Feasibility Study on the Use of Wintry-Rainwater for Radiative Cooling

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ABSTRACT

The holistic aim of this study is to make clear the possibility of passive cooling systems using natural cool sources produced by cyclic weather changes. Here in this study, we focused on a possible use of rainwater for cooling. First, we set up two rooms in an experimental apartment building: one has radiative cooling panels and external shading; and the other internal shading alone. The panel surface temperature of the radiative cooling was controlled at approximately 24 ℃ and the water to be supplied in the panel was produced by a heat pump system. We measured the indoor thermal environment of these two room spaces.

We then made a numerical analysis on the use of rainwater as a source of coolness, which may contribute to more efficient use of heat pumps. We estimated the accumulated water volume and its temperature from winter to summer using annual weather data of Tokyo, and calculated the amount of cool exergy.

The rainwater was assumed to be collected in a tank underground. The rainwater collection of eight months from October 1^{st} to March 31^{st} allows 1.7MJ/m^3 of cool exergy to be generated. The exergy of the rainwater increases gradually with the rise of outdoor temperature towards the summer. If this rainwater with cool exergy is circulated in the radiative cooling panel of 3.2m^2 in a room of 20m^2 of the floor area, the rainwater can supply cool exergy to the radiative cooling panel for 40 days.

We compare the exergy consumption of a radiative cooling system using the rainwater with that of a heat pump for a convective cooling system. In the radiative cooling system using rainwater, 24 W of exergy is supplied to the power plant to deliver 2 W for a circulating pump of cool exergy contained in the water from the tank to the radiative cooling panel. On the other hand, in the case of convective cooling system with a heat pump, 472 W of exergy is supplied to the power plant and 60 W of cool exergy is produced. The input exergy to the power plant is very much different from each other case. In the case of convective cooling system, the input exergy is twentyfold larger than that in the case of radiative cooling with the use of rainwater.

The result obtained from this calculation clarified the value of coolness of wintry rainwater, namely the cool exergy, which is to be produced by a smart use of the yearly cycle in the nature.

1. INTRODUCTION

In conventional radiative cooling systems as well as convective cooling systems, low temperature for water to be 5 to 10℃ is required. This is usually provided by a heat pump with a compressor driven by the electricity. The exergy consumption of such a heat pump is very large, for example, about 85 to 90 percent of the input exergy.

The chemical exergy contained by fossil fuel is unearthed, refined and then carried to the power plants. This is all the way from Middle East. The exergy of fossil fuels is consumed to be the exergy in electricity at the power plants. The exergy in electricity is supplied to the heat pump to produce cool exergy. However, cool exergy can be found also in our immediate outdoor environment such as ground, sky, rainwater, snow and others.

Therefore the electricity should be consumed not for cooling but for delivering the exergy available from the immediate natural environment to the cooling demand. For example, it may be interesting to use the rainwater to provide cool exergy into a room space with low electricity supply and thereby reduce the whole exergy consumption in summer seasons.

In Japanese climatic conditions, there is much precipitation. It could be a relative merit in our location in the world. Therefore, it is important to make use of the potential of rainwater.

In our previous research (e.g. Iwamatsu et al. 2007), we gradually make clear the possibility of high-temperature radiant cooling with natural ventilation.

Therefore we first measured the thermal environments of two experimental rooms in an experimental building to confirm the effectiveness of radiant cooling with natural ventilation. Based on these results, we then examined a possible use of cool exergy achievable in summer from the rainwater collected in winter.

2. EXPERIMENTAL SET-UP

We used two living rooms of an experimental building assuming typical condominiums in Tokyo area. The second floor has two radiative cooling panels: one in front of the south-facing window and the other as a front of partition. There is external shading in front of the window. We call this second floor as Room RC. The first floor has a conventional air conditioner and internal shading. We call this first floor Room NV.

Photo 1 shows the front view of this experimental building and a radiative cooling panel installed in the interior side of the south-facing window. *Figure 1* shows the floor plan of the building. The building structure is reinforced concrete and its thermal insulation is installed internal side.

The radiative cooling panel is made of cross-linked polyethylene tube, whose inside dimension is 7 mm. One unit of the panel is made of a metal frame,whose height is 2 m and width is 0.6 m. There are twenty-four pipes going up and down in the metal frame. We had four panels in front of the window and three panels as the partition in the living room.

The experiment was made from 22^{nd} to 27^{th} of August, 2007. In Room RC, two cases of cooling and ventilation were examined: the first is radiative cooling with natural ventilation (22^{nd} and 27^{th}); the second is natural ventilation only (20^{th} and 25^{th}). In Room NV, natural ventilation only (20^{th} and 22^{nd}) was examined. The surface temperature of the radiative cooling panel was controlled at approximately 24 ℃ by an electricity-driver heat pump.

Measured environmental quantities were wall surface temperature, air temperature, relative humidity, transmitted solar irradiance and others.

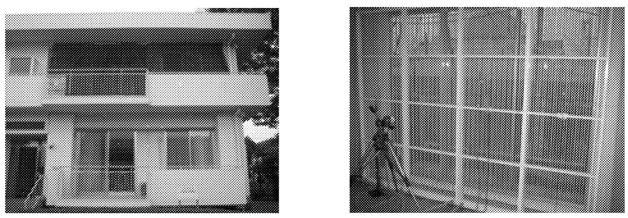

Photo 1: The front view of the experimental building (left), and a radiative cooling panel (right).

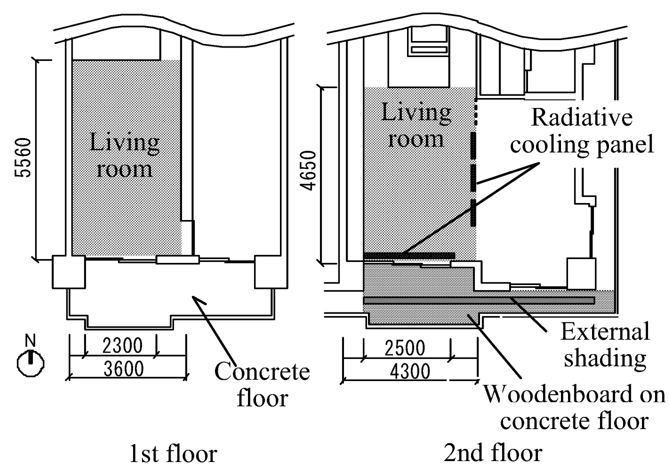

Figure 1: Floor plan of the building.

3. EXPERIMENTAL RESULTS

Figure 2 shows the variations of outdoor air temperature and horizontal solar irradiance from 20th to 27th of August, 2007. Outdoor air temperature rose above 32 ℃ for four days of experiment. The highest outdoor air temperature reached over 36 ℃ on 20th and 22nd .

Figure 3 shows the relationship between incident vertical solar irradiance and transmitted solar irradiance. In Room RC, the maximum transmitted vertical solar irradiance is 12 W/m^2, while on the other hand, it is 88 W/m^2 in Room NV. These results are due to the fact that there is an external shading on the 2nd-floor balcony but no external shading on the 1st-floor. The external shading reduces the transmitted solar irradiance very effectively.

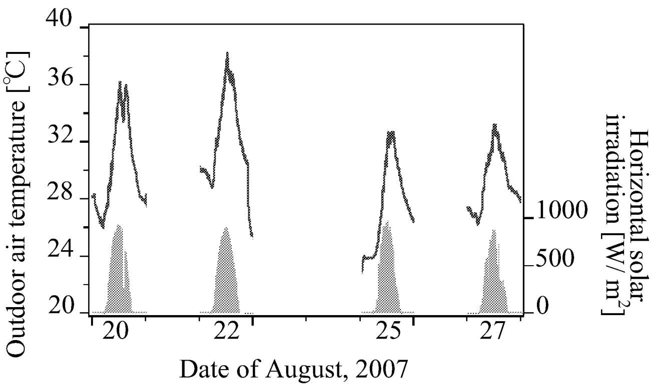

Figure 2: The variations of outdoor air temperature and horizontal solar irradiance from 20th to 27th of August, 2007

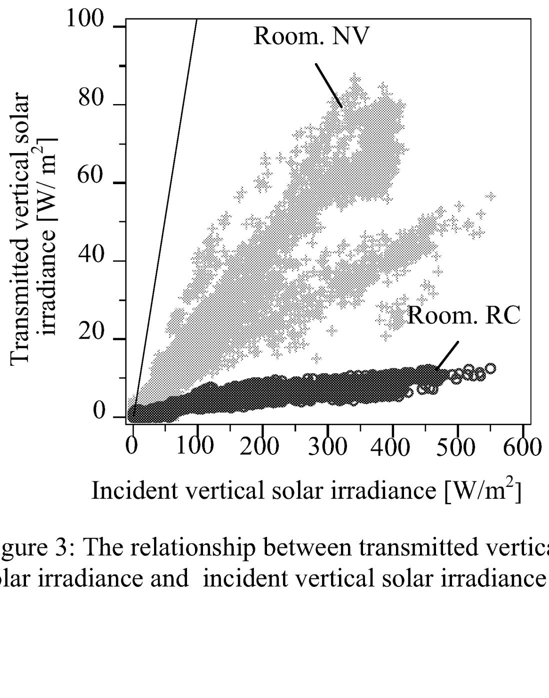

Figure 3: The relationship between transmitted vertical solar irradiance and incident vertical solar irradiance

Figure 4 shows the temperature variations of outdoors, indoors, panel surface, inlet and outlet water together with incident solar irradiance on 27th of August. Indoor air temperature and mean radiant temperature are about the same. The difference in water temperature between inlet and outlet is about 3 ℃, with the panel surface temperature at about 23 ℃ which is almost the same as outlet temperature. There is a temperature rise from 13:00 to 14:00, for the heat pump did not work during this one-hour period.

4. AVAILABILITY OF RAINWATER AS COOL EXERGY SOURCE

4.1 Water temperature and cool exergy of wintry rainwater to be collected

The temperature of rainwater is more or less the same as outdoor air temperature, if the rainwater collected in winter is kept, for example, somewhere underground; its temperature becomes the same as underground temperature soon or later. As the outdoor air temperature increases gradually month by month, the relative coolness of the water underground grows gradually. Exergy is one of the thermodynamic concepts to indicate the ability of energy or matter to disperse into its environmental space. Exergy is useful to quantify such coolness of rainwater.

We assumed a room with 20 m^2 of floor area and collected rainwater to be stored in a tank located under the ground floor, 1 m below the

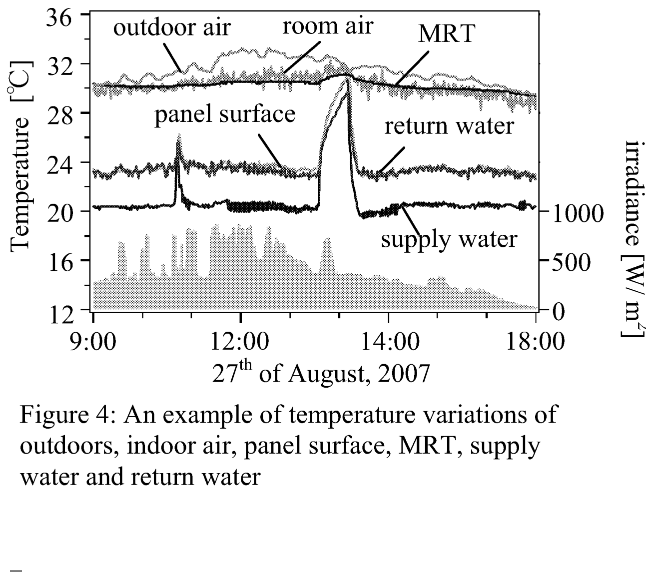

Figure 4: An example of temperature variations of outdoors, indoor air, panel surface, MRT, supply water and return water

ground surface. The tank is made of 100mm of concrete with 50mm of urethane boards.

Figure 5 shows the amount of precipitation each month with outdoor air temperature and ground temperature at the depth of 1 m for an average year in Tokyo taken from "Expanded AMeDAS Weather Data". Rainwater temperature while being collected is assumed to be the same as outdoor air temperature. Underground temperature is almost 15 ℃ throughout the year. We examined three lengths of period for collecting rainwater: one from October 1st to May 31st (A); another from November 1st to April 30th (B); the last from December 1st to May 31st (C). We assumed that the rainwater is used for radiative cooling from July 15th.

Figure 6 shows the relationship between water temperature and cool exergy density in three cases of A, B and C on July 15th. The plot size is proportional to the length of period for

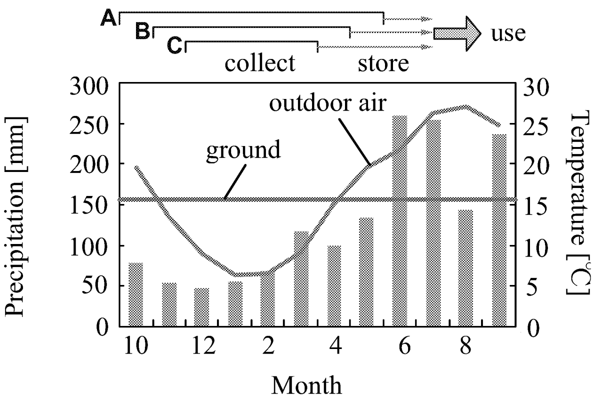

Figure 5: Variations of precipitation, outdoor air temperature and underground temperature for one average year in Tokyo

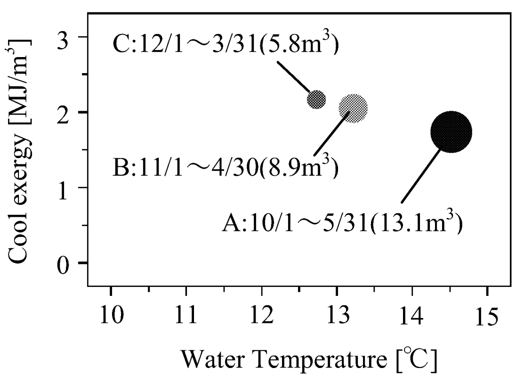

Figure 6: The relationship between water temperature and cool exergy in the tank

collecting. In case A, the water temperature in the tank is 14.5℃, which is the highest among three cases, and the cool exergy density available is the lowest at 1.7 MJ/m^3. The shorter the period of collecting rainwater is, the larger the density of cool exergy. As we limit collection of rainwater only during the period of low outdoor temperature, more cool exergy is available in the following summer. If the heat-loss of the tank is greater, the water temperature approaches the ground temperature. Therefore, it is not difficult to get the cool exergy density higher than 1.7 MJ/m^3.

4.2 Cool exergy supply for radiative cooling

The cool exergy of collected rainwater is assumed to be supplied to a radiative cooling panel from July 15th. We calculated the outlet water temperature of the panel surface, using the measured data of room air temperature and mean radiant temperature in the period of the outdoor temperature higher than 30 ℃ and with natural ventilation only. The outlet water temperature of the panel can be calculated from the following equation.

$$T_{fo} = T_p - \left(T_p - T_{fi}\right) e^{-\frac{A_{FP}K_{FP}}{c_{pw}\gamma_w V_w}},$$

where:

T_{fo} : Outlet water temperature of the panel [℃]

T_p : Surface temperature of the panel [℃]

T_{fi} : Inlet water temperature of the panel [℃]

e : Napier's constant [–]

c_{pw} : Specific heat of water $[kJ/kg \cdot K]$

γ_w : Density of water $[kg/m^3]$

V_w : Flow rate of water $[m^3/s]$

A_{FP} : Surface area of the panel $[m^2]$

K_{FP} : Coefficient of heat transmission between water and outer surface of the panel $[\mathrm{W}/m^2 \cdot K]$

The water temperature in the tank is then calculated with the outlet water temperature of the panel as the inlet water temperature of the tank.

Figure 7 shows the comparison of water temperature calculated and measured. Their difference is within ± 0.3 ℃. Therefore we thought the model is reasonable.

Figure 8 shows the water temperature in the tank and outdoor air temperature for 60 days of the radiative cooling panel being used. The rainwater was assumed to be circulated at 1.5 ℓ/min in the panel from 9am to 6pm everyday. In this calculation, we assumed that the indoor environmental condition measured use on August 25th continues everyday. When the water temperature in the tank reaches 26 ℃, the average panel surface temperature turns out to be over 30 ℃. We assumed this to be the condition for the termination of water circulation.

The water temperature in the case of 11.2 m^2 of the panel reaches 26℃ shorter than ten days. This panel size is the same as the panel used in the experiment. In the case of panel size of 6.4 m^2, we can use the radiative cooling panel for 15 days. In the case of 3.2 m^2, 30 days and in the case of 1.6 m^2, 60 days. The collected rainwater can supply cool exergy around two weeks to the radiant cooling panel located at the window or the partition.

Figure 9 shows cool radiant exergy emitted from the panel surface for the whole summer period in the case of 3.2 m2 of panel surface. The rate of cool exergy of 4.7 W in the beginning decreases gradually everyday and after 40 days, it diminishes totally.

4.3 Exergy consumption patterns of a radiant cooling system with the use of rainwater

Figure 10 shows a comparison of exergy consumption patterns of the radiant cooling system using rainwater and of a conventional convective cooling system. The exergy consumption pattern of the convective cooling system was taken from our previous research (Kataoka et al. 2007).

Exergy consumption partterns are very different from each other. In the case of radiative cooling system using rainwater, 24 W of exergy availabble from fossil fuel is supplied

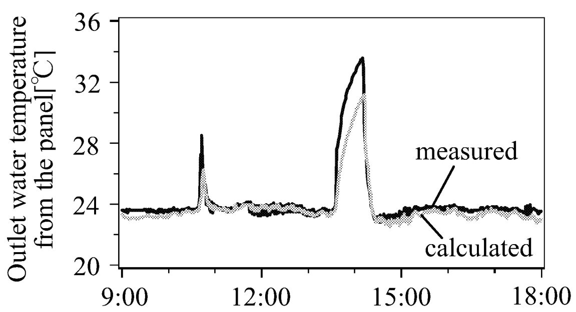

Figure 7: Comparison of water temperature calculated and measured

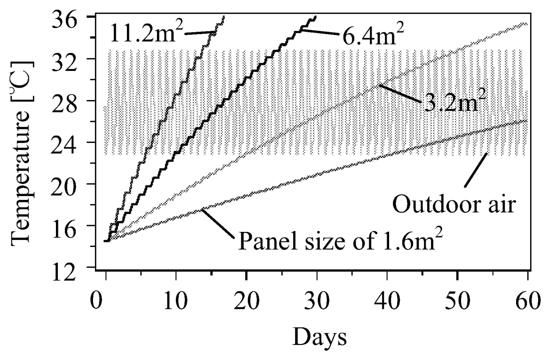

Figure 8: Water temperature rise in the tank during the period of 60 days of the radiative cooling used

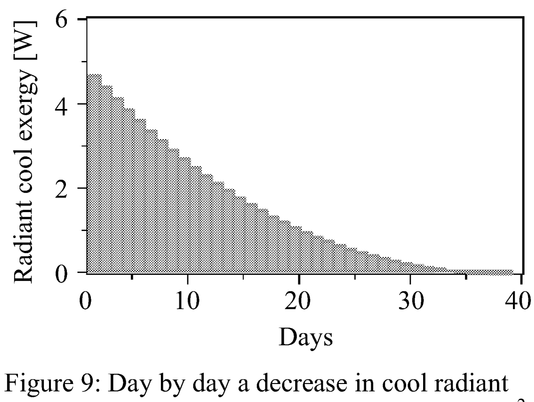

Figure 9: Day by day a decrease in cool radiant exergy emitted from panel surface area of 3.2 m^2

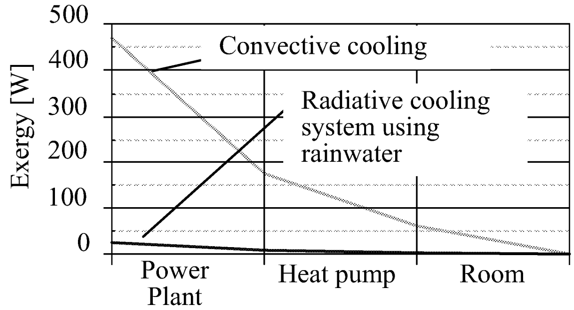

Figure 10: A comparison of exergy consumption rate for two cases of the space cooling system.

to the power plant and 9 W of exergy is produced as electricity. This 9 W of exergy is then supplied to a pump and thereby, 2 W of cool exergy is supplied to the panel. The difference in exergy between primary input and delivered to the panel, 22 W (=24-2), is consumed from the power plant to the pump. On the other hand, in the case of the convective cooling system, 472 W of exergy available from fossil fuel is supplied to the power plant and 176 W of exergy is produced, and then the heat pump generates 60 W of cool exergy to be supplied to the room space. The difference in exergy between primary input and delivered to the room space, 412 W (=472-60), is consumed from the power plant to the heat pump.

The amount of exergy consumption in the case of radiative cooling using rainwater is one twentieth of that in the case of conventional convective cooling.

5. CONCLUSION

We investigated the possibility of passive cooling system using wintry-rainwater. First, we measured two experimental rooms assuming the living rooms of a condominium building to confirm the effectiveness of radiative cooling combined with natural ventilation.

In the case of radiative cooling making use of rainwater, cool radiant exergy of 4.7 W was available from the panel surface in the beginning of summer and decreased gradually everyday for 40 days. This system requires 24 W of exergy from fossil fuel to deliver the cool exergy from the tank underground to the room space. This exergy supply is much lower than that for a convective cooling system.

The above mentioned investigation showed that cool exergy can be produced by the annual cycle of time. The amount of cool exergy to be supplied with wintry rainwater to the room space is rather small if compared with that produced by a heat pump system, but it is possible to use such small amount of cool exergy by combination of effective passive system such as external shading together with natural ventilation. Then, if the required cool exergy is not fulfilled by the use of cool exergy to be supplied from the immediate natural environment, then we have only to use a heat pump system to supply cool exergy required in the end.

ACKNOWLEGDEMENT

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