Performance Improvements of the Air-Based Solar Heating System (Improvement Method of Thermal Performance)

Youngjin Choi

Kyushu University, Platform of Inter/Transdisciplinary Energy Research, 8128581 Fukuoka, Japan

Abstract. In this study, it is proposed a heating and hot water system for a house using the air-based solar collection. The performance of existing solar heating system is analysed by annual simulation and the problems and the effect of thermal characteristics of the system are investigated due to change of heat collecting surface, heat storage method, capacity, building insulation performance and so on. Furthermore, it presents an improvement plan that maximizes the effect of the system and the performance of the system.

1 Introduction

Solar energy is essentially an intermittent, time-dependent energy source. Due to the nature of the use of solar heat that only weekly heat can be collected, there is a difference between the heatable time and the time of heating load and hot water load. These offsets and intermittency complicate the use of solar energy. In other words, heat storage is necessary for effective use of solar energy. In the case of the air-based solar heat system, since the heat capacity of air is small, it is necessary to store the heat by heat exchange with the material of the large heat capacity. There are a number of studies that attempt to solve daily-scale offsets (day-night) and annual-scale offsets (summer-winter) through various regenerative methods. In order to solve the offset of the annual scale, a lot of costs (for example, a large-scale heat storage tank) is required, so in this study, a method of compensating the offset of the daily scale is examined. The daily-scale offsets are relatively easy to compensate with water tanks or other short-term storage methods (eg, utilizing the thermal mass of the building). Recently, there are many studies that use PCM to store heat in the form of latent heat. Although the effect has been proven in many studies, the possibility of applying it to real houses is unknown due to cost problems. In this study, it is proposed a heating and hot water system for a house using air-based solar collection using foundation concrete and a space between the floor and foundation (placing plastic bottles with water) as a heat storage medium. In order to maximize the performance of the solar heating system, it is necessary to consider the overall heat balance of the thermal characteristic change of the whole building by applying each elemental technology. In this research, the air-based solar heating system is modeled and the validity of simulation model examined through comparison with experiment result. In addition, the performance of existing solar heating system is analyzed by annual simulation and the problems and the effect of thermal characteristics of the system are investigated due to change of heat collecting surface, heat storage method, capacity, building insulation performance and so on. Furthermore, it presents an improvement plan that maximizes the effect of the system and the performance of the system.

2 Simulation conditions

The simulation (ExTLA, Excel-based Thermal Load Analysis) used in this study is a thermal load calculation tool developed in the MAE laboratory of the University of Tokyo [1]. It calculates the convergence of simultaneous equations by Gauss-Seidel method using circular reference and iterative calculation function of Microsoft Office Excel. It is a feature of Excel-based simulation that it is possible to input mathematical formulas to each cell and to refer to the values of other cells from users. In the calculation method of ExTLA, it is adopted that a thermal network calculation in which the indoor temperature, the room humidity, the surface temperature of the indoor, the wall body temperature and so on. The backward difference of finite-difference methods was applied for the calculation of unsteady-state thermal conduction of the wall. The calculation is made in which convection and radiation are separated in the heat balance of the indoor surface.

An annual simulation was conducted to grasp the performance of the air-based solar heating system. The target building is a standard house prescribed by "Japanese energy saving standard (next generation energy saving standard)", and the interior space was divided into a heating space and a non-heating space. In order to secure the heat collecting area, the roof surface was set as the south-facing inclined surface, and the inclination angle of the roof surface and the heat collector was set as the latitude of Tokyo (35.4°). Also, assuming the surrounding buildings, we set the solar transmittance of the window to zero on the first floor so that there is no solar radiation acquisition from the window. Fig. 1 and Table 1 show building information. In this simulation, we were targeting a standard 4-person family, and assumed 450L/day hot water consumption (corrected M1 mode at 40°C by hot water supply) [2].

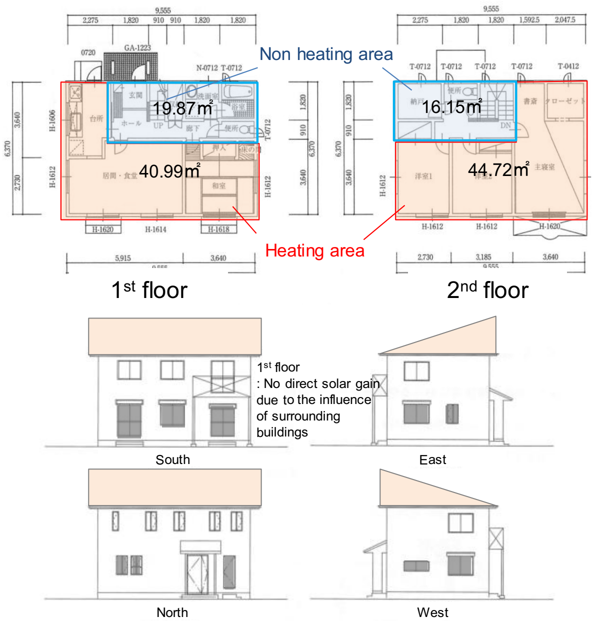

Fig. 1. Target building.

Table 1. Specification of target building.

Area	Whole floor area: 121.73m^2 Heating area of 1st floor: 40.99m^2, Non heating area of 1st floor: 19.87m^2 Heating area of 2nd floor: 44.72m^2, Non heating area of 2nd floor: 16.15m^2
Volume	328.06m^3 (including underfloor space)
Insulation of each part	Ceiling: glasswool 18K t=210mm Wall: glasswool 16K t=100mm Roof: glasswool 32K t=50mm Basis concrete: Extruded polystyrene foam t=50mm
Window	Plain double-glazed glass (Uw: 4.65W/m^{2}K)
Overall coefficient of heat transfer	UA-value: 0.83W/m^{2}K
Surface heat transfer rate of hot water tank	0.70W/m^{2}K (Insulation: 50mm, Thermal conductivity: 0.036W/mK)

The area ratio of a preliminary collector and a glass collector was set to 3:1 as preliminary collector 45m2 and glass collector 15m2. The capacity of the hot water storage tank was set to 1000L. The tank surface heat transmission coefficient of 0.7 W/m2K was input assuming a thermal insulation material of 50mm (Thermal conductivity 0.267 W/mK), and the heat loss was calculated from the difference between the outside air temperature and the temperature inside the tank. In addition, the length of heat collection side piping of the hot water storage tank was set to 30m and the thermal conductivity was set to 0.267 W/mK, and the heat loss from the pipe to the outside air was taken into consideration by the previous study. Table 2 shows the simulation condition.

Table 2. Simulation condition.

Weather data	ExpandedAMeDAS standard year (2000) Tokyo
Heating setpoint	20 °C
Heating schedule	7:00-10:00, 12:00-14:00, 16:00-23:00
Collector inclination angle	Latitude of Tokyo (35.4°)
Calculation period	Pre-calculation: January 1st - April 30th Target calculation: May 1st - April 30th
Time step	1hour
Hot water consumption	450L/day (40°C)
Internal heat generation	13.26 kWh/day
Collector area, air volume	preliminary collector: 45m^2, glass collector: 15m^2 Air flow rate: 780 m^3/h

3 Understanding the performance of the solar heating system

3.1 Simulation result of the typical house (non-solar heating collection)

In order to examine the effect of load reduction by application of solar thermal system, we first conducted an annual simulation of a typical house without a heat collecting system installed. In order to confirm the time series fluctuation of room temperature and load at a typical house, we show the result of 5 days of sunny weather that the solar thermal utilization is possible during January when the annual outside temperature is low. Fig. 2 shows the direct solar radiation from January 7th to 11th (5 days) and the direct solar radiation and the sky solar radiation intensity on the heat collecting surface (south, inclination angle 35.4°). As shown in Fig. 3, the temperature fluctuation in the room during the period (January 7th to 11th) is always lower than the heating set temperature (20°C) in the first-floor heating room where there is no solar radiation from the window. The Heating load is generated by raising the room temperature to 20°C by auxiliary heating during heating time. On the contrary, in the second-floor heating room, the room temperature rises to 20°C or more due to the influence of the solar radiation from the window during the daytime, but the room temperature has dropped from the evening when the solar radiation acquisition

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disappears and the auxiliary heating operation is carried out.

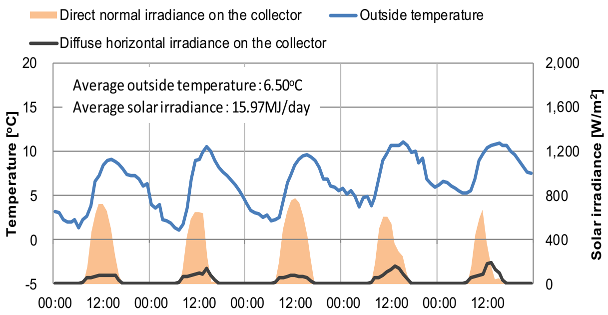


Fig. 2. Weather conditions (January 7th - 11th)

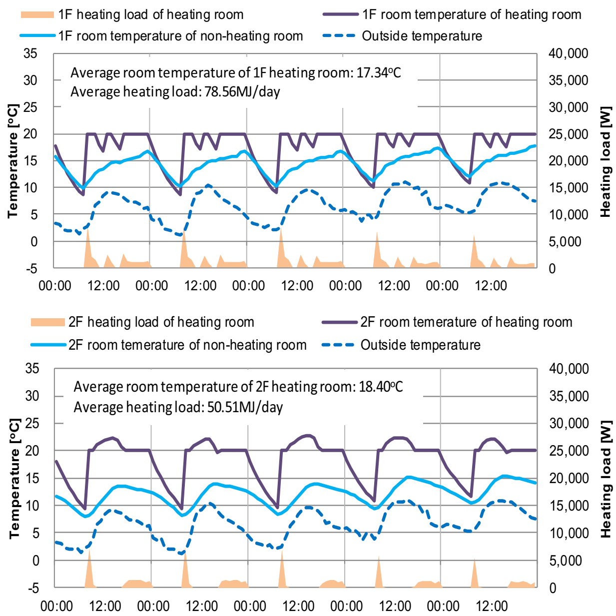


Fig. 3. Room temperature results of a typical house.

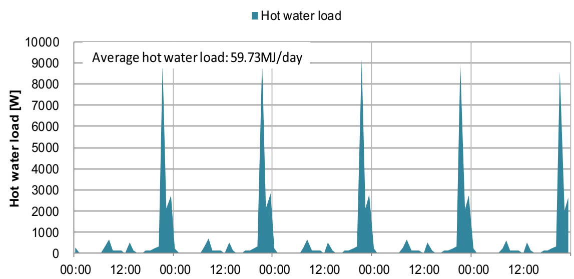


Fig. 4. Hot water supply load of typical house.

Fig. 4 shows the hot water supply load by the auxiliary heat source during the examination period. A load of 8,612W to 9,167W is generated at 21 o'clock when the usage amount becomes maximum, and a hot water supply load of about 59.73 MJ per day occurs on January 7th to 11th.

3.2 Study on air-based solar heating system

In order to improve the performance of the air-based solar heat collecting system, we examined the effect of annual heating and hot water supply load reduction by changing heat absorption/heat release of the heat collector, heat storage, and control of heat collection operation control. Regardless of the angle of the roof surface regardless of the angle of the roof surface, the area ratio of the preliminary collector to the glass heat collector is set to 3:1 based on the floor area where the minimum area is secured, and the preliminary collectors 45m2, Glass collector 15m2 was set. Fig. 5 shows the operation control of the system. Fig. 6 shows a conceptual diagram of the air-based solar heat collecting system to be studied in this research [3]. By applying the air-based solar heating system, room temperature rises by blowing the heated air during the day into the room as shown in Fig. 7, but hot air enters the room and overheats during the daytime. On the other hand, there is a problem that the room temperature drops at night. At that time, the temperature inside the hot water storage tank (Fig. 8) according to the hot water storage mode reaches a maximum of about 35°C.

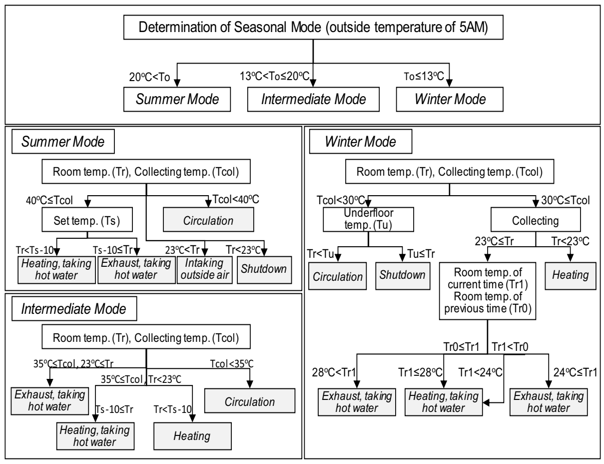


Fig. 5. Operation control of the air-based solar heat collecting system

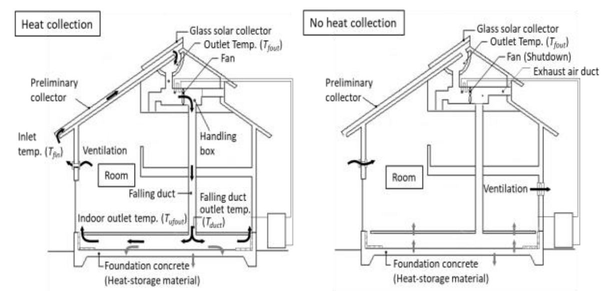
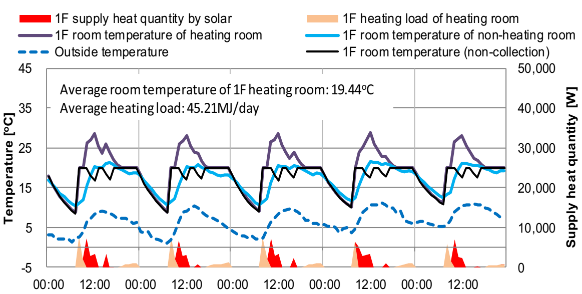


Fig. 6. Conceptual diagram of the air-based solar heat collecting system



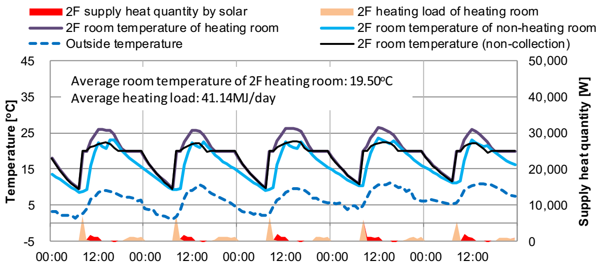


Fig. 7. Room temperature results of air-based solar system

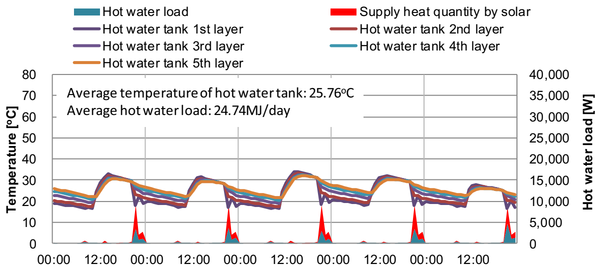


Fig. 8. Temperature inside hot water storage tank

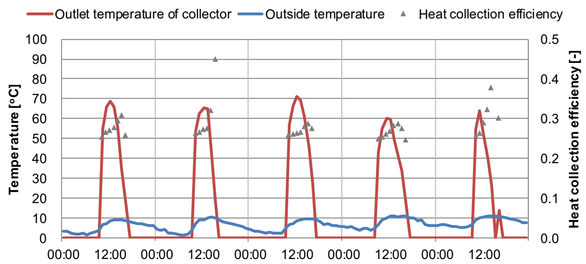


Fig. 9. Outlet temperature of collector and heat collection efficiency

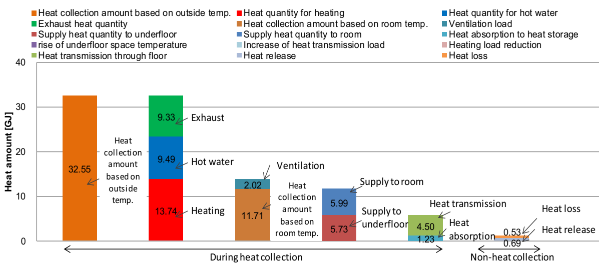


Fig. 10. Heat flow due to heat collection of air-based solar system

Table 3. Load reduction effect by application of the air-based solar heating system.

[GJ/year]	1F heating load	2F heating load	Hot water load	Reduction of heating load	Reduction of hot water load	Reduction rate of load [%]
Typical house	9.72	6.92	15.87			
Air-based solar heating system	5.67	5.58	5.55	5.39	10.32	48.3%

Fig. 9 shows the entrance and the exit temperature of the collector and the heat collection efficiency from January 7th to 11th when the air-based solar heating system is applied. Fig. 10 shows heat flux due to heat collection of air-based solar system. In order to increase the heating load reduction effect of the air-based solar heating system, it is important not only to improve the performance of the heat collector but also to increase the heat absorption performance of the heat storage. The heat storage helps that overheating in the daytime will not occur and that room temperature will not decrease by sufficiently dissipating the absorbed heat at night. In addition, it can be considered that it is possible to increase the annual heating and hot water supply load reduction effect by adjusting the hot water supply control according to the heating condition. Table 3 shows the load reduction effect by application of the air-based solar heating system.

4 Improvement plan for the air-based solar heating system

First, the glass of the collector is changed to a Low-E glass as a method of reducing the heat loss of the solar collector (case 1). It is thought that although the glass transmittance is slightly reduced due to the change of the glass, the heat resistance of the glass is increased and the heat loss to the atmosphere is reduced. Next, as a method of increasing the heat radiation amount of the thermal storage, a heat insulating material is installed below the base concrete (case 2). This is believed to reduce the loss of heat absorbed in the base concrete to the ground. In addition, as a method for releasing the heat from thermal storage, the indoor air is forcedly convected to increase the heat transfer coefficient of the surface (case 3). Since the base concrete has a limited installation area and heat capacity as a thermal storage, the additional 20L water packs are installed in the underfloor space to increase the heat capacity (case 4). In order to enlarge the surface of the additional thermal storage, the 500ml water bottles are used instead of 20L (case 5). Table 4 show the simulation cases.

Table 4. Simulation cases of air-based solar heating system.

Case1	Changing the glass of collector Existing glass: Solar radiation transmittance 0.88, U-value 6.0W/m^{2}K Low-E glass: Solar radiation transmittance 0.74, U-value 2.7W/m^{2}K
Case2	Case1 + insulation under base concrete
Case3	Case2 + indoor circulation during non-solar heat collection
Case4	Case3 + additional thermal storage (20L water packs 3000L)
Case5	Case3 + additional thermal storage (500ml plastic bottles 3000L)

The annual simulation results of the improvement of the air-based solar heat collection system are shown in Table 5. For the condition of the buildings, weather data, and system conditions of this study, 48.3% of heating and hot water load was reduced annually due to the application of the conventional air-based solar heat collection system. Also, by replacing the glass in the collector with Low-E, it was found that the heating load of the system can be reduced by about 2.5% compared to the existing system. Insulation below the base concrete resulted in a load reduction of about 0.2%. However, when the additional thermal storage is installed, the temperature of the underfloor space rises and the effect of the heat insulation is expected to increase. Lastly, it was shown that installing 3000L of 500ml plastic bottles with additional thermal storage can save the annual load up to 66.5% and keep the room temperature constant.

Table 5. Load reduction effect.

[GJ]	Heating load of 1st floor	Heating load of 2nd floor	Hot water load	Load Reduction rate [%]	1st floor	
					Avg. Temp[°C]	Daily difference [°C]
Non heat collection	9.72	6.92	15.87			
Existing system	5.67	5.58	5.55	48.3%	20.2	14.6
Case1	5.31	5.49	5.20	50.8%	20.2	14.8
Case2	5.29	5.47	5.18	51.0%	20.2	14.8
Case3	3.62	4.77	5.59	57.0%	20.7	11.1
Case4	3.32	4.59	5.81	57.8%	20.8	10.0
Case5	0.93	2.76	7.30	66.2%	21.8	4.1

5 Conclusion

As a result, the annual load reduction rate has increased by about 17.9% over the conventional air-based solar collection system. In this study, the improvement plan including various improvement factors was examined as a method to maximize the performance of the solar thermal system. However, the improvement of the indoor thermal environment by each factor and the examination of the load reduction effect are examined in the future. In this study, the performance of existing air-based solar heat collection system was evaluated. In addition, an annual simulation was conducted to examine the improvement effect for reducing the annual heating load and the hot water supply load. In order to improve the air-based solar collecting system, the glass of the solar collector was changed from ordinary glass to Low-E glass with less heat loss, and thus the effect of increasing the amount of solar heat collection and reducing the annual load was examined. In order to increase the amount of heat releasing by the thermal storage, it was examined to install insulation at the bottom of the base concrete. It was investigated the effects of forced circulation (indoor circulation) of room air and underfloor air to increase the amount of heat dissipation from the thermal storage during non-solar heat collection, and additional heat storage to increase the heat capacity of the floor space.

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