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Fundamental Study of the Green Roof Building Air-conditioning System using a Reduction Model Apparatus

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Abstract

The heat island or urban warming effect by the consumption of energy in a megalopolis would make better recognizing the importance of planting such as rooftop garden and efficient use of energy such as high efficiency building air-conditioning system. Accordingly, the author proposed a green roof building air-conditioning system using light weight soil as heat storage materials. The author has designed and developed a prototype test unit of rooftop garden as a thermal energy storage unit. The heat transfer characteristics of this unit have been evaluated. As a result, the heat transfer characteristics of the test unit have been clarified with respect to design factors such as apparent thermal diffusivity. Experiment was performed in which heat energy stored in the unit is recovered, revealing thermal storage properties of this unit. Furthermore, the author has designed a apparatus as a reduction model which we produced to evaluate the effectiveness of this compound system. These results demonstrate that the green roof building air-conditioning system is one of the promising candidates as a new building air-conditioning system. We believe firmly that this system is useful in Thailand.

Keywords: Heat pump, Green roof, Heat storage, Artificial sun, Heat recovery

1. Introduction

In recent years, urban areas in Japan have been experiencing a phenomenon called the heat island effect, which causes the temperature in cities to increase to a few degrees warmer than the surrounding suburban areas. It has attracted attention as one of many environmental issues. The heat island effect is a phenomenon in which atmospheric temperature is elevated due to increases in artificial heat releases and artificial land surfaces. In urban areas, the heat release rate is high because of the higher energy consumption rate. Additionally, since the coverage of artificial land surfaces such as roads or concrete buildings is extensive in urban areas, these materials act as a thermal storage medium through energy consumption, causing temperature increases in these areas. Especially in summer time, there is concern about health issues related to heat exhaustion, etc. caused by the temperature rise, and it becomes a serious environmental issue when a vicious spiral occurs due to the temperature rise driving up energy consumption. As a preventive measure, attention is being given to green roof projects that allow for a reduction in asphalt or concrete surface coverage in urban cities and are expected to promote the transpiration effect of plants. Consequently, various types of green roof units have actually been made available for practical use. In addition to the remedial measure against the heat island effect, green roofs are also expected to provide other positive impacts including prolonging a building’s life span and saving energy consumption as a result of reductions in air conditioning usage, since it increases building insulation. One of the global environmental problems of importance is global warming. To suppress global warming requires a decrease in load in the power plants. Thus, increasing the energy efficiency of electrical equipment is an important policy. Especially, the energy efficiency of air-conditioning systems for buildings should be improved immediately, because they are less efficient than household air conditioners.

From these facts, the author and other staff have been conducting fundamental researches by focusing on a combined system of a green roof and air-conditioning for buildings[1,2]. Current building air-conditioning systems are operated under excessive heat loads, and when a green roof unit is used as a thermal storage tank, the excessive heat can be utilized by establishing an energy saving type air-conditioning system which produces efficient energy use. However, a combined system of a green roof and air-conditioning is currently not on the market. By utilizing the green roof units as thermal storage tanks, and combining it into the building air-conditioning system which has an auxiliary heat source apparatus, a new air-conditioning system with low energy consumption can be designed, and there is the possibility that this technology could provide a solution to both the heat island effect and global warming. Experiment was performed in which heat energy stored in the thermal storage unit is recovered, revealing thermal storage properties of this unit.

This paper relates to a thermal characteristic of an experimental apparatus and a reduction model which is designed to evaluate the effectiveness of this compound system.

2. A System to Target

If a green roof unit is utilized as a thermal storage unit for air conditioning, an air-conditioning system for a building can be made energy efficient. In winter time, excess waste heat is transferred from the interior to a green roof unit in the building, which allows the plants to grow without dying all year. A green roof improves the thermal insulating properties of the building, which increase the energy efficiency of the air conditioning. A green roof can also receive solar energy to boil water.

2.1 Summer mode of a system

Figure 1 shows expected summer mode of a system with a green roof unit for a building.

In figure, heat energy is recovered in the following sequence.

(1)Plants are cultivated in a green-roof thermal storage unit ① installed on the roof of a building, resulting in the reduction of both wall temperature and CO^2 emissions. Hot water can be obtained, because pumped water circulates through buried heat exchangers. The heat of water extracted from the light-weight soil can also be recovered via heat exchangers. Water warmed by heat exchangers is fed into the interior of the building.

(2)A Stirling cooler[3,4] ② for air cooling or refrigeration is operated in the interior of the building. The hot water obtained in the process (1) absorbs waste heat produced by the high-temperature-side heat exchanger of this cooler.

(3)In the interior of the building, a Stirling engine ③ using a woody biomass pellet stove is also operated for generating electricity to meet power demand and driving heat pumps. The hot water obtained in the process (2) absorbs waste heat from the stove, the heat of exhaust gas, and waste heat produced by the low-temperature-side heat exchanger of the engine.

(4)The hot water obtained in the process (3) is recovered into the hot water storage tank installed downstairs (e.g., in the basement), and used for supplying hot water throughout in the building.

2.2 Winter mode of a system

Figure 2 shows expected winter mode of a system with a green roof unit for a building.

In figure, energy is similarly recovered in the following sequence.

(1)Excess waste heat produced by heating equipment, etc., is recovered through heat exchangers, producing hot water.

(2)A Stirling cooler ② for refrigeration is operated in the interior of the building. The hot water obtained in the process (1) absorbs waste heat produced by the high-temperature-side heat exchanger of this cooler.

(3)In the interior of the building, woody biomass pellet stoves are operated, the waste heat of which is used to operate a Stirling engine ③ for electric power demands. The hot water obtained in the process (2) absorbs waste heat produced by the low-temperature-side heat exchanger of this engine.

(4)The hot water obtained in the process (3) is pumped into buried heat exchangers of the green-roof thermal storage unit ① installed on the roof. Thus, the light-weight soil can be warmed to promote growth of the plants even in winter, while reducing CO^2 emissions.

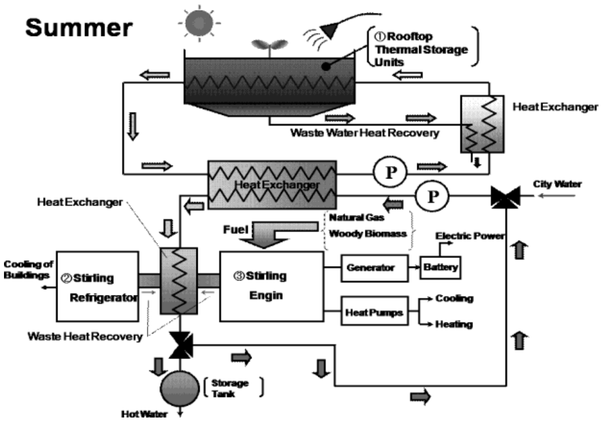

Figure 1 Summer mode of expected system

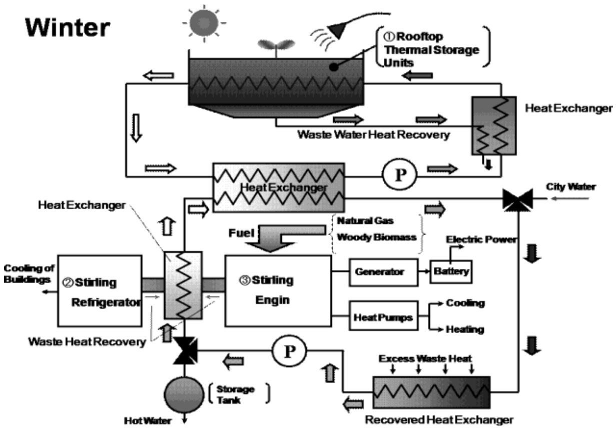

Figure 2 Winter mode of expected system

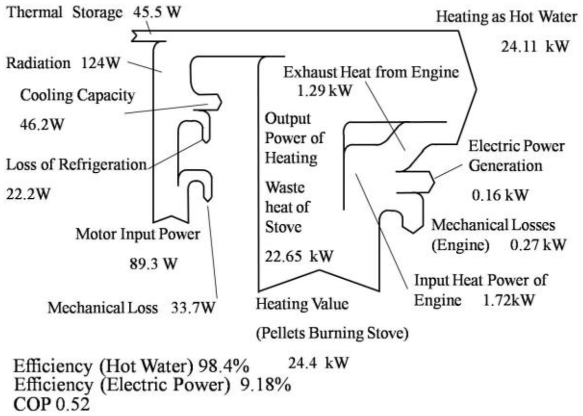

Figure 3 Heat balance of summer mode

2.3 Heat balance

The efficiency of these co-generation systems for buildings was evaluated. The results were summarized in the energy flow diagram, as shown in figure 3 and 4. Figures 3 and 4 correspond to figures 1 and 2, respectively. As shown in figure 3, input consisting of 45.5 W of stored heat, a motor input of 89.3 W, and a pellet-stove heat generation of 24.4 kW gives a cooling capacity of 46.2 W, a power generation output of 0.16 kW, and a heat of 24.11 kW for hot-water

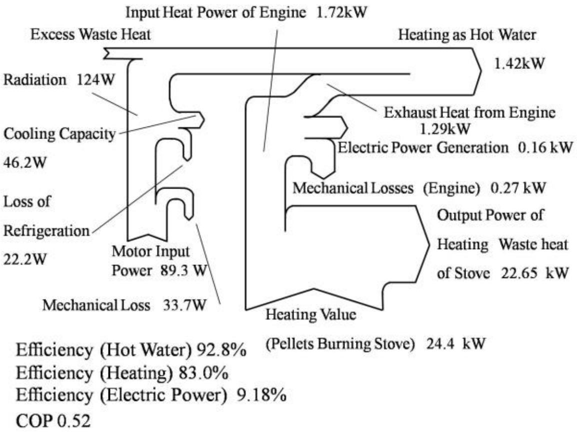

Figure 4 Heat balance of winter mode

supply. In this operation, the hot-water supply efficiency is 98.4%, power generation efficiency is 9.18%, and COP is 0.52.

In figure 4, the same input as that used in figure 3 gives a cooling capacity of 46.2 W, a power generation output of 0.16 kW, a heating output of 22.65 kW, and a heat of 1.42 kW for the hot-water supply. In this operation, heating efficiency is 92.8%, hot-water supply efficiency is 83.0%, power generation efficiency is 9.18%, and COP is 0.52. Both systems shown in figures 3 and 4 are overall highly efficient. Not only do these systems provide higher efficiency, but all their components produce a low environment impact, and are therefore considered an earth-friendly energy-recovery system: the Stirling cooler causes neither ozone depletion nor global warming because of its natural refrigerant; the Stirling engine using a pellet stove emits clean waste gas, which is effective for the suppression of CO^2 emissions; and the green-roof thermal storage unit contributes to preventing the heat-island phenomenon as well as global warming.

3. Green-rooftop Thermal Storage Unit

3.1 Outline of the modeling experiment system

A design of the system used for the modeling experiment is shown in figure 5. Halogen light was used as an alternate light source instead of the sun, and it was placed at 700 (mm) from the soil surface. The applied voltage for the halogen light could be changed so that its light volume and heat volume were adjustable. For greening units, the bottom part had holes for drains so that the excess water could always be discharged from the unit. Furthermore, on the ground, thermocouples were placed at depths of 0 m, 0.05 m, 0.10 m, 0.15 m, and 0.20 m from the surface so that the temperature at each depth of the ground could be measured. Insulation materials were used at the side and bottom surface of the greening unit to avoid temperature effects from the outer environment. As shown in figure 6, in the bottom of the experiment system, some copper pipes are laid through which water can run continuously at a constant flow and temperature. By measuring the temperature and flow at the inlet and outlet of these copper pipes, the amount of heat energy that transfers between the water running through the copper pipes and the light-weight soil is determined.

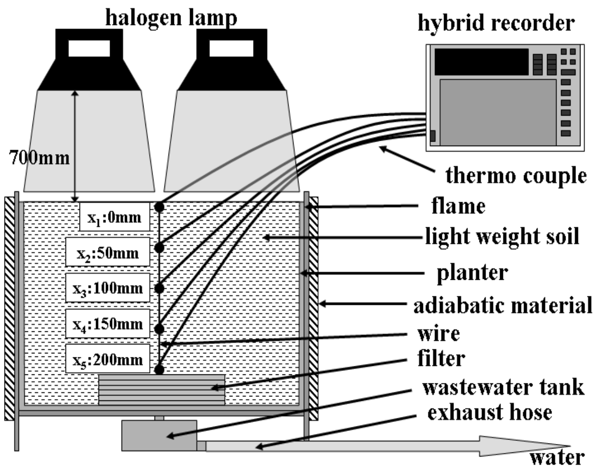

Figure 5 Model experiment system

Figure 6 Photograph of Test Planter

Figure 7 Phenol forming resin

Figure 8 Coconut bark based material

3.2 Outline of light-weight soil

In general, the soils used for a green roof system are required to minimize the weight load to the building, and light-weight soils are used in accordance with laws and ordinances in Japan. In this report, phenol foaming resin that is shown in figure 7 and coconut bark based material that is shown in figure 8 are used. Both materials demonstrate good water-retention properties, and since these materials are porous, they could form soils containing a lot of air as well as water when they are used for greening units. Table 1 shows the water retention rates where these rates were measured at appropriate times after the light-weight soils absorbed water. It indicates that phenol foaming resin has a higher water-retention rate than the normal compost, while coconut bark based material shows a lower rate. Coconut bark based material has better drainage properties and drying characteristics than the phenol foaming resin.

Table1 Water retention rates of soil

	Mass [kg]$\times 10^{-3}$		Water retention rate [%]
	wet	dry	
Normal Compost	100	48.9	51.1
Phenol foaming resin	100	30.9	69.1
Coconut bark based material	100	73.9	26.1

3.3 Apparent thermal diffusivities of the soil

Apparent thermal diffusivities of the light-weight soil in the thermal storage tank are obtained by solving a heat conduction equation, under the assumption that this tank consists of a one-dimensional soil with semi-infinite depth. Here, soils are assumed to be a uniformly combined solid containing water and air; the obtained thermal diffusivity is defined as an apparent thermal diffusivity, and this term is used hereafter in this document. The theoretical heat transfer equation for the lightweight soil in the greening unit is presented below.

[F.E.]

$$\frac{\partial v}{\partial t} = \kappa \frac{\partial^2 v}{\partial x^2}$$

[B.C.]

$$v = v_0 \qquad \text{when } t = 0$$

and $v = A\sin(\omega t + \varphi)$ at $x = 0$

The solution is

$$v = A_0 e^{kx} \sin(\omega t + \varphi - k x) + v_0$$

$$k = \sqrt{\omega / 2a}$$

v : Temperature [K]
x : Depth [m]
ω : Angular speed [rad./s]
φ : Phase [rad.]
t : Time[s]
a : Thermal diffusivity [m^2/s]
A_0 : Amplitude of a temperature swing [K]

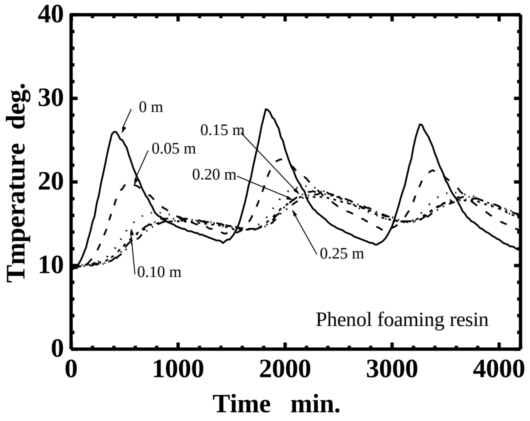

Figure 9 Temperature responses

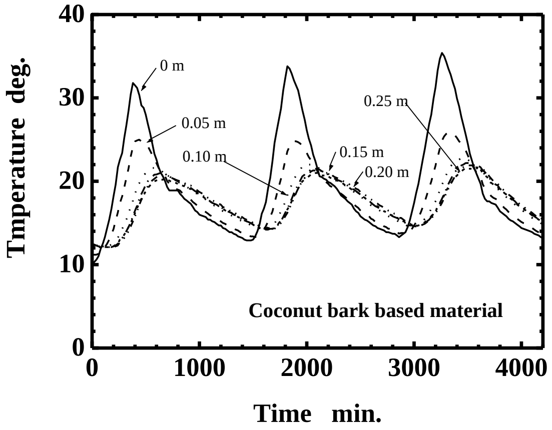

Figure 10 Temperature responses

Experiments were carried out in the following manner. First, after the soil had absorbed enough water, the soil was subjected to halogen light for 12 hours, followed by a 12-hour break, with no water run through the copper pipes. This pattern was repeated continuously for 3 days, and soil temperatures were recorded at 20 minutes intervals throughout the period. The surface temperature changes of the soil were taken as the sine wave and the apparent thermal diffusivity was calculated based on the damping rates of the temperature variances to the soil depth direction.

Secondly, the soil was subjected to halogen light, with water running through the copper pipes. The irradiation intensity of halogen light was altered by changing the voltage every 20 minutes during the 12-hour periods. The amount of heat energy that was absorbed by the water in the pipes was recorded. Power consumption of the halogen lamps was read on the wattmeter, and recorded. This power consumption was assumed to be equivalent to the amount of heat energy supplied to the light-weight soil.

Temperature responses for each measurement taken for soil in the greening unit that uses phenol foaming resin are shown in figure 9. The results for coconut bark based material are shown in figure 10 in a same manner as those for the phenol foaming resin. In both results, the soil surface temperatures indicate a virtual sine wave. The temperature variances become stable and the phase is delayed as it goes deeper into the soil. Decrement of these temperature amplitude is different. From these figures, respective temperature variances are aligned with the depths of the soil and these are shown in figures 11 and 12. The linear lines in the figures represent linear approximations of the data so that the apparent thermal diffusivities can be estimated based on the curves of the linear lines.

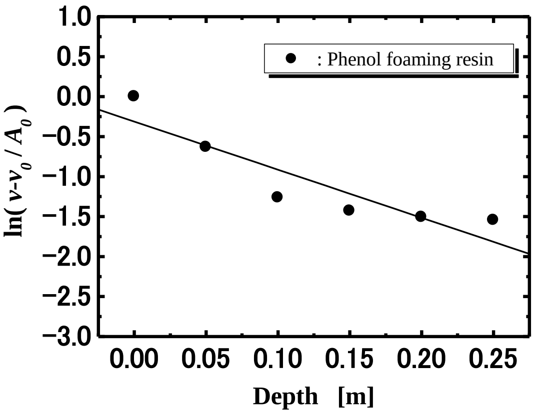

Figure 11 Temperature amplitude ratios

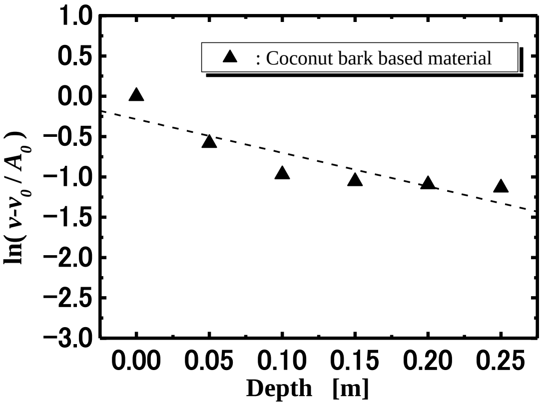

Figure 12 Temperature amplitude ratios

Table 2 shows apparent thermal diffusivities for each soil type. For reference purposes, standard thermal diffusivities for water, concrete and soil are also shown in the table. The apparent thermal diffusivity for light-weight soil is higher than that for water or soil. This is considered to be as a result of interference from air highly contained in the light-weight soil. In many cases, a thin layer structure for a green roof unit is sought because of the ease of installation and weight reduction, but even for the thin layer structure, sufficient building-insulating properties are expected and it provides good temperature responses from the soil, since the light-weight soil shows a large apparent thermal diffusivity.

Table 2 Apparent thermal diffusivity

Soil	Apparent thermal diffusivity $[m^2/s] \times 10^{-6}$
Phenol foaming	2.09
Coconut bark based material	0.16
Normal Compost	0.25
Water	0.15
Concrete	0.57

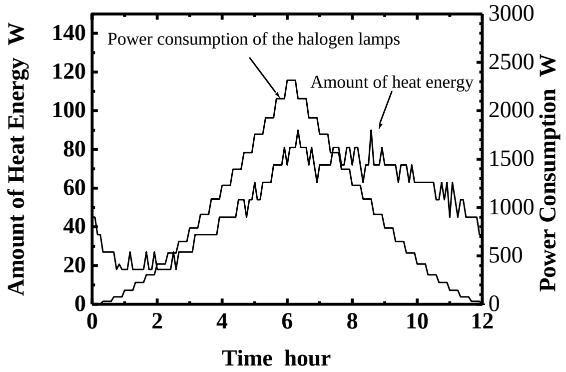

Figure 13 Amount of heat energy

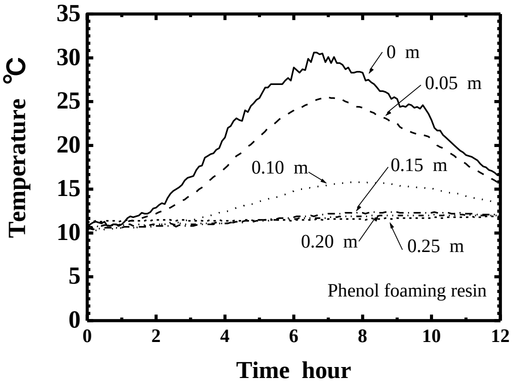

Figure 14 Temperature responses

When comparing the phenol foaming resin and coconut bark based material, the coconut bark based material could provide a better performance to the soil used for the system than the phenol foaming resin because the coconut bark based material has a higher apparent thermal diffusivity. However, from the point of view of plant growing, the phenol foaming resin, which has better water-retention properties than the coconut bark based material, provides a better performance. Therefore, it may be necessary to consider the use of a mixed light-weight soil of these materials in future plans.

Figure 13 shows the power consumption of the halogen lamps and the amount of heat energy absorbed by the water in the pipes, when voltage across the halogen lamps was changed every 20 minutes during the 12-hour periods, with water running through the copper pipes. The amount of heat energy absorbed by the water in the pipes changed periodically, with its phase delayed by approximately 1.5 hours, in comparison with the power consumption of the halogen lamps.

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This heat-transfer response speed can be applied to the air-conditioning systems load, which varies day-to-day. It was revealed that the water in the pipes recovers approximately 25% of the maximal power consumption of the halogen lamps. Figure 14 shows the temperature responses of the soil. Almost no temperature variances were observed at depths more than 0.15 m, at a depth of which the copper pipes were laid.

4. Reduction Model Apparatus

The author has designed a apparatus as a reduction model which we produced to evaluate the effectiveness of this compound system based on these experimental results. We assumed a building which has 8 rooms of 23 m^2 and total floor area of 200 m^2. The reduction model reduced this to 1/16. Table 3 shows specifications of the reduction model apparatus. Figure 15 shows the reduction model apparatus. And also figure 16 shows a circuit diagram of this model. This apparatus has a heat storage planter, a tank of hot water, and an air conditioner. The heat storage planter is heated by artificial solar heat, and collected heat is done heat storage of by hot water tank. The hot water tank is united with an air-conditioning system through a heat exchanger.

Figure 17 shows temperature change of water flowing to a planter as one of the reduction model apparatus operation check test. They become quasi-steady in about 60 minutes after a startup. These seem to be almost good performance.

Table 3 Specifications of the reduction model

	A building to assume	A Reduction model
A floor area	200 m^2	13.3 m^2
Planter area	3.75 m^2	0.25 m^2
Hot water supply	28 L/min.	1.8 L/min.
Capacity of air conditioner	2 HP ×8	1 HP
Waste heat from a building	6.51 kW	0.43 kW
Amount of radiation from an artificial sun		800 W/m^2 (max.)

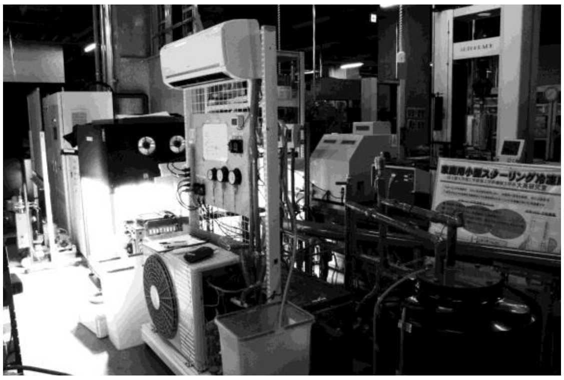

Figure 15 Reduction model

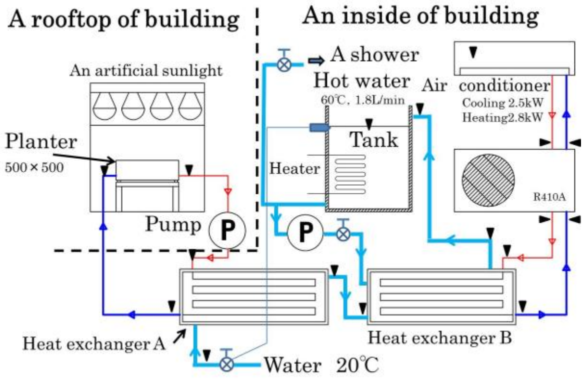

Figure 16 Circuit diagram of reduction model

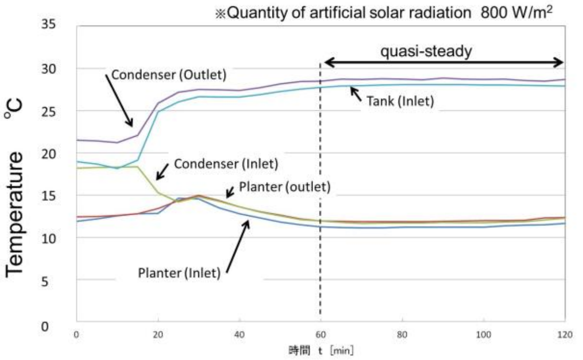

Figure 17 Temperature change

5. Conclusion

Fundamental experiment was performed in which heat energy stored in the planter unit is recovered, revealing thermal storage properties of this model apparatus. Moreover, we perform a function usability test of this reduction model apparatus, and report the result because utility was confirmed in this apparatus. These results demonstrate that the green roof building air-conditioning system is one of the promising candidates as a new building air-conditioning system.

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