Performance of Wall-Mounted Non-Tracking Solar Thermal Collector with a Parabolic Mirror for Concentration

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Abstract

This study examined the performance of a solar collector with a linear parabolic mirror mounted vertically on walls. In order to simplify the system, it does not have sun tracking function and focuses on hot water supply only during winter which dominates annual hot water demand. The objectives are to design optimal shape of the parabolic concentrator by simulations and to demonstrate the heat recovery by experiments. The inclined angle and the focal length of the paraboloid are the design parameters. Since the parabolic mirror does not truck the sun, there should be the optimal setting of the design parameters which maximize the thermal energy collection during winter season. The simulation results indicated that the inclined angle of 25 ° and the focal length of 95 mm would be optimal, based on which the proposed collector was made and tested outdoors. The experimental results showed that the temperature of the hot water actually gained 45.8 degC in February, 2015.

Keywords: *Solar Water Heater, Parabolic mirror, Solar concentration,*

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1. Introduction

In energy use of residential sector in Japan, the share of hot water demand is about 30%. Therefore, solar water heaters are considered effective to save fuel consumption for hot water supply. While solar water heaters are set on the roof conventionally, vertically–installed type solar collectors are also available in the market recently, especially for apartment houses. They are placed on the fence of veranda. One drawback of vertical setting is that solar collecting performance is not high enough so that the temperature of hot water is relatively low. Therefore, this study proposes a vertical solar collector with a parabolic mirror to concentrate solar light to get higher temperature.

CPC (compound parabolic concentrator) is a well-known technique for solar collectors with concentration, which consists of two parabolic mirrors. Although CPC is capable to collect sun light within a certain range of incident angle without sun tracking, the structure is complicated. In contrast, the device proposed by this study simply consists of one parabolic mirror without sun tracking. The merits of the proposed device are the following. It can be mounted on building walls which are not used for solar collectors in Japan. The area of solar absorber is much smaller than flat type collectors, which leads to cost reduction because the absorbers are expensive component due to anti-reflective coating.

There are two design parameters for the parabolic mirror, that is, inclined angle and focal length. Tamata[(1)] investigated the effect of the inclined angle on the performance of the parabolic mirror when the

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focal length of the parabolic mirror was assumed constant. In this study, the focal length is also considered in addition to the inclined angle. Since the parabolic mirror does not truck the sun, there should be the optimal setting of the design parameters which maximize the thermal energy collection.

The objectives of this study are to find optimal design of the parabolic concentrator by ray-tracing simulations and to demonstrate the heat recovery by experiments. It should be noted that the performance of heat recovery in winter season is discussed in the study because hot water demand is much larger in winter than that in summer in Japan.

2. Solar thermal collector with a parabolic mirror

Figure 1 shows the cross-sectional view of the thermal collector. The thermal collector is assumed to be installed on vertical walls. It consists of a linear parabolic mirror for concentration and an absorber at the bottom. The focus of the parabolic mirror is designed to be located on the top surface of the absorber. In this study, the collector is assumed to be 100 mm wide as shown in Fig.1. The angle noted as φ is the inclined angle of the parabolic shape. P represents the focal length, and H indicates the aperture width of the collector. The absorber is divided into five segments to investigate the position that sun light is reflected by the mirror.

Sun light coming to the parabolic mirror is reflected to the focus when the angle φ is equal to the sun elevation. In the other cases, the reflected sun light is distributed on the absorber. The local energy flux changes time to time due to the sun movement.

Figure 2 shows the shape of paraboloid corresponding to various combinations of φ and P. The larger φ and P become, the longer the paraboloidal shape expands. It indicates that the aperture width H strongly depends on φ and P. Because the amount of sun light captured by the absorber is determined by the aperture size of H. It is necessary to find the optimal combination of φ and P in order to maximize the heat recovery.

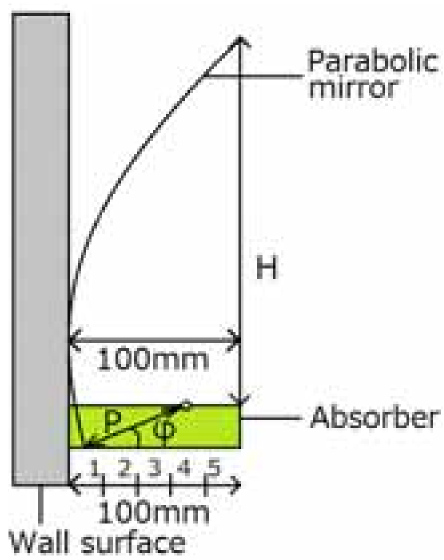


Fig.1 Cross-section of the proposed solar collector

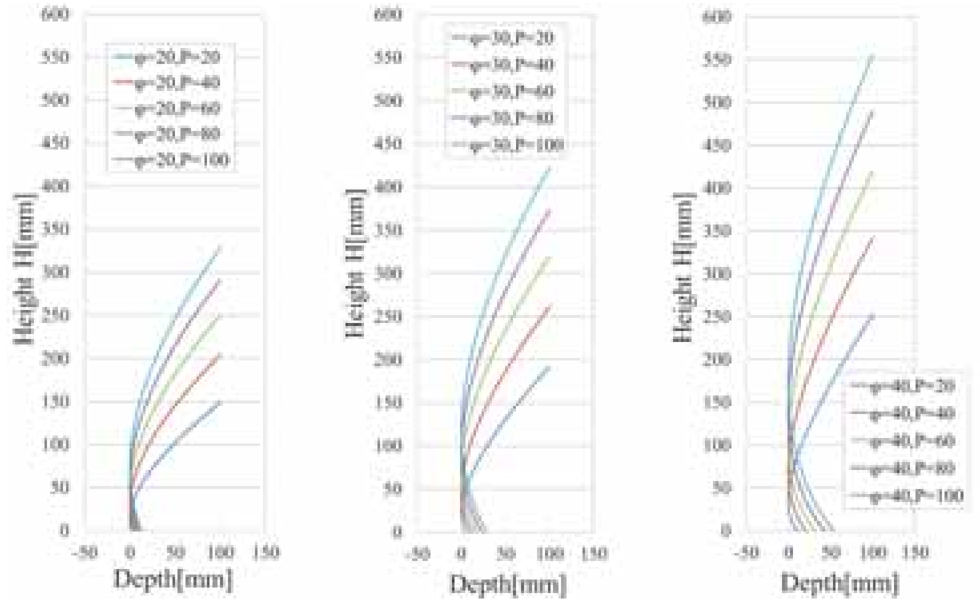


Fig2. Parabolic shape change by design parameter

3. Optimal design of the parabolic mirror

3.1 Simulation method and assumptions

This study investigates the influence of P change when φ is 15~40 degree. The ray tracing tool named Trace Pro was employed to calculate the sun light directly captured by the absorber and indirectly reflected by the mirror.

Simulation period is from November to February and location is Tokyo. Both Light reflectance rate of a parabolic mirror and heat absorption rate of the absorber are assumed 100 % to observe the maximal performance. The solar collecting device faces to the south and solar constant is 1067 W/m^2.

3.2 Thermal energy collection in winter season

Figure 3 shows the results for various combinations of P and φ. The graph indicates that there is a peak over P for a given φ. The reason why collected thermal energy increase is that H is extending as P is increasing. Larger H collects more sun light to the absorber. On the other hand, in the case where P becomes too large, thermal energy collection decreases because parabolic mirror cannot reflect sun light to the absorber enough when the sun elevation is low. Figure 4 shows example of the light collecting behavior when P is 30 mm or 90 mm and the sun elevation is 20 degree. Sun light is reflected to the absorber when P is 30 mm. In contrast, sun light is reflected out of the absorber when P is 90 mm.

Figure 3 also indicates that optimal P that obtains the peak of thermal energy collection becomes small when φ becomes large. The peaks of every φ settings seem to make a concave curve which has a peak at 95 mm of the focal length when φ is 25 degree. The peak is understood as the global maximum of the heat recovery by the proposed way.

According to this analysis, the optimal design is obtained with the parameters of φ=25 degree and P=95 mm. The aperture width H =321mm. The position of the focal length on the absorber is 86 mm from the wall surface. Therefore, sun light is reflected to the inside of the focal length on the absorber when the sun elevation is larger than 25 degree. Sun light is reflected to the outside of the focal length on the absorber or outside of the device when the sun elevation is lower than 25 degrees.

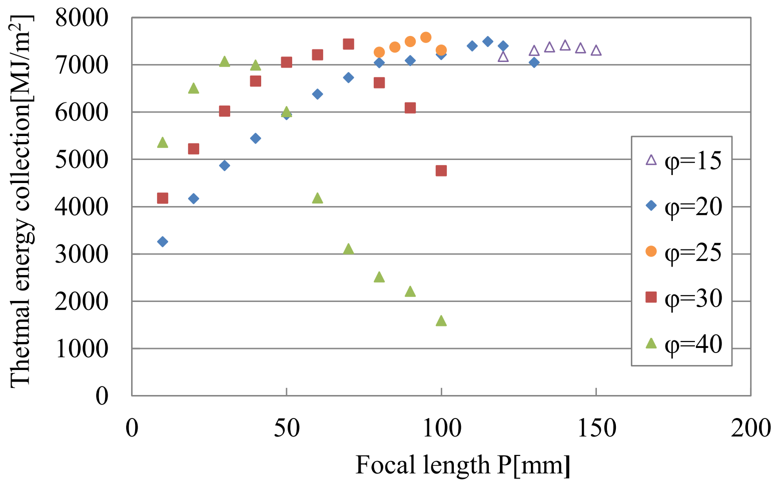


Fig.3 Thermal energy collection

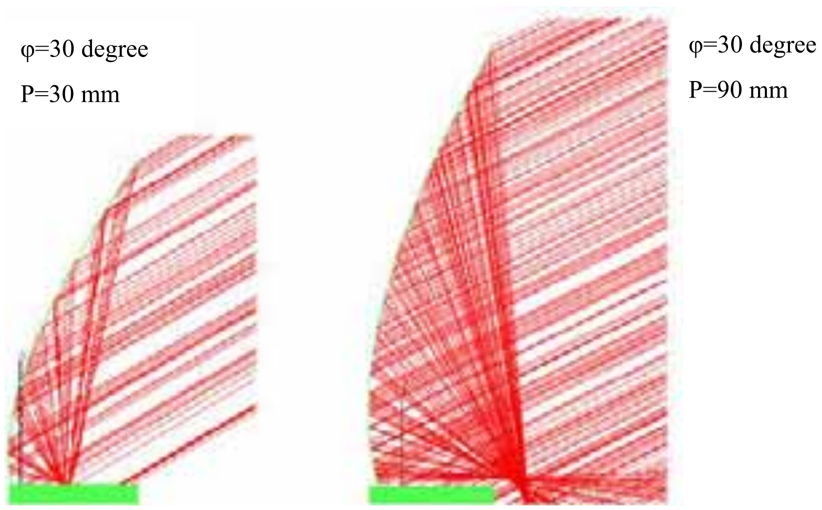


Fig.4 Light collecting behavior

(The φ is larger than the sun elevation)

4. Energy density distribution on the absorber

Figure 5 shows the energy recovery of the entire absorber in each month in the optimal design case with φ=25 degree and P=95 mm. The monthly performance is almost same approximately. It should be noted that the distribution of sun light changes because the reflection by the parabolic mirror depends on the sun elevation. The local heat recovery performance is evaluated in this section in order to understand the profile of the solar concentration on the absorber. The absorber is divided into five segments as shown Figure 1 to investigate which part collects solar energy well. In this optimal design case, the focus is located in the part 5 of the absorber. Figure 6 shows the light collecting behavior when the sun elevation is 20, 25, 30, and 40 degree. It can be seen from the Figure that sun light is reflected to the part 5 or outside of the absorber when the sun elevation is lower than 25 degree while sun light is reflected to the part 4 and 5 when the sun elevation is higher than 25 degree. As the sun elevation becomes larger, the reflected rays shift inward on the absorber so that the part 1, 2, and 3 get heated when the sun elevation is considerably higher than 25 degree. Figure 7 indicates local heat recovery by the segments. The highest performance is observed at the part 5 in December. It is because the maximum sun elevation is 31 degree in December. The contribution of the part 5 is significantly large compared with that of the other parts. In November and January, the performance of the part 4 and 5 dominates the heat recovery. In contrast, the part 3 takes the maximum position in February where the performance of the part 5 is much reduced. In sum, the part 4 and 5 are recognized as important parts to recover solar thermal energy while the part 3 works well in February. It is also suggested that the contribution of the part 1 is insignificant.

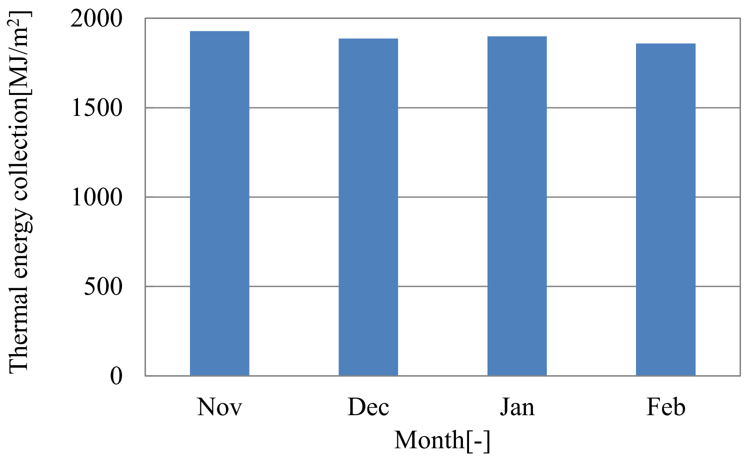
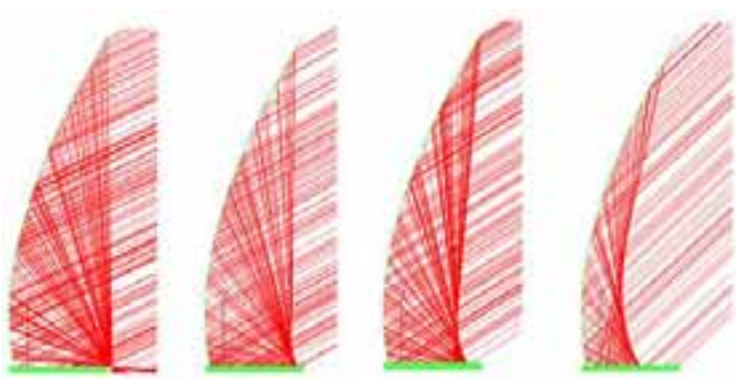


Fig.5 Thermal energy collection in each month



Sun elavation

20 degree 25 degree 30 degree 40 degree

Fig.6 Light collecting behavior (φ=25°, P=95mm)

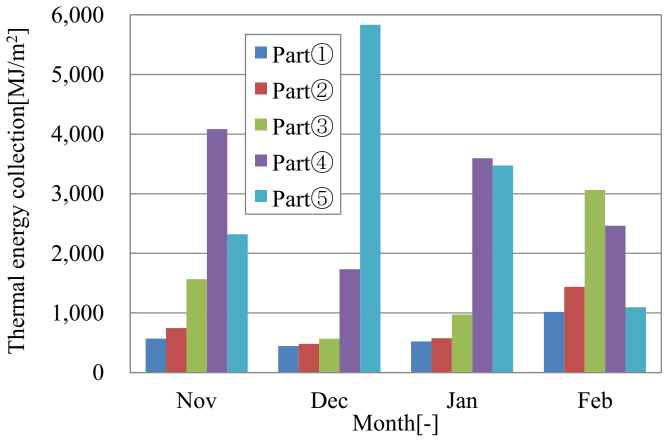


Fig.7 Thermal energy collection of each part

5. Monthly performance compared with conventional solar collectors

To demonstrate the usefulness of the proposed device, comparison of monthly performance was conducted among three collectors. One is the device proposed in this study, another is a flat plate collector of vertical type, and the other is a conventional flat plate collector inclined at 30 degree. The index is the average energy density on the absorber because higher temperature is beneficial for domestic hot water production. Figure 8 shows the results of monthly thermal energy density of above 3 collectors. It is seen that the proposed device and the vertical type flat collector have similar profile throughout a year while the conventional flat type collector holds almost stable energy density in any month. The proposed device collects solar energy significantly higher than the others, more than twice from October until March in terms of the density. On the other hand, the performance of the proposed device is less than the conventional collector from May until July. Heating load for hot water increases in winter, but reduces in summer. Because the pattern is in accordance with the profile of energy density of the proposed device, the proposed device is advantageous to produce hot water required in each month.

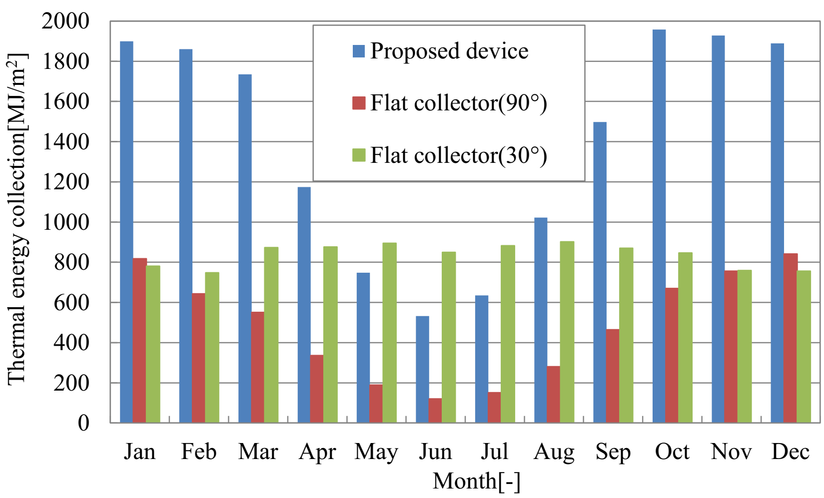


Fig.8 Monthly thermal energy collection

6. Heat collection experiments

6.1 Experimental setup and conditions

The experimental device was made based on the optimal design, which photo is shown in Figure 9. Five copper pipes with chrome plating were used as the absorber. The pipes were not thermally insulated just for preliminary experiments. The water in the tank was circulates through the device by a pump. Figure 10 illustrates the water flow in the absorber. In addition, Figure 10 shows temperature measurement points and corresponding thermocouple number. Thermocouple numbers from 1 to 6 were for water temperature measurement and numbers from 7 to 11 were for surface temperature measurement of the copper pipes.

The device was set up to face south at Tokyo University of Agriculture and Technology Koganei Campus in Tokyo. Measurement days were 29th January and 2nd February. Measurement time was from 9:00 to 16:00 in order to avoid the shade. The maximum temperature was 8.0 degC and the minimum temperature was 3.9 degC during the experiment on 29th January. On the other hand, the maximum temperature was 9.4 degC and the minimum temperature was 5.4 degC during the experiment on 2nd February. Thermocouples ware calibrated to have the accuracy of water temperature measurement to be ± 0.5 degC and the accuracy of surface temperature measurement of copper pipes to be ± 1.0 degC. Measurement interval of temperature was 10 s. The amount of water was 2 litters and the flow rate was controlled to be 0.2 l/s.

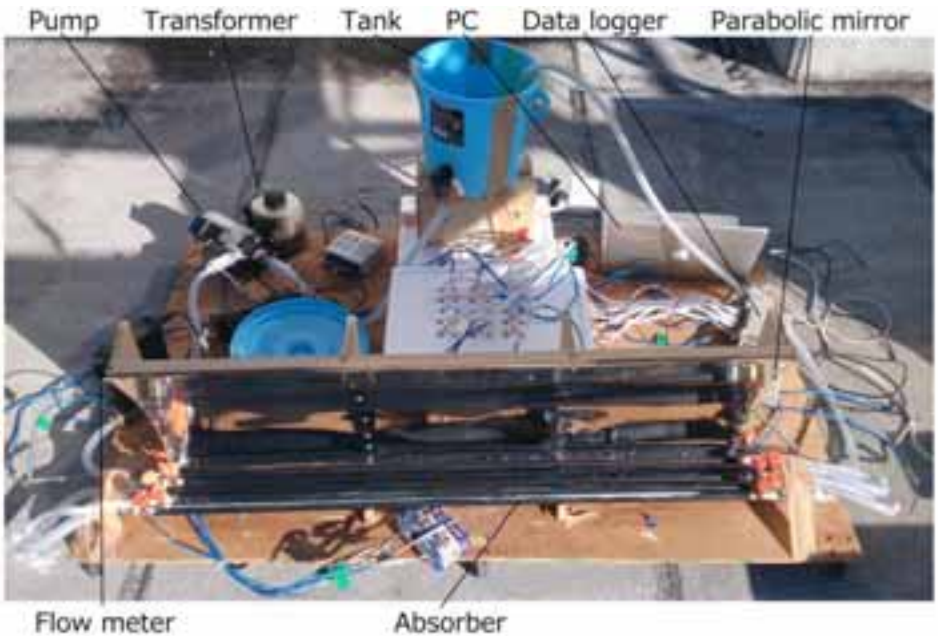


Fig.9 Experimental setup

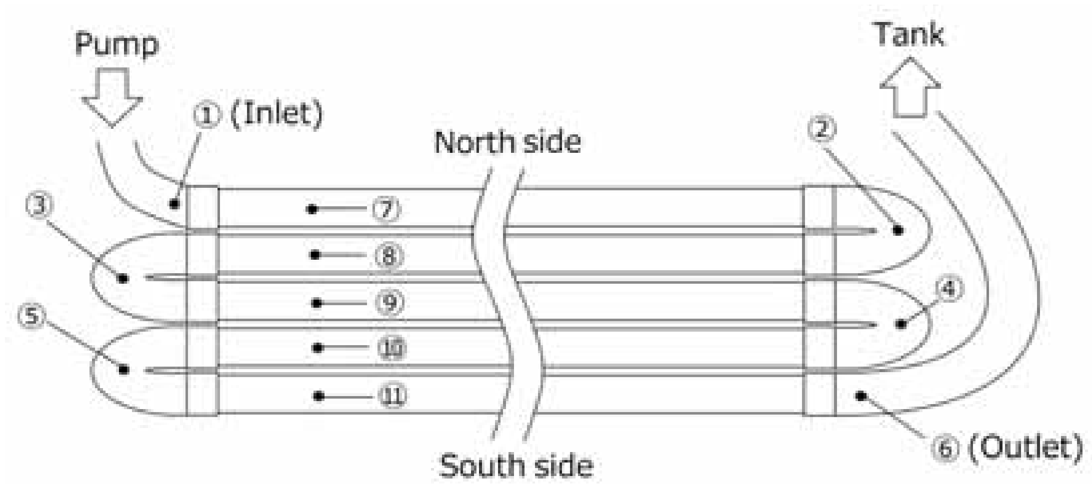


Fig.10 Schematic of the absorber

6.2 Water temperature behavior with / without parabolic mirror

Figure 11 shows the measurement results of the water temperature behavior with the parabolic mirror on 2nd February, which also shows the direct irradiance. The measurements of thermocouples from 2 to 4 were similar to that of number 1 and the measurement number 5 was similar to that of number 6. Therefore, the results of number 2, 3, 4, and 5 were not shown in Figure 11. As the graph shows the water temperature continued to rise over time, and rose up to 45.9 degC at around 12:00. Temperature difference of 5 degC was obtained from the inlet (Thermocouple number 1) to the outlet (Thermocouple number 6). Direct irradiance was 0 kW/m^2 after 15:30 due to the shade of other building. Therefore, the temperature of number 6 is lower than number 1 due to heat dissipation because the pipes have no insulation.

Figure 12 shows the results of the water temperature behavior without the parabolic mirror on 29th January. Although the water temperature rose to 30.9 degC at around 13:00, temperature difference between inlet and outlet of the absorber was very small. The water temperature was falling because the weather became cloudy after 13:30.

The experimental results with / without mirror clearly reveal that the concentration by the parabolic mirror is certainly effective to boost the temperature of hot water. It should be noted that the temperature could be higher than the experiment if the absorber is well insulated.

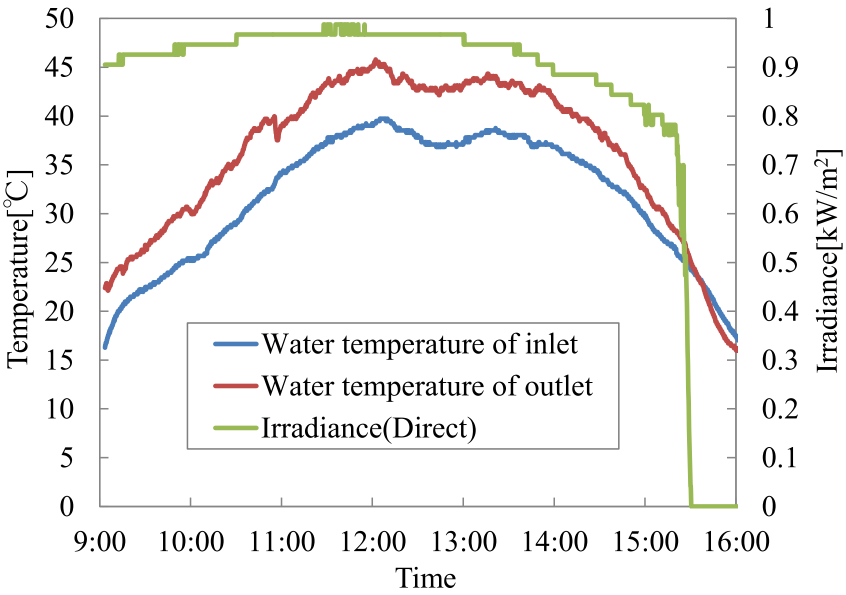


Fig.11 Behaviors of water temperature and irradiance

(With concentration)

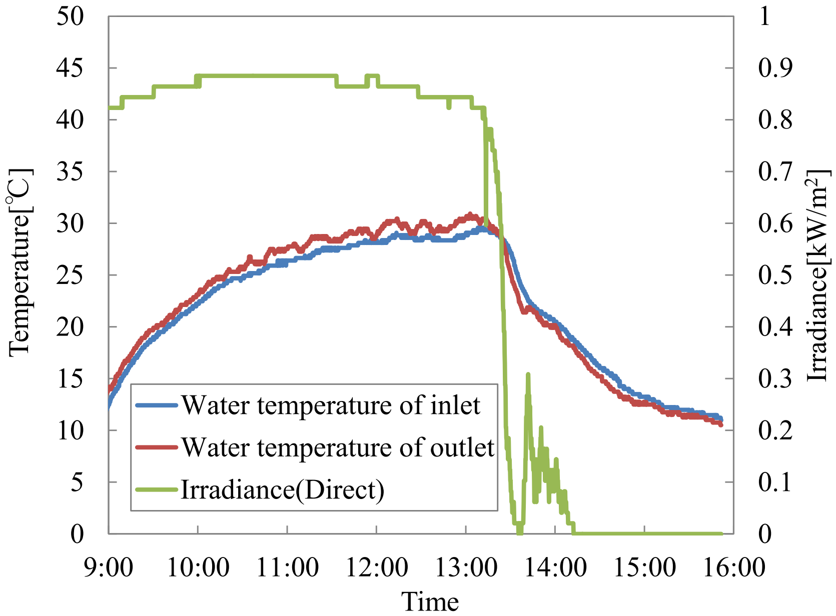


Fig.12 Behaviors of water temperature and irradiance

(Without concentration)

7. Conclusion

This study proposed a solar collector with concentration by a parabolic mirror which is assumed to be mounted on vertical walls. To be simplified, the mirror shape is just a parabola and no sun tracking is equipped. The optimal design of the parabolic mirror was derived from sensitivity analysis to maximize solar heat recovery in winter, which is achieved with the parameter settings of φ=25 degree and P=95 mm.

The simulation results suggest that the attained energy density by the proposed debice is more than twice as much as that of conventional inclined flat plate collectors in winter. It will be advantageous to get high temperature hot water.

The performance of the proposed device was also examined by experiments in winter. Even though they were considered preliminary, the concentration by the parabolic mirror was confirmed effective to produce higher temperature than that without mirror by 15 degC.

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