q' is 20.61 kJ, which is equivalent to M of 4.121×10^{-4} kg. However, if solar-hydrogen system is used, i.e., the heat transfer media is preheated in solar collector first then heated by the utility gas, the Q' required would be much less. Table 4 lists Q', M and R(%) in the case of using methane or ammonium in solar-hydrogen system. From this table, R of methane for January, April, July and October is 1.67%, 4.10%, 7.05% and 3.46%, respectively. On the other hand, R of ammonium for January, April, July and October is 2.06%, 5.0%, 8.73% and 4.29%, respectively. The reforming or decomposition temperature is too high compared to the temperature preheated by evacuated tube collector, as a result, the Rs in Table 4 are small. Therefore, it is necessary to use concentrating solar collectors if R is to be improved.

In the case of using hydrogen and air as heat transfer media, Q'' was calculated by Equation (6). When hydrogen is heated from the room temperature of 293 K to the operation temperature of PEFC system of 353 Kper the mass of hydrogen in an evacuated tube collector, Q'' is 1.619 kJ, which is equivalent to M of 3.238×10^{-5} kg. When air is heated from the room temperature of 293 K to the operation temperature of PEFC system of 353 Kper the mass of air in an evacuated tube collector, Q'' is 1.671 kJ, which is equivalent to M of 3.342×10^{-5} kg. Similar to Table 4, Table 5 lists Q'', M and R in the case of using hydrogen and air as heat transfer media in the solar-hydrogen system. From Table 5, it can be seen that R of hydrogen for January, April, July and October is 6.67%, 33.3%, 56.7% and 30.0%, respectively, while R of air for January, April, July and October is 23.3%, 55.0%, 96.7% and 46.7%, respectively. When using hydrogen and air, the big effect of saving thermal energy was obtained. In summary, the proposed solar-hydrogen system is effective to provide heat to operate PEFC system.

In the case of using methane or ammonium as heat transfer media, the amount of hydrogen produced is calculated by the following equations:

$$CH_4 + H_2O = CO_2 + 4H_2 \tag{8}$$

$$2NH_3 = N_2 + 3H_2 \tag{9}$$

Table 4. Amount of heat needed from temperature preheated by evacuated tube collector to reforming or decomposition temperature (Q'), mass of utility gas needed (M) and ratio of saving thermal energy (R) for methane and ammonium.

	Methane	Ammonium
Q' (January) (kJ)	26.36	20.18
Q' (April) (kJ)	25.71	19.56
Q' (July) (kJ)	24.92	18.81
Q' (October) (kJ)	25.88	19.73
M (January) (kg)	5.271×10^{-4}	4.036×10^{-4}
M (April) (kg)	5.141×10^{-4}	3.912×10^{-4}
M (July) (kg)	4.983×10^{-4}	3.761×10^{-4}
M (October) (kg)	5.175×10^{-4}	3.945×10^{-4}
R (January) (%)	1.67	2.06
R (April) (%)	4.10	5.08
R (July) (%)	7.05	8.73
R (October) (%)	3.46	4.29

Table 5. Amount of heat needed from temperature preheated by evacuated tube collector to operation temperature of PEFC system (Q''), mass of utility gas needed (M) and ratio of saving thermal energy (R) for hydrogen and air.

	Hydrogen	Air
Q'' (January) (kJ)	1.511	1.281
Q'' (April) (kJ)	1.080	7.521×10^{-1}
Q'' (July) (kJ)	7.017×10^{-1}	5.571×10^{-2}
Q'' (October) (kJ)	1.133	8.914×10^{-1}
M (January) (kg)	3.022×10^{-5}	2.562×10^{-5}
M (April) (kg)	2.159×10^{-5}	1.504×10^{-5}
M (July) (kg)	1.403×10^{-5}	1.114×10^{-6}
M (October) (kg)	2.267×10^{-5}	1.782×10^{-5}
R (January) (%)	6.67	23.3
R (April) (%)	33.3	55.0
R (July) (%)	56.7	96.7
R (October) (%)	30.0	46.7

When the conversion ratio is assumed to be 100%, the amount of hydrogen produced from methane and ammonium is 3.787 mol and 2.376 mol, respectively. According to Equation (7), the power generated by PEFC system per effective area of anevacuated tube collector in the case of using methane or ammonium is 3.309×10^{-2} kWh/m² and 2.076×10^{-2} kWh/m², respectively.

These performances are obtained for a day.

In the case of using hydrogen and air as heat transfer media, the amount of hydrogen in an evacuated tube collector is 1.882×10^{-3} kg, which is 9.410×10^{-1} mol. The amount of air is 2.769×10^{-2} kg, which is 9.558×10^{-1} mol. According to Equation (7), 1/2 mol of oxygen is necessary per 1 mol of hydrogen. Therefore, 5/2 mol of air is necessary per 1 mol of hydrogen. Since the amount of hydrogen and air is 9.410×10^{-1} mol and 9.558×10^{-1} mol, respectively, 3 units of evacuated tube collector are needed for the air to complete the chemical reaction with the hydrogen per an evacuated tube collector. Under this condition, the power generated by PEFC system per effective area of 4 units of evacuated tube collectors needed for heating hydrogen and air as mentioned above is 2.055×10^{-3} kWh/m². This performance is obtained for a day.

In Japan, the electric consumption of household per a day is 9 kWh [40]. Therefore, 91 or 145 units, which have effective area of 273 m² and 435 m², respectively, of evacuated tube collector are necessary in the case of methane or ammonium, respectively. On the other hand, 1460 units, which has effective area of 4380 m², of evacuated tube collector are necessary in the case of hydrogen and air. Consequently, it can be suggested that the evacuated tube collector having large effective area should be applied for solar-hydrogen system.

4. Conclusions

This study has investigated the performance of solar-hydrogen system when methane, ammonium, hydrogen, air or water is used as heat transfer media in the solar collector. The energy saving ratio of solar-hydrogen system to conventional utility gas heating only system has been calculated for each heat transfer media. The power generation performance of PEFC system has also been evaluated. As a result, the following conclusions have been drawn:

1) When methane, ammonium or air is used as heat transfer media, the temperature inside the collector depends on the horizontal solar radiation intensity strongly irrespective of seasons, and the highest temperature that they can reach are almost the same. The temperature response of hydrogen is slower than methane, ammonium or air namely reaches the peak temperature later during the day. When water is used as heat transfer media, the temperature is lower compared to the other heat transfer media irrespective of seasons. These results can be explained by the specific heat and mass of each heat transfer medium.

2) It has been found that the biggest thermal energy saving is obtained when hydrogen and air are used as the heat transfer media.

3) The power generated by PEFC system per effective area of an evacuated tube collector in the case of using methane or ammonium is 3.309×10^{-2} kWh/m² and 2.076×10^{-2} kWh/m², respectively. On the other hand, the power generated by PEFC system per effective area of 4 units of evacuated tube collector is 2.055×10^{-3} kWh/m² in the case of using hydrogen and air. These performances are obtained for a day.

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