The Exergetic Performance of a Solar Hot Water Pre-heating System

Y. Hoshino, and
TETENS ENGINEERING CO., LTD., Japan
M. Shukuya
Graduate School of Environmental Information Studies
Musashi Institute of Technology, Yokohama, Japan

ABSTRACT

This paper discusses the possibility of a simple solar hot water pre-heating system for domestic hot water supply. In Japan, the fossil fuel use for hot water supply amounts to about 30% of the total in residential buildings. The use of conventional solar hot water heaters has been decreased dramatically over the last 30 years, although the extensive use should have been expected. They are regarded to be not necessarily cheap and moreover their appearance has not been preferred by quite a few building designers. Their rather high cost and bad appearance must have been the main reasons of declining the use of solar hot water heaters. Therefore, it is important to investigate the possibility of a solar hot water pre-heating system which is easy to install with low price and can even be hidden, e.g, as a part of building envelopes, upon necessity.

We built a simple solar hot water heater which is assumed to be installed at a condominium balcony, and made an experiment in summer, 2007. The measured average water temperature turned out to be 41.8℃. The exergy balance model of this system was developed and its numerical calculation was performed. We found that the warm exergy obtained from this pre-heating system with area of 3m^2 for one family house reaches 140kJ/day and this contributes very much to the reduction in the use of fossil fuel for hot water supply.

The exergy balance of the balcony space in summer was also calculated and we found that the water carries off the warm exergy to the bath and thereby the warm radiant exergy emitted from the balcony surface to the outdoor environment decreased by 20～60%, comparing to a case without solar hot water pre-heating system. The solar hot water pre-heater embedded in vertical walls performs not only pre-heating but also mitigating the thermal environment outdoors and balcony space. These results of experiment together with simulation suggest a new direction of the development of a hot water heating system in the future.

1. INTRODUCTION

In Japan, the annual energy use for residential buildings in 2005 had become 2.5 times larger than that in 1965 and the energy use for hot-water supply has always been about 30% over those years. Since the amount of energy use for hot-water supply has never decreased, it is important to redevelop solar hot water heating systems.

The conventional solar hot water heaters have not been in good progress. In 1980, the number of the systems sharply rose because of the recognition of scientists and engineers being reflected by the then oil crisis. Since then, the number has decreased year by year and it reached almost 10% of 1980 in 2005 If it decreases at this rate, it will reach 5% or less within a few year[1]. There are a couple of reasons for this trend: one may be that these solar hot water heating systems are regarded not cheap; the other may be their bad appearance. It is necessary to take these into consideration to realize the revival of solar hot water heating systems.

The fundamental characteristic of solar radiation is to change from time to time so that it should be considered in designing solar hot water heating systems. That is to say, it would be wise to make moderate warm water with a simple system which is cheap and easy to install. We assume a simple solar collector to be installed at a condominium balcony as an example case[2)3)].

There are many hot places in summer especially in urban areas to install simple solar collectors, e.g. roofs, walls, and roads. If the simple solar collectors are embedded so that they are accepted in the design of buildings, they will provide not only the highest possible pre-heated warm water, but also they may contribute to mitigating the outdoor thermal environment in urban areas. As a result of such simple installation, we may be able to expect that the solar hot water pre-heating systems spread more easily and the amount of fossil fuel for hot water supply is reduced substantially.

We investigated the exergetic performance of an example of simple solar hot water heating systems for domestic hot water supply and for thermal mitigation.

2. SETIING-UP OF A SOLAR WATER HEATER

Photo 1 shows the appearance of a simple solar pre-heating system we made with the DIY principle. It is an assembly of a tank, a solar collector and a rubber tube in between.

The solar collector consists of a long rubber hose rolled in spiral and painted black and it is placed on a one-square-meter polystyrene board with an aluminum sheet on the surface. The total length of the rubber hose is 30m. The hose and the polystyrene board were fastened tightly with wires, in order to keep the whole of collector in good shape with an amount of water in it. A one-square-meter transparent vinyl chloride sheet was finally put over the rubber hose rolled spiral, and then the whole system was sealed firmly with adhesive tapes in order to decrease the heat loss by infiltration.

The tank consists of a plastic box whose capacity is 250L and is covered with polyethylene boards of 50mm thickness. One hole opened in the tank was connected with the outlet of the solar collector. The hose between the solar collector and the tank was also thermally insulated. The inlet of the solar collector is also connected with the same type of hose, the other end of which is connected to the faucet of city water was in the place 25m away from the solar collector. Total cost of setting up this system was 24000 yen.

Photo 1: A simple solar water pre-heater set up

3. EXPERIMENT

The experiment was made for six days from 14th to 22nd of August, 2007, at Yokohama campus of Musashi Institute of Technology. The water faucet was opened at 9:30 and was closed at 16:30. The flow of city water in this solar hot water pre-heating system was made only by the primary water pressure. The water flow rate was adjusted to be about 200ml/min so as to accumulate 84L of water in the tank for 7 hours in the experiment. The water accumulated in the tank was drained assuming the use at night. Measured were water temperature in the tank, surface temperature of the hose, ground surface temperature, outdoor air temperature, solar irradiance and others.

Figure 1 shows the variation of the water temperature, outside air temperature and solar irradiance during the whole period of experiment. The highest water temperature of 43.0℃ obtained in the experiment was on 15th of August. The average water temperature was 41.8℃.

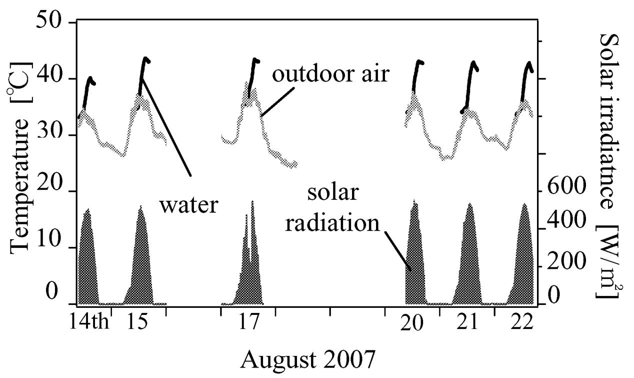

Figure 1: The variation of water temperature, outdoor air temperature and solar irradiance

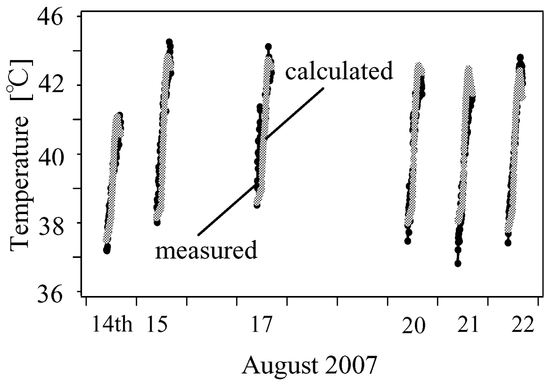

Figure 3: Comparison of measured and calculated water temperature in the tank.

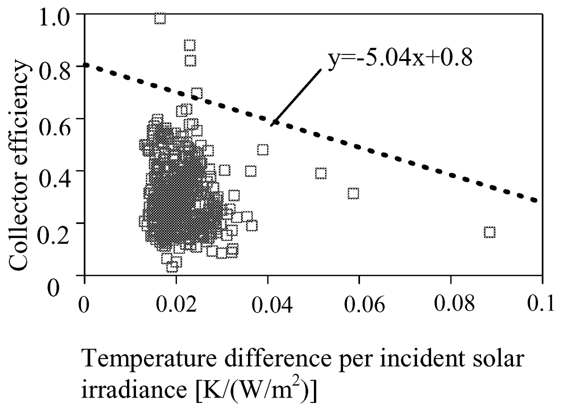

Figure 2: The performance of the simple solar pre-heater

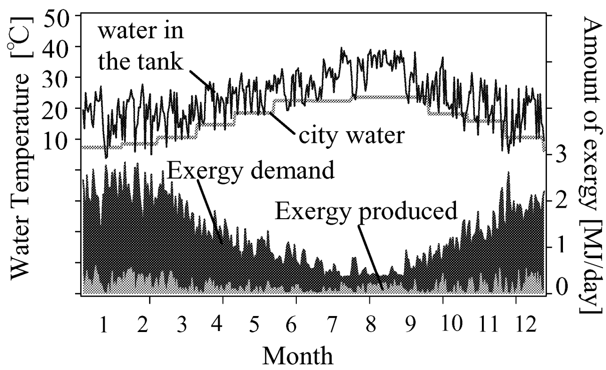

Figure 4: The variation of water temperature and the relationship between exergy produced and exergy demand

Figure 2 shows the relationship between the ratio of thermal energy and the temperature difference between the collector surface and the ambient per incident solar irradiance. The squire point shows experimental date. On the other hand, the doted line shows that of a conventional typical solar water heater.

The performance of the simple collector is not good. But, the importance of this result is to recognize that it is possible to generate warm water, namely an amount of water at moderate temperature, even with such a simple devise.

4. THE EXERGETIC PERFORMANCE

Before doing exergy calculation, the energy balance model of the simple solar collector and the tank has set up and examined whether it can simulate water temperature accurately.

Figure 3 shows the comparison of measured and calculated water temperatures in the tank.

The calculated temperature is consistent with the measured temperature. We then developed the entropy balance equation corresponding to the energy balance equation and combined them to develop the exergy balance equation.

For annual exergy simulation of solar hot water pre-heating system, we assume one family and the whole system consisting of three sub-systems; a solar collector of 3 m^2, a bath tub whose capacity is 250L and a gas fired water-heater. It is assumed that warm water accumulates in the tank after passing through the solar collector for 7 hours from 9:30 to 16:30 every day. If the water temperature does not reach 42℃ at 20:00, the water is heated up to 42℃ by the gas-fired water heater.

Figure 4 shows the variation of water temperature in the tank at 16:30 p.m. and the relationship between the exergy produced by the solar system and the exergy demand for one year. The average water temperature in the tank

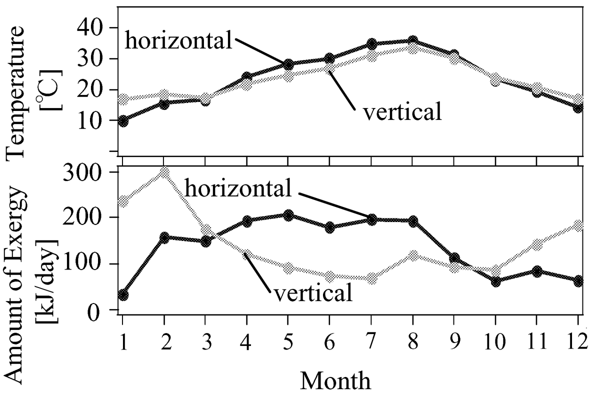

Figure 5: Comparison about water temperature and amount of warm exergy horizontal type and vertical

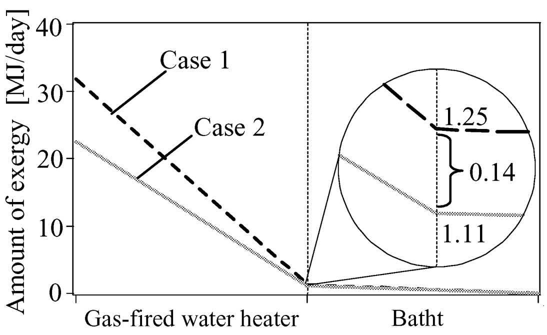

Figure 6: The exergy consumption patterns of the whole process of hot-water heating

in summer is 12 degrees higher than the city water temperature. In winter, it is 5 degrees higher than city water temperature. As a result, 11 % of the annual exergy requirement is supplied by the simple solar hot water pre-heating system.

Figure 5 shows a comparison of the variation of water temperature in the tank and the amount of warm exergy before heated up to 42℃ in the cases of the solar collector at vertical angle and at horizontal angle type. Both the amount of warm exergy of horizontal type is larger than that of vertical type from April to September. The opposite is true from October to March. Both of horizontal and vertical types more or less the same possibility as a solar hot water pre-heating system.

Figure 6 shows a comparison of the exergy consumption patterns for the whole process of hot water heating from the gas-fired water heater to the bath averaging one year in Yokohama city. The vertical axis shows the amount of

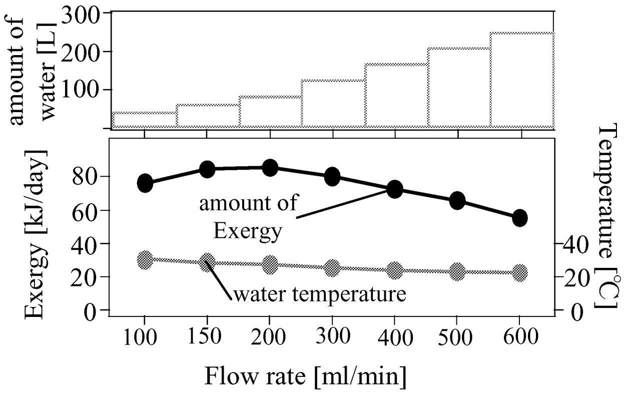

Figure 7: Relationship between available exergy and flow rate

exergy input and output. For this analysis, the vertical type is again assumed. Horizontal axis shows where exergy is consumed. The annual average outdoor temperature is 16℃ and the average water temperature is 23.6℃. Case 1 shows the exergy consumption pattern of the use of the gas-fired water heater alone. Chemical exergy of 32MJ is supplied to the water heater and 1.25 MJ of warm exergy contained by the water to the bath tub. Case 2 shows the exergy consumption pattern with the use of the solar pre-heating system. Chemical exergy of 22.7MJ is supplied to the gas-fired water heater and 1.11 MJ of warm exergy to the bath tub. The accumulated amount of warm exergy obtained from the simple solar hot water heating system is 0.14 MJ only, but this relatively, small amount of warm exergy results in a rather large reduction of 9MJ the difference in chemical exergy supply to the gas-fired water heater.

In the simulation described above, we assumed 200 ml/min of water flow in the solar hot water heater. We also investigated the sensitivity of the change of flow rate. *Figure 7* shows the relationship between the water flow rate and the exergy of contained by warm water for one day together with the average water temperature reached. The larger the flow rate is the lower the warm water temperature. The simulation assuming the flow rate of 200ml/min was suitable to collect the largest amount of exergy.

5. MITIGATING EFFCT IN SUMMER

The wall surface temperature of the balcony may be moderated by this simple solar collector, since it absorbs and remove the solar heat to produce warm water. The exergy balance model of a balcony wall made of concrete facing south which embeds the simple solar water heater was developed and numerical calculation was performed for a summer condition.

The upper graph in *Figure 8* shows an example of the measured interior surface temperature of a balcony without a solar collector and that calculated assuming a solar collector with the solar absorptance of 0.9. The lower graph shows the variation of the rate of warm or cool exergy to be stored in the balcony. The negative value indicates the exergy to be emitted from the balcony surface to the surrounding space. The surface temperature of the balcony with the embedded solar water heater is lower than that without. The maximum difference of the temperature is 1.9℃ at 14:00.

In the case of balcony without solar water heater, the rate at which exergy is accumulated becomes the largest as solar irradiance reaches the largest. Warm exergy keeps emitted from the balcony until midnight. On the other hand, in the case of balcony with the solar water heater, a little bit of cool exergy is emitted from the balcony from 8:00 to 13:00. In addition, warm exergy emitted at night is very small. This is because that the water passing through the solar water heater carries off warm exergy to the bath tub.

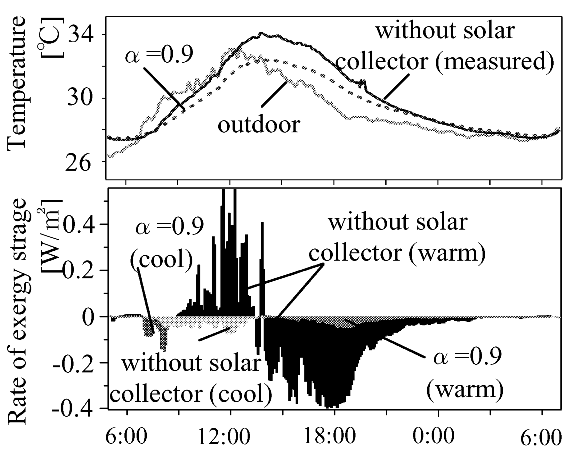

Figure 8: Comparison of the balcony surface temperature and the rate of warm/cool exergy stored in the cases with and without an embedded solar collector.

Figure 9 shows a comparison of exergy balances of three cases of balcony condition at 12:00 on 27th of August, 2007. The three cases are as follows; case A is without solar hot water heater at the exterior surface of the balcony; case B is with the simple solar hot water heater whose solar absorptance is 0.6; case C is the same as case B, but the solar absorptance is 0.9.

In case A, most of the absorbed solar exergy of 190W/m^2 is consumed at exterior surface with the absorptance of 0.64, and the warm radiant exergy of 0.15W/m^2 is emitted from the exterior surface. Only 0.002W/m^2 of cool radiant exergy is emitted from the interior of the balcony surface.

In case B, most of the absorbed solar exergy of 212W/m^2 is consumed at the exterior surface, and 0.13W/m^2 of warm radiant exergy is emitted from the exterior surface. But, a relatively large amount of cool radiant exergy is emitted from the interior surface compared to case A. The reason for this is that the water carries off the 2.82 W/m^2 of warm exergy to the bath tub and thereby warm radiant exergy is reduced, and cool radiant exergy emerges.

In case C, the amount of solar exergy absorbed is the largest at 318 W/m^2. The warm exergy of 6.28W/m^2 carried off is larger than that in case B. This is due to the higher absorptance value.

Figure 10 shows the exergy input and output for one day. The upper graph shows the amount of solar exergy and exergy consumed; the middle graph the amount of warm exergy to be carried off by water to the bath tub; and the bottom graph warm radiant exergy emitted from both exterior and interior balcony surfaces. Looking at upper and middle graphs, we can see that it is necessary to consume a large portion of solar exergy in order to get a botto warm exergy. Looking at the lower graph, in case A the largest amount of warm radiant exergy is emitted from the surfaces of the balcony. In case B, the warm exergy of 40kJ/day goes to the bath and thereby the warm radiant exergy emitted fr-

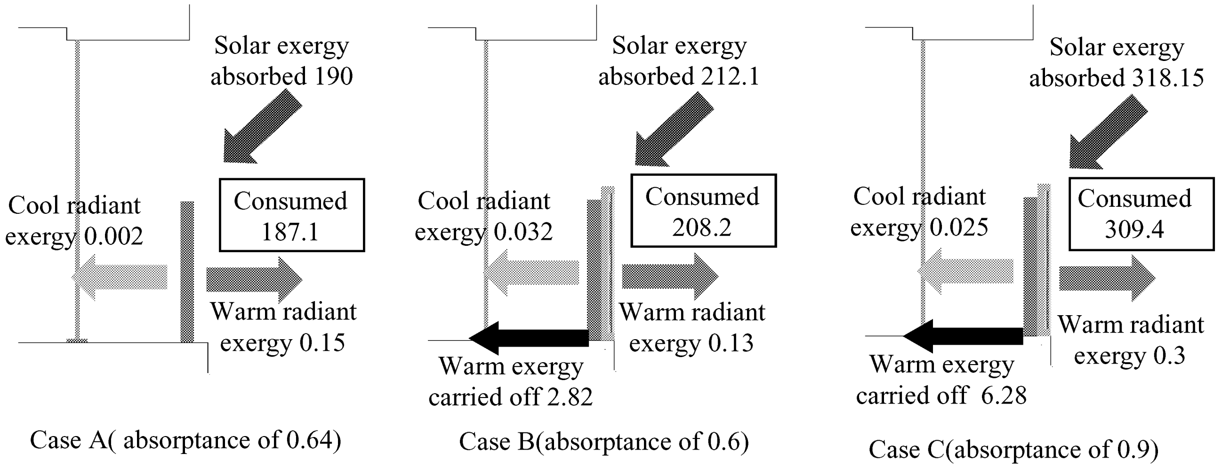

Figure 9: Comparison of exergy balance at 12:00 on 27th of August, 2007. The unit is W/m^2
(Outdoor air temperature and incident solar exergy are assumed to be 33.1℃ and 442W/m^2, respenctively)

om the balcony surface to the outdoor environment decreases by 3kJ. In case C, the warm exergy of 80kJ/day goes to the bath and thereby the warm radiant exergy emitted from the balcony surface to the outdoor environment decreases by 1.3kJ, compared to case A.

5. CONCLUSION

We built a vertical type of simple solar hot water pre-heating system assuming to be installed at a condominium balcony wall, and measured its thermal performance in summer. The average water temperature reached 41.8℃ for the whole of experimental period.

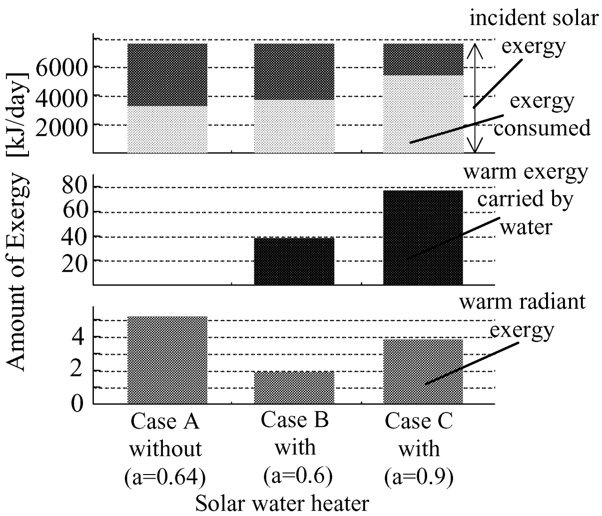

Figure 10: Comparison of exergy input and output at the balcony for one day

The exergy balance model of this system was developed and its numerical calculation was performed. The warm exergy supplied by the pre-heating system was 11％ of the anuual warm exergy requirement for one family, but it leads to the 30% reduction in chemical exergy to be supplied into a gas-fired water heater. This implies that such a simple solar hot water heating system is regarded to be one of the low-exergy systems.

The exergy balance of the balcony space was also calculated in order to reveal a change in the thermal environment of the balcony space in summer. The solar hot water pre-heating system helps reduce the warm radiant exergy to be emitted from the balcony surface to the outdoor environment by 1.5~3 kJ/day, in the course of solar hot water pre-heating. Such synergetic performance should be taken into account to promote a practical use of natural potentials such as solar exergy.

REFERENCES

1) Solar System Development Association, htt://www.ssda.jp/energy/result.html (in Japanese).
2) Akashi, K., Hoshino, Y. and Shukuya, M. (2007), Experimental Study on a Solar Pre-Heating System for Domestic Hot-Water Supply, pp.617-618 (in Japanese).
3) Hoshino, Y., Akashi, K. and Shukuya, M. (2007), Experimental Study on a Solar Pre-Heating System for Domestic Hot-Water Supply, Architectural Institute of Japan, pp.615-616 (in Japanese).