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Performance of the air-based solar heating system

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Abstract

Solar energy technology has good potential for heat generation of residential space heating and domestic hot water production. It has been reported that solar energy entering the roof of a typical home exceeds energy consumption per year. A liquid type is widely used as a medium to convert solar energy entering the roof into thermal energy. However, an air is the ultimate receiver of energy, and there is no problem of leakage, and it can be used by ventilation. By these reasons, in this study, air-based solar heat collection system is examined. In this research, an annual simulation was conducted to grasp the performance of air-based solar heat collecting system. It was prepared with reference to the past research of the solar thermal system simulation model. In addition, the accuracy of the simulation model was examined by comparison with the experimental results, and the validity of the simulation was confirmed.

Keywords: Solar heating system, validation, simulation, heat balance

1. Introduction

It is noteworthy that the renewable energy of various sources is utilized more efficiently due to the continuous increase of energy demand, the environmental deterioration due to greenhouse gas emissions, and the rise of fuel prices. Because the energy consumed in the building sector is about 40% of the total, the increase in the use of renewable energy is required. There has been a lot of research on the possibility of using renewable energy sources such as geothermal, solar and solar heat in particular. Among these, there is a strong interest in using solar energy because the system is simple and easy to maintain. Much of the energy consumed in houses is used for air conditioning and hot water supply. Solar energy is widely used as one of the most important renewable energy resources due to safety and an abundant amount. In past decades, global solar thermal capacity increases rapidly and it has been widely used for heating and cooling [1].

Since the temperature required for heating or hot water supply is relatively low, the effect of solar heat collection is relatively high. Solar energy technology has good potential for heat generation of residential space heating and domestic hot water production. It has been reported that solar energy entering the roof of a typical home exceeds energy consumption per year. A liquid type is widely used as a medium to convert solar energy entering the roof into thermal energy [2]. However, an air is the ultimate receiver of energy, and there is no problem of leakage, and it can be used by ventilation [3]. By these reasons, in this study, air-based solar heat collection system is examined. This paper shows the validation results from the experiment of the real house scale and examines the performance of the annual scale by the simulation of this system.

2. Simulation Conditions

The simulation (ExTLA, Excel-based Thermal Load Analysis) used in this study is a thermal load

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calculation tool developed in the MAE laboratory of the University of Tokyo. 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 [4, 5]. 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. By performing an iterative calculation (up to 32767 times), the convergence judgment is made when the change value of the calculation result is not more than the set maximum change value, and the divergence is prevented by using the alleviation coefficient. By the Excel's properties calculated from the upper cell, it calculates solar radiation related items, then calculates the node temperature inside the wall, and calculates finally the room temperature including ventilation, latent heat etc. For the purpose of improving calculation speed and convenience of use, calculation conditions such as weather conditions and air conditioning settings are input to the "input sheet”, the composition of the building and the characteristics of the members are set to the "setting sheet", the calculation result of the previous time is classified as the "T0 sheet", and the thermal load calculation of building and equipment are carried out in the "T1 sheet". The items for calculation can be freely set and can be outputted periodic and daily data of building and equipment.

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℃ by hot water supply) [6]. Table 2 shows simulation conditions. The area ratio of preliminary collector and glass heat collector was set to 3:1 as preliminary collector 45m^2 and glass collector 15m^2. The capacity of the hot water storage tank was set to 1000L. The tank surface heat transmission coefficient of 0.7W/m^{2}K was input assuming a thermal insulation material of 50mm (Thermal conductivity 0.267W/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 0.267W/mK, and the heat loss from the pipe to the outside air was taken into consideration by the previous study [7, 8].

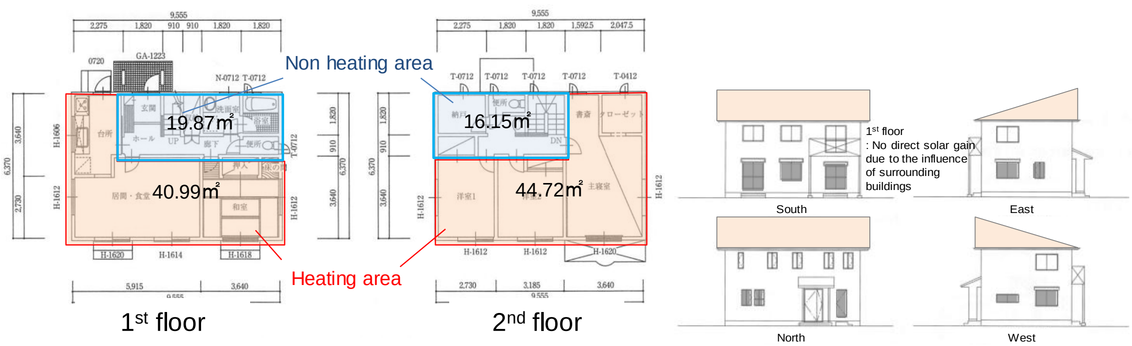


Fig. 1. Target building [9]

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 (U_w: $4.65W/m^2K$)
Overall coefficient of heat transfer (U_A-value)	$0.83W/m^2K$
Surface heat transfer rate of hot water tank	$0.70W/m^2K$ (Insulation: 50mm, Thermal conductivity: 0.036W/mK)

Table 2. Simulation conditions

Weather data	Expanded Amedas data standard (2000) Tokyo
Heating setpoint	20℃
Heating schedule	7：00～10：00、12：00～14：00、16：00～23：00
Inclination angle of collector	Latitude of Tokyo (35.4°)
Calculation	Preliminary calculation: From January 1st to April 30th, Target period: May 1st to April 30th of the following year
Time step	1 hour
Usage of hot water	450L/day (40℃ for using hot water) [10]
Internal heat gain	13.26kWh/day
Collector area	Preliminary collector: $45m^2$、glass collector: $15m^2$
Air volume	Air volume: $780m^3/h$

3. Simulation Modeling of Solar Collector

By the calculation model of the air-based solar heat collector [11], the temperature of the heat medium of the collector and the heat collection intensity was calculated. As shown in Equations (1) and (2), the outlet temperature and heat collection intensity of the collector are calculated from the inlet temperature, the sol-air temperature, and the coefficient of heat transmission of the collector. The sol-air temperature corresponding to the collector is obtained from Equation (4) and Table 3.

$$T_{fout} = T_{cole} - (T_{cole} - T_{fin})exp(-K_cA_c/c_fG_f) \tag{1}$$

$$Q_c = c_fG_f(T_{fout} - T_{fin}) = c_fG_f\varepsilon_c(T_{cole} - T_{fin}) \tag{2}$$

$$\varepsilon_c = 1 - exp(-K_cA_c/c_fG_f) \tag{3}$$

$$T_{cole} = k_uT_{coleu} + k_dT_{coled} \tag{4}$$

$$K_{cu} = K_{su}f_{cu}\ ,\ K_{cd} = K_{sd}f_{cd} \tag{5}$$

$$f_{cu} = \alpha_cW_{sd}b_{12} + \alpha_cW_{su}b_{22} \tag{6}$$

$$f_{cd} = \alpha_cW_{sd}b_{11} + \alpha_cW_{su}b_{21}$$

$$\mathrm{b}_{11} = (\alpha_r + \alpha_c + K_{su})/Det\ ,\ \mathrm{b}_{12} = \alpha_r/Det\ , \tag{7}$$

$$\mathrm{b}_{21} = \alpha_r(W_{su}/W_{sd})/Det\ ,\ \mathrm{b}_{22} = (\alpha_rW_{su}/W_{sd} + \alpha_c + K_{sd})/Det$$

$$Det = (\alpha_rA_{su}/A_{sd} + \alpha_c + K_{sd})(\alpha_r + \alpha_c + K_{su}) - \alpha_r^2(A_{su}/A_{sd}) \tag{8}$$

here,

T_{fout}, T_{fin}:	Outlet and inlet temperature of collector [℃]
T_{cole}:	Sol-air temperatureof collector [℃]

K_c :	Coefficient of heat transmission of the collector [W/m^{2}K]
A_c :	Collector area [m^2]
c_f :	Specific heat of air static pressure [J/kgK]
G_f :	Air volume [kg/s]
Q_c :	Heat collection intensity [W]
ε_c :	Efficiency of Heat Exchanger in Collector [-]
α_c :	Convective heat transfer rate on the collector surface [W/m^{2}K]
α_r :	Radiation heat transfer rate on the collector surface [W/m^{2}K]
W_{sd}, W_{su} :	Width of Collector frontside and backside (area per unit length) [m]
A_{sd}, A_{su} :	Area of Collector frontside and backside [m]

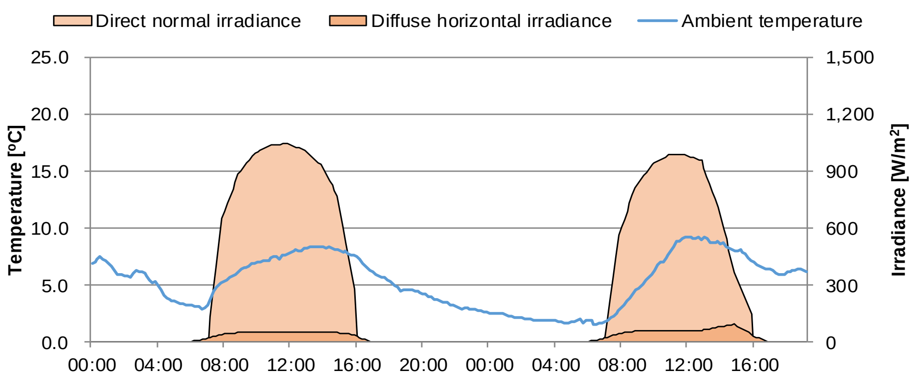
Table 3. Parameters of air-based solar heat collector calculations [11]

	K_{su}	K_{sd}	K_c	T_{coleu}	T_{coled}	SG	T_{cole}
Glass collector	$\frac{1}{r_a + 1/\alpha_o}$	$\frac{1}{r_b}$	$K_{cu} + K_{cd}$	$\frac{SG}{K_{su}} - \frac{R_{skyc}}{\alpha_o} + T_0$	T_x	$(\tau_g a_{su} I)_e$	$k_u = \frac{K_{cu}}{K_c}$
Preliminary collector	α_o		$K_{cu} + K_{cd}$	$\frac{SG}{K_{su}} - \frac{R_{skyc}}{\alpha_o} + T_0$		$(a_{su} I)_e$	$k_d = \frac{K_{cd}}{K_c}$

Here,

r_a :	Thermal resistance of the hollow layer [m^{2}K/W]
α_o :	Surface heat transfer coefficient [W/m^{2}K]
r_b :	Thermal resistance of surface material [m^{2}K/W]
R_{skyc} :	Night radiation on the outside surface of the collector [W/m^2]
T_o :	Outside temperature [℃]
T_x :	Collector backside temperature [℃]
τ_g :	Glass Transmission [-]
a_{su} :	Absorption rate of solar collector [-]
I :	Solar Irradiation on surface [W/m^2]

In order to examine the accuracy of the calculation model of the air-based solar heat collector, the outlet temperature of the collector of the experiment and simulation were compared under the same condition of the outside temperature, the inlet temperature, and the air volume. Fig. 2 shows the results for two days from December 19th to 20th 2012, when the preliminary collector area is 3.45m^2 and the glass collector area is 1.32m^2. Although there is a slight difference in temperature from the simulation, it is judged to be influenced by the temperature distribution on the backside surface of collectors and the measurement error of each equipment. However, in this study about the effect on the presence or absence of solar heat collector, it is considered that the accuracy of the simulation is sufficient.



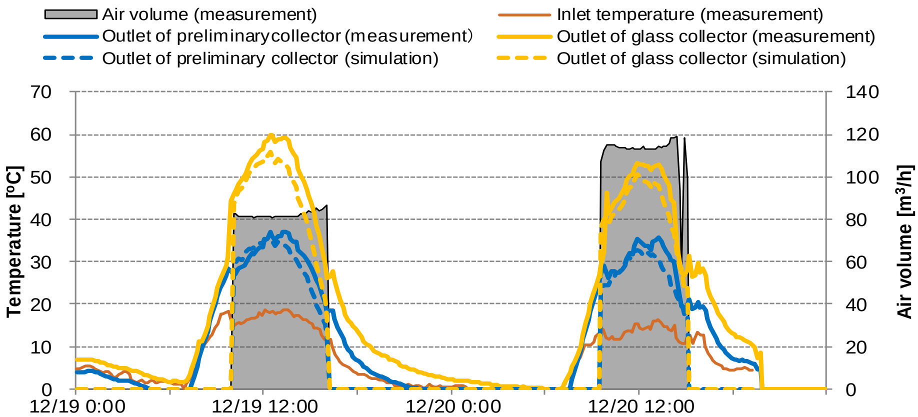


Fig. 2. Examination of accuracy of air-based solar collector model (December 19th to 20th, 2012)

4. Understanding the Performance of the Solar Heating System [12, 13]

4.1. 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. 3 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. 4, the temperature fluctuation in the room during the period (January 7th to 11th) is always lower than the heating set temperature (20 ℃) 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 ℃ by auxiliary heating during heating time. On the contrary, in the second-floor heating room, the room temperature rises to 20 ℃ 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 disappears and the auxiliary heating operation is carried out. Fig. 5 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.

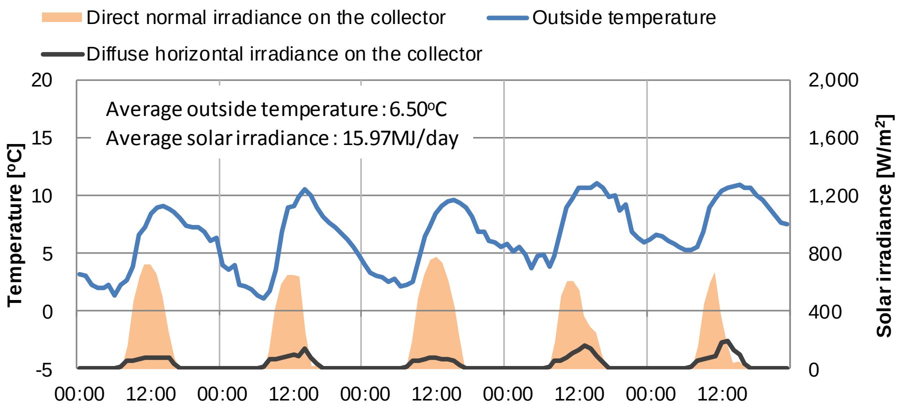


Fig. 3. Weather conditions (January 7th - 11th)

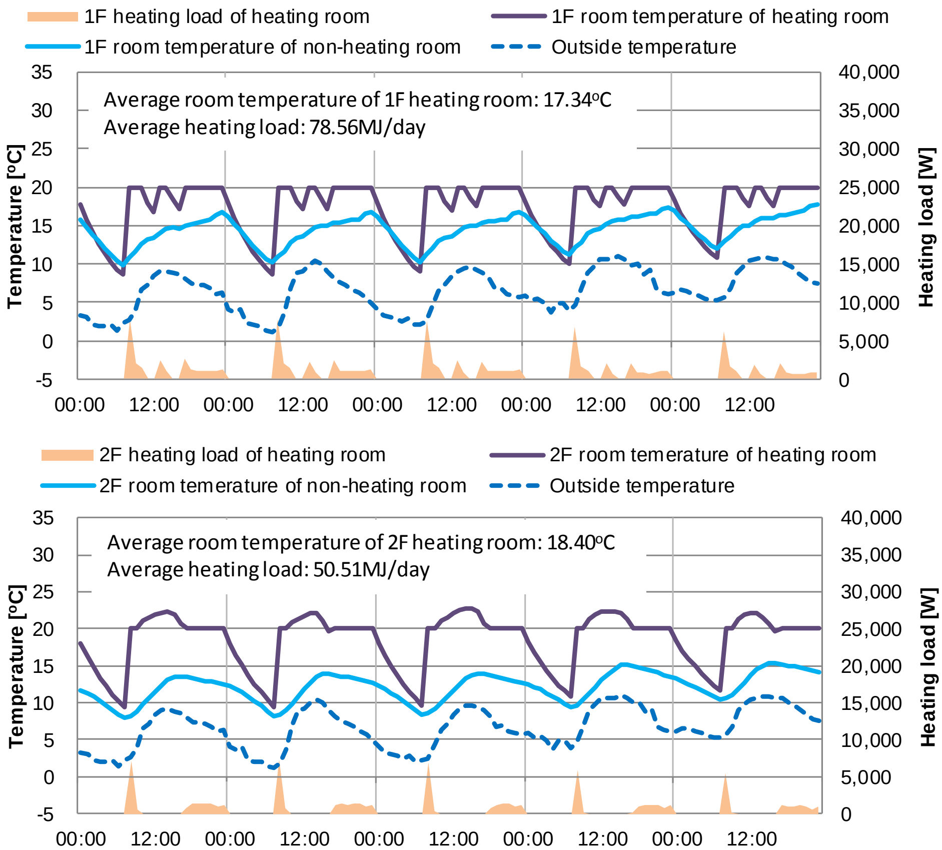


Fig. 4. Room temperature results for the first and the second floors of a typical house

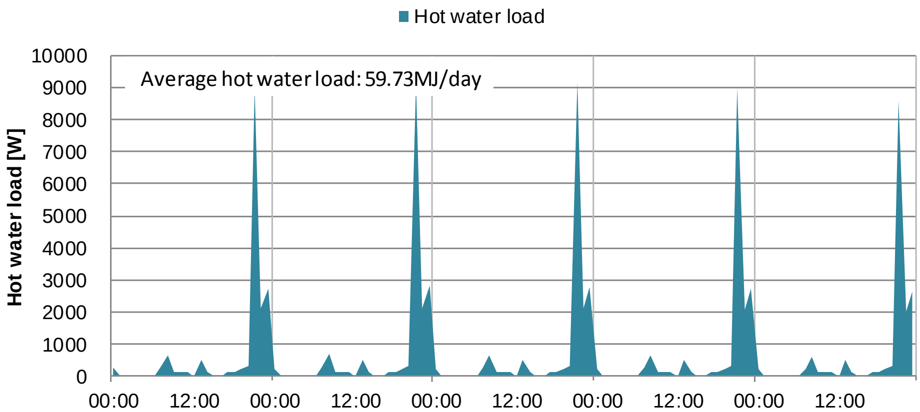


Fig. 5. Hot water supply load of typical house

4.2. 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 45m^2, Glass collector 15m^2 was set. Fig. 6 shows the operation control of the system. Fig. 7 shows a conceptual diagram of the air-based solar heat collecting system to be studied in this research.

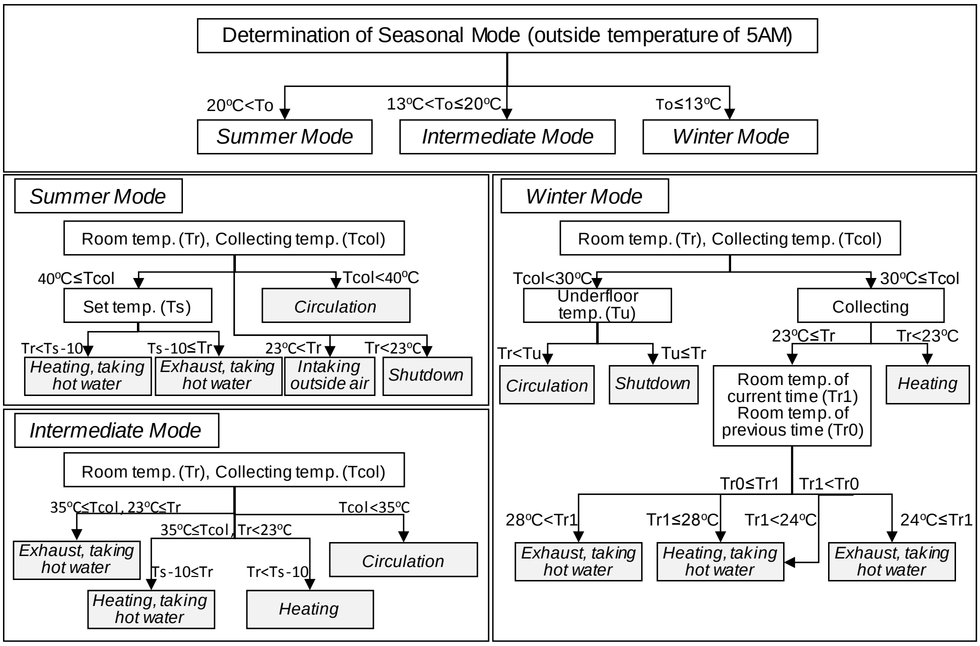


Fig. 6. operation control of the air-based solar heat collecting system

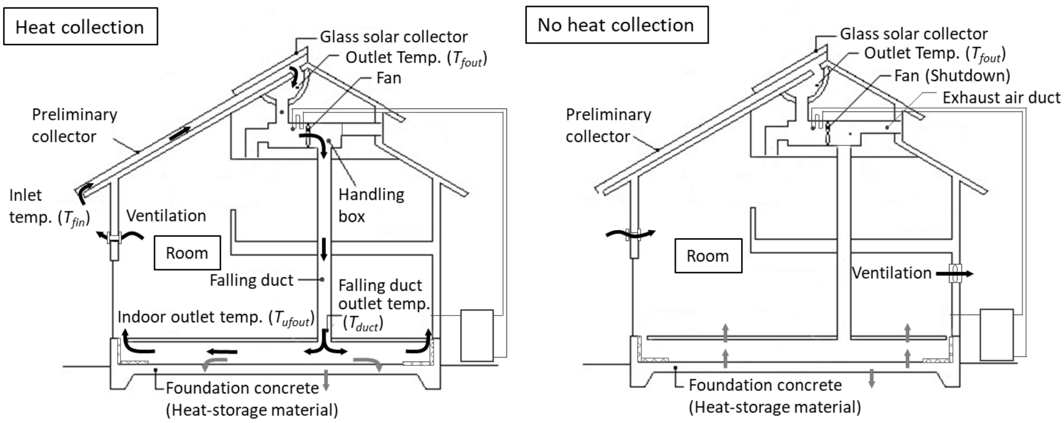


Fig. 7. Conceptual diagram of the air-based solar heat collecting system

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. 8, 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. 9) according to the hot water storage mode reaches a maximum of about 35 ℃. Fig. 10 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. 11 shows heat flux due to heat collection of air-based solar system. As shown in Table 4, the application of the air-based solar heating system proposed in this study showed that it was reduced the heating load by 32.4%, the hot water load by 65.0% and total load by 48.3%.

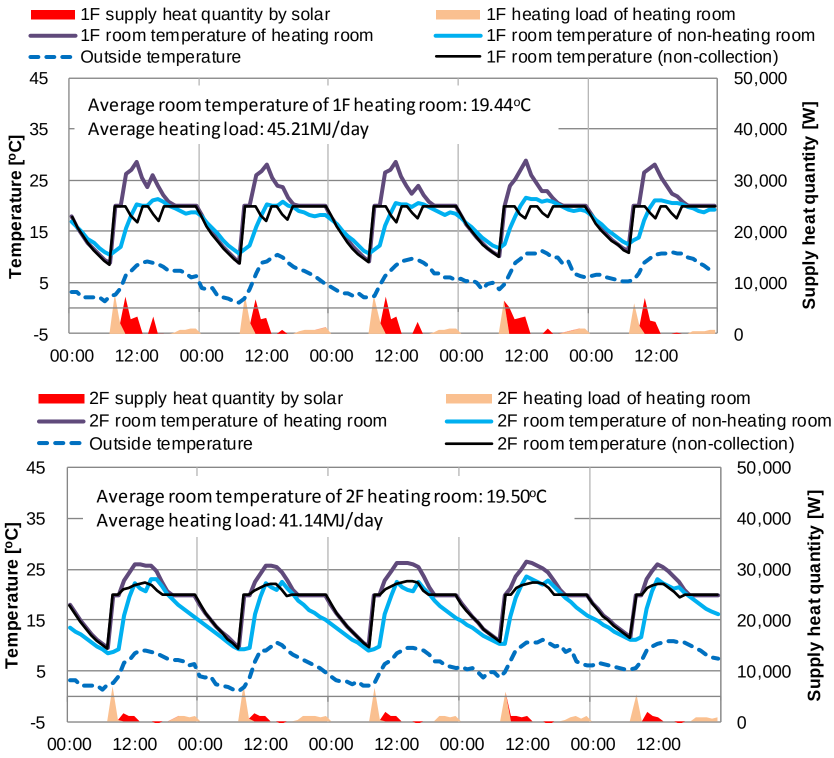


Fig. 8. Room temperature results for the first and second floors of air-based solar system

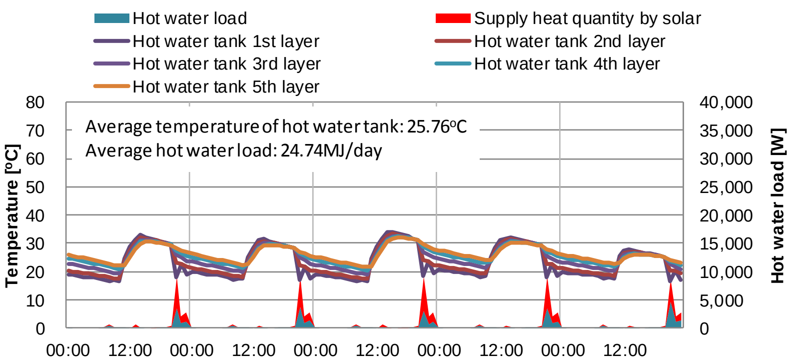


Fig. 9. Temperature inside hot water storage tank of air-based solar system

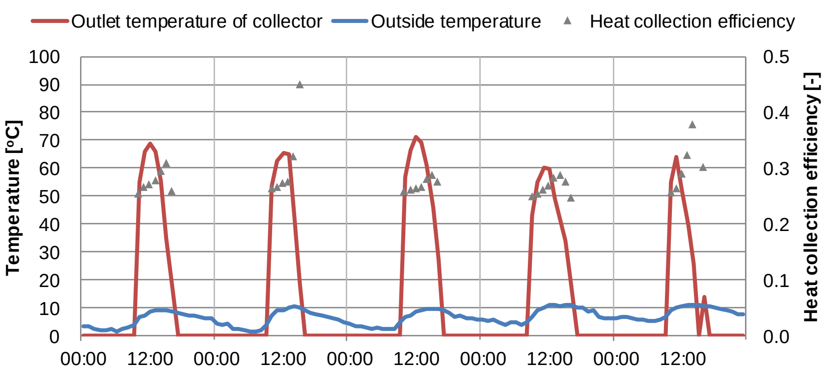


Fig. 10. Outlet temperature of collector and heat collection efficiency of the air-based solar system

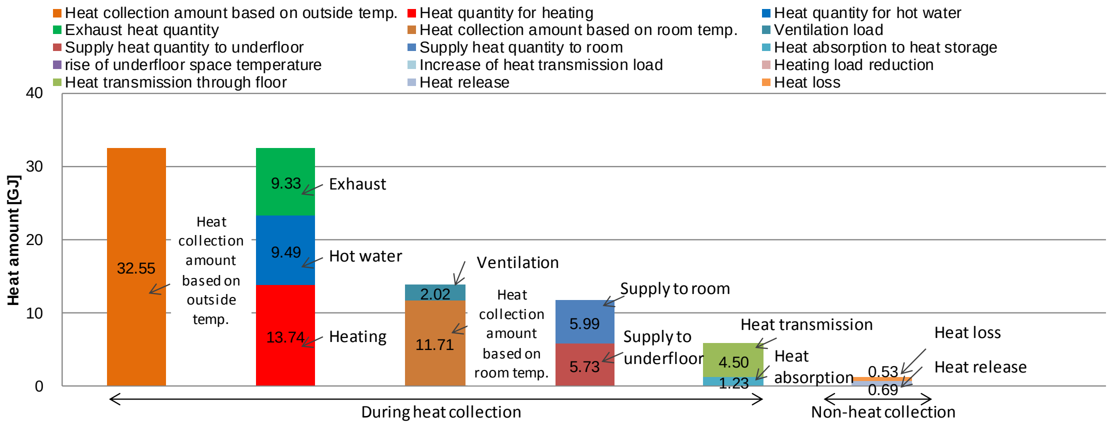


Fig. 11. Heat flow due to heat collection of air-based solar system

Table 4. Load reduction effect by application of the air-based solar heating system

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

5. Conclusion

In this research, an annual simulation was conducted to grasp the performance of air-based solar heat collecting system. It was prepared with reference to the past research of the solar thermal system simulation model. In addition, the accuracy of the simulation model was examined by comparison with the experimental results, and the validity of the simulation was confirmed.

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.

In the next study, the study on the air solar collecting system will be progressed. The effect of load reduction and room temperature stabilization by glass change of collector, insulation of base concrete, indoor circulation, additional heat storage material, and so on will be examined.

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