Radiant Cooling System with Water Flow on Roof

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ABSTRACT: The aim of the present study is to clarify the thermal performance of the Radiant Cooling System with Water Flow on Roof, which employs the evaporative cooling effect on the roof surface. In this paper, the thermal performance of this system, which uses a newly developed ceiling panel, is examined experimentally using a test house and simulation of energy consumption. Measurement results reveal that the room temperature of the test house is maintained at approximately 23-27ºC on summer days when the maximum outside temperature exceeds 30ºC. The simulation results clarify that the energy consumption of the radiant cooling system is lower than that of the normal air-conditioning system.

Conference Topic: 5 Materials and building techniques
Keywords: water flow on roof, radiant cooling, evaporative cooling, energy saving

1. INTRODUCTION

Recently, cooling systems are indispensable for residences in urban areas due to the improvement of the living standard and the heat island phenomenon. However, normal air-conditioning systems, which operate by electric power, enhance the heat island phenomenon and cause the air-conditioning disease. The utilization of natural energy is the most effective means by which to solve these problems.

Even in cities, the roofs of buildings are exposed to the sky, allowing the utilization of natural energy, not only solar radiation but night outgoing radiation, rain and so on. However, the use of natural energy has generally been limited to the use of solar energy for hot water supplies. Passive cooling techniques that make use of roofs exposed to the sky are needed for residences located in warm and hot climates.

From these points of view, the radiant cooling system, which utilizes the evaporative cooling effect of water flow on a roof, has been investigated [1]. In the present paper, the thermal performance of this system, which uses a newly developed ceiling panel, is examined experimentally. In addition, the energy saving effect of this system is discussed based on a simulation analysis.

2. OUTLINE OF RADIANT COOLING SYSTEM WITH WATER FLOW ON ROOF

Figure 1 shows a schematic diagram of the radiant cooling system with water flow on roof. This system consists of radiant panels, tanks, pumps, pipes and a usual insulated roof. As it flows down the roof surface, the water is cooled primarily by the evaporative cooling effect. The cooled water then circulates through the heat-storage tank and the radiant panels in the ceiling, cooling both the water in the storage tank and the inside of the rooms. In the daytime, radiant cooling is maintained using the cooled water in the heat-storage tank. At the same time, the water in the adjustment tank can be circulated through the roof surface for solar shading.

In this system, the ceiling radiant panels cool the inside of the room by radiation. Thus, the system provides a comfortable indoor environment, as compared to normal air-conditioning equipment, which blows cold air into the room. In addition, in this system, no condensation forms on the surfaces of the radiant panels because the lowest temperature of the cooled water is higher than the dew point, which is in accordance with the principles of cooling.

3. OUTLINE OF EXPERIMENTS
3.1 Description of Test House

Figure 2 shows a cross section of the test house examined in the present study. The floor plan of the test house is shown in Figure 3. The test house is of wood-frame construction and was built on the test field of the Tokyo Metropolitan University campus. The test house has twice the amount of thermal insulation as much as the new energy conservation standard in Japan. The east and west walls contain 200-mm-thick foam polystyrene board, and the other walls of the house have 100-mm-thick foam polystyrene board. The roof is covered with white-painted galvanized steel sheet and is insulated by 50-mm-thick foam polystyrene board. The south window has double-glazing. In these experiments, the south room is used as the test room and is kept airtight.

3.2 Radiant Panels and Experimental Conditions

The radiant ceiling panel is constructed of aluminum and is designed to cover the entire area (11.3 m²) of the ceiling of the test room, as shown in Figure 4. Table 1 shows the panel specifications. One panel is approximately 1.1 x 1.8 m and consists of header pipes (40 x 30 mm), branch pipes (30 x 10 mm) at 90 mm intervals, and a 2-mm-thick aluminum sheet, as shown in Figure 5. The sheets are spot-welded together at elliptical holes in the upper side of the branch pipes. In order to reduce the heat loss to the attic space, phenol foam board (0.02 W/mK, 25 mm) and glass wool (0.05 W/mK, 50 mm) are installed on the panels.

Table 2 shows the experimental conditions for each test case. A total of five tests were carried out in the summer of 2003. The period of night circulation for cooling and cool-heat storage is between 18:30 and 05:30. The measurement points are shown in Figures 2 and 3. Water was supplied to the adjustment tank at approximately 18:00 every day.

4. EXPERIMENTAL RESULTS

4.1 Indoor Thermal Environment and Water Temperature

(1) Natural Condition (Case1)

Figure 6 illustrates the temperature at various points under the natural condition (without the cooling system). Although the globe temperature was over 31°C, the highest outdoor temperature did not exceed 30°C. Since the storage tank was well insulated, the...
temperature of the water in the tank did not change. The maximum temperature of the attic space was approximately 36°C and remained 2 to 8°C higher than the outdoor temperature throughout the day.

(2) Radiant Cooling and Roof Solar Shading Condition (Case 2)
In this case, the radiant cooling system was operated as described in Table 2. Figure 7 shows that the water temperature in the heat-storage tank dropped to approximately 22°C, which is approximately 1°C higher than the wet-bulb temperature, in the early morning. In the daytime, while the water circulated through the panels, the water temperature in the heat-storage tank rose to 24°C. At night, the temperature of the panel surface varied the same as the water temperature in the storage tank, while in the daytime, the temperature of the panel surface was slightly higher than the temperature of the water in the storage tank. On August 22, the globe temperature was lower than 27°C, whereas the outdoor temperature rose to 32°C. The temperature difference between the room temperature and the water temperature in the storage tank remained less than 3°C. These results indicate that the thermal performance of the aluminum panel is excellent. On the other hand, the highest temperature in the attic space was approximately 2 to 3°C lower than the outdoor temperature due to the flow of water on the roof.

(3) Controlled Radiant Cooling Condition (Case 5)
In this case, the radiant cooling system was operated under an indoor temperature of over 26°C, and roof solar shading by water flow was not performed in the daytime. The highest indoor temperature was lower than 26°C. And operation time of radiant cooling was fewer, while the wet-bulb temperature in this period dropped lower than other periods, as shown in Figure 8. Thus, an indoor temperature of 26°C is considered to be maintainable.

4.2 Temperature Distribution
Figure 9 shows the vertical temperature distributions for a clear day. The vertical temperature difference varied only slightly. Figure 10 shows the surface temperature distribution of the test room at 13:30 on the same day. Although the temperature of the window was higher, the temperature difference between the other areas did not vary greatly. Therefore, the thermal environment of the test room was maintained in good condition.

4.3 Indoor Thermal Environment
Figure 11 shows the relationship between the indoor/outdoor temperature difference and the outdoor temperature for Cases 2 to 4. For all cases, the indoor/outdoor temperature difference increased with increasing outdoor temperature. The indoor/outdoor temperature difference at a flow rate of 12 L/min was less than those at 24 L/min and 36 L/min. The reason of this is that the cooling performance of the ceiling panel is reduced with decreased flow rate.
5. THERMAL PERFORMANCE ANALYSIS

5.1 Fluctuations in Heat Flow and Storage Rate

Figure 12 shows an example of the fluctuation of the heat release rate on the roof surface, the heat storage rate and the heat removal rate from the test room by the ceiling panel for Case 2. The heat release rate on the roof surface was calculated using water flow rate, specific heat and outlet/inlet temperature difference. At night, the maximum and average heat release rates on the roof surface were 4.7 MJ/h and 2.6 MJ/h, respectively. The average heat storage rate was 1.14 MJ/h. The heat removal rate from the test room by panel is approximately 0.3MJ/h at night, and is approximately 1MJ/h at maximums in the daytime. The mean value in the daytime was 0.7 MJ/h (60.4 kJ/m²h).

5.2 Thermal Performance of the Radiant Panel

Figure 13 shows the relationship between the cooling power of the ceiling panel and the temperature difference (the difference between the room temperature and the water temperature in the ceiling panel and temperature difference [between outdoor mean temperature and the outdoor wet-bulb temperature]). The cooling power of the panel increases with increasing temperature difference. The difference in cooling power per unit temperature is approximately 9.8 W/m²K at circulating flow rates of 24 L/min and 36 L/min and approximately 8.4 W/m²K at a circulating flow rate of 12 L/min.

5.3 Heat Release Rate on the Roof Surface and Heat Storage Rate

Figure 14 shows the relationship between the heat release rate on the roof surface and the temperature difference (the difference between the room temperature and the outdoor wet-bulb temperature). The heat release rate on the roof surface increases with increasing temperature difference. The relationship between heat rate and water flow rate remains unclear. Figure 15 shows the relationship between the heat storage rate and the heat release rate on the roof surface from 18:30 to 05:30. The heat-storage rate clearly increases with the absolute value of the heat release rate on the roof.

5.4 Heat Removed From the Room in the Daytime

Figure 16 shows strong correlation between the total values of the heat removed from the test room...
6. DISCUSSION ON ENERGY CONSUMPTION BASED ON SIMULATION

6.1 Outline of Simulation and Comparison Between the Measurement Value and the Calculation Value

A computer program to calculate room temperature and cooling load was developed. The calculation of water flow on the roof surface was based on the wet sol-air temperature method. [2]

Figure 17 compares the measured and calculated temperatures in the test room, the water in the heat-storage tank and the outlet of the roof surface for Case 2. The measured and calculated temperatures are approximately the same, although the peak calculated value of the water temperature at the outlet of the roof surface is 1 to 2ºC lower than the measured temperature. The difference between the calculated room temperature and the measured room temperature is less than 0.5ºC. Although not shown in the figure, the water temperature in the adjustment tank varies the same as the water temperature at the outlet of the roof surface.

6.2 Simulation Conditions

Table 3 shows the calculation conditions. The building model was the same as the test house. In these simulations, for the radiant cooling system, we assumed the flow rate of the system to be 24 L/min during the day and that no solar shading was performed on the roof by water flow. The radiant cooling system was assumed to operate under room temperatures of over 26ºC, 27ºC and 28ºC during the daytime (05:00 - 18:00), and the heat generation inside the room was assumed to be constant at either 50 W or 100 W all during the day. In each case, the air-conditioner was operated when the room temperature exceeded the mean room temperature during the cooling time of the radiant cooling system. The standard climate data of Tokyo was used for this simulation.

6.3 Examination of Energy Saving Effect

Figure 18 shows the room temperatures for the cases in which the daytime room temperature was set to 27ºC. The room temperature for Case C-2, in

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Table 3: Calculation conditions

<table>
<thead>
<tr>
<th>Case</th>
<th>Room temperature setpoint during daytime</th>
<th>During night</th>
<th>Internal heat generation</th>
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<tr>
<td>C-1</td>
<td>27ºC</td>
<td>27ºC</td>
<td>50W</td>
</tr>
<tr>
<td>C-2</td>
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<td>100W</td>
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</table>
which the internal heat generation was 50 W, was maintained under 29°C and the mean value during cooling was 27.4°C. The room temperature for Case C-8, in which the internal heat generation was 100 W, was kept within approximately 21 to 31°C, and the highest room temperature was 7°C lower than the highest outdoor temperature during the daytime.

Figures 19 and 20 show the comparison of total energy consumption in July and August between this radiant cooling system and the normal air-conditioning system for internal heat generations of 50 W and 100 W. The energy consumption of the radiant cooling system is calculated as the electric consumption of the pump and that of the air-conditioning system is calculated assuming a COP of 2.5. [3] In the case of an internal heat generation of 50 W, the energy consumption of this system is approximately 70 MJ lower than that of the normal air-conditioning system at the mean room temperature of operation for each case, as shown in Figure 19. With respect to the operation of the radiant cooling system at 27°C, the reduction in energy consumption is 19%, or 28% in the case of an internal heat generation of 100 W, as shown in Figure 20. Therefore, for this radiant cooling system, the possibility exists that a larger internal heat generation may improve performance.

7. CONCLUSION

In the present paper, the thermal performance and the energy saving effect of the radiant cooling system with water flow on roof were examined experimentally and by simulation. The most important results are listed below.

1) The temperature of the water in the heat-storage tank was approximately 22 to 25°C and the room temperature in the test house was maintained at approximately 23 to 27°C on summer days when the outside temperature exceeded 30°C. Therefore, the cooling system can provide comfortable indoor climate.

2) Strong correlation exists between the total values of the heat removed from the room during the daytime and the temperature difference between the mean outdoor temperature during the daytime (05:30 - 18:30) and the lowest wet-bulb temperature during the previous night (18:30 - 05:30). The average heat removed from the room during the daytime was approximately 60 kJ/m²h.

3) The energy consumption of the radiant cooling system is 20 - 30% lower than that of the normal air-conditioning system, and the possibility exists that a larger internal heat generation may improve the performance of the radiant cooling system.

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