Cool-Radiant and Dry Exergies Available from the Ceiling with an Attic Space Conditioned by an Air-Conditioner

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ABSTRACT

A radiant cooling system with the use of an ordinary air conditioner in attic space, which may cope with natural ventilation, was developed as a trial. In this system, the ceiling surface is made of "Washi", a Japanese paper material; this to provide the room space below the attic space not only with the coolness by long-wavelength radiation but also with the dryness by transmission of dehumidified air generated in the attic space through the ceiling. The aim of the trial is to create a good radiant indoor climate making use of an ordinary air conditioner widely used now.

Measurement was carried out in August 2007. To understand better the combined performance of the radiant cooling system and natural ventilation, two cases were picked up: one without natural ventilation measured on 22nd of August, and the other with natural ventilation measured on 25th of August.

For our analysis, we used the concept of exergy to quantify coolness and dryness given by this system. The coolness given by long-wavelength radiation can be quantified by "cool" radiant exergy, which is available in the case of wall surfaces having lower temperature than the outdoor environment. The humidity of a volume of humid air is lower than outdoor environment.

Dry exergy in the room space is supplied by an air conditioner in the attic space. The boundary surface made of Washi with wooden frameworks allows dry exergy to transmit the ceiling into the room space together with cool radiant exergy to decrease mean radiant temperature in the room space. The removal of moisture from the room space by natural ventilation together with the supply of dry exergy available from the ceiling could allow the radiant cooling to be in the primary position for conditioning the built environment in summer.

1. INTRODUCTION

Nowadays, convective cooling is widely used in Japan whose summer is very hot and humid, but there are some problems such as cold stress, heat island, and the waste of fossil fuels. It is necessary to reexamine the present method of indoor environment conditioning and find a new way.

For this purpose, a system making good use of natural ventilation together with a radiant cooling system was set up in a small wooden experimental house and we investigated the realized indoor thermal environment. The radiant cooling system here is the one composed of an air conditioning unit installed in the attic space. It cools the air within the attic space and the ceiling surface is indirectly cooled. For our analysis, we used the concept of exergy to quantify coolness and dryness given by this system.

2. THE RADIANT COOLING SYSTEM

The experimental house has an air-conditioner in the attic space, which provides cool and dry air and thereby decreases the ceiling surface temperature. The ceiling is made of wooden frame works with "Washi", a Japanese paper material, which has moisture -absorbing, -desorbing, -transmiting characteristics. (see *Figure 1*) *Figure 2* shows the points where

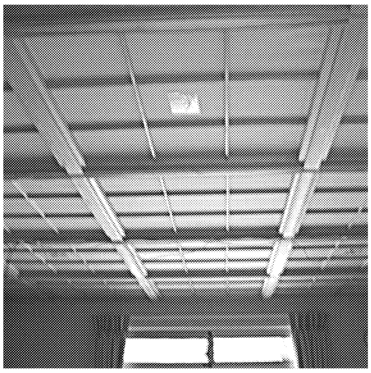
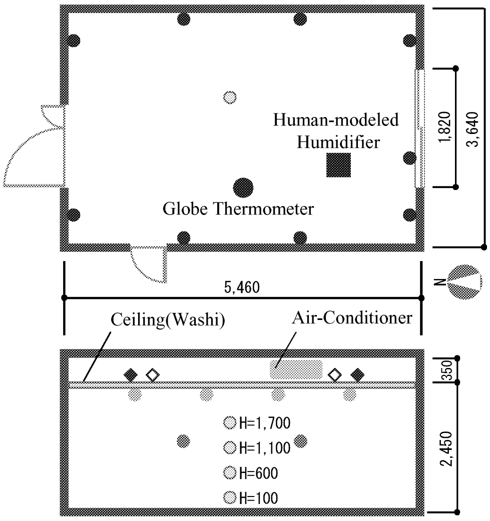


Figure 1: The ceiling surface made of "Washi" and wooden frameworks



The following symbols indicate the points where thermo couples were placed: ●and●: wall surface; ○: four points in the room space; ●: ceiling surface; ◆: attic space. The symbol ◇ represents a hygrometer.

Figure 2: The points where temperature and humidity are measured.

temperature and humidity were measured. There is a thermostat in the air-conditioner to control the temperature and humidity of the attic space. The temperature and humidity of the room space run rather freely being affected.

3. MEASURED RESULTS

Measurement was carried out in August 2007. To know the performance of the combination of the radiant cooling system and natural ventilation, two cases were picked up: one is without natural ventilation measured on 22nd of August, and the other with natural ventilation measured on 25th of August.

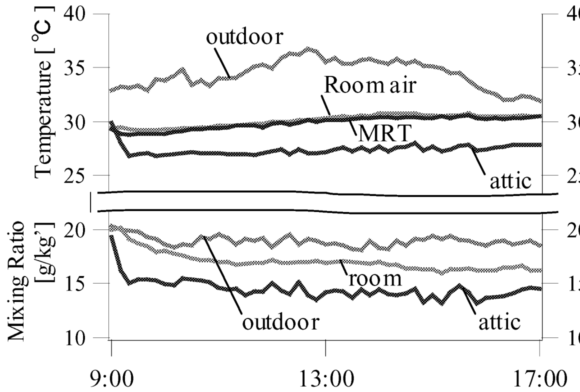


Figure 3: Variations of temperature and humidity measured on 22nd, August.

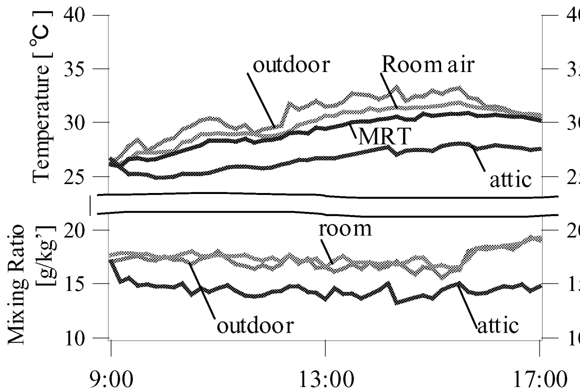


Figure 4: Variations of temperature and humidity measured on 25th, August.

Figures 3 and *4* show measured indoor conditions on 22nd and 25th of August, 2007. Mean radiant temperature (MRT) is slightly lower than room air temperature on both days. This is due to the ceiling temperature lowered by the attic space air conditioning. The ceiling temperature ranged from 25.3 to 30.4℃.

The humidity (mixing ratio) of room and attic spaces on 22nd is lower than outdoor air humidity (mixing ratio). This is because the air conditioner installed in the attic space is running and a certain amount of dehumidified air flows out from the attic to the room space. An amount of water vapor equivalent to that emitted from one person was generated by a humidifier so that, if the windows are closed and no natural ventilation is made, room air humidity would be higher than outdoor air humidity. But, as can be seen in Figure 3, the fact that room air humidity is lower than outdoor air humidity confirms that there is the transmission of dehumidified air from the attic space to the room space.

On 25th, on the other hand, room air humidity is almost the same as outdoor air humidity since the windows are opened for natural ventilation. The similar tendency can be seen in the relationships between room and outdoor air temperatures, but the attic air temperature and also the mean radiant temperature is quite low compared to outdoor air temperature. This is due to the coolness stored by the operation of air-conditioner for a series of experiment in the previous days.

4. RADIANT EXERGY

Thermal radiant exergy represents the ability of long-wavelength radiation emitted from wall surfaces into the environmental space. If a wall surface has a higher temperature than the environment, it has an ability to warm up other surfaces by radiation. It is called “warm radiant exergy”. If the wall surface has a lower temperature than the environment, it has an ability of cooling down by radiation. It is called “cool radiant exergy”. The quantity of these radiant exergies in the unit of W/m^2 can be calculated from the following equation (1).

$$X_r = \varepsilon\sigma\left\{\left(T_w^4 - T_o^4\right) - \frac{4}{3}\left(T_w^3 - T_o^3\right)\right\}, \qquad (1)$$

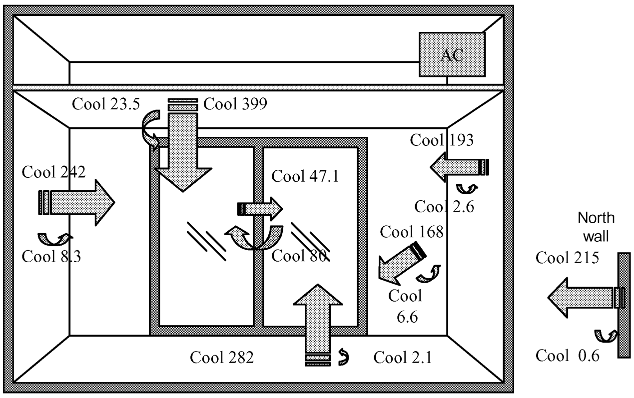
where T_o is the environmental (outdoor air) temperature for exergy calculation [K]; T_w is wall surface temperature [K]; ε is overall emittance of the wall surface; and σ is Stefan-Boltzmann constant [W/ (m^{2}K^4)].

Figure 5 shows the radiant exergy emitted from all wall surfaces together with convective exergy transfer at 13:30 on 22nd and 25th of August. All surfaces except the glass window on 25th of August are emitting cool radiant exergy. The largest cool radiant exergy is given from the ceiling. This is due to the radiant cooling system with an air conditioner in the attic space.

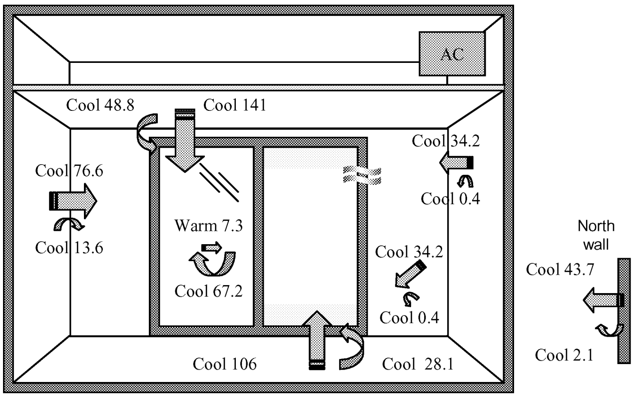
5. WET/ DRY EXERGY

Wet/dry exergy represents an ability of a certain amount of humid air to disperse into the environment. If the humidity of a volume of humid air is lower than that of the environment, then it has “dry” exergy. If the humidity is higher, then it has “wet” exergy. Dry exergy in the unit of J/m^3 can be calculated from following equation (2).

$$x_d = \frac{X_d}{V} = \frac{T_o}{T}\left((P - p_v)R \ln\frac{P - p_v}{P - p_{vo}} + p_v R \ln\frac{p_v}{p_{vo}} \right), \qquad (2)$$



13:30, 22nd August, 2007



13:30, 25th August, 2007

Figure 5: Radiant exergy emitted from the interior surfaces of the room and convective exergy flow over those surfaces. The symbol ⇨ denotes radiation and ↷ convection.

Table 1: Six cases for the comparison of wet/dry exergy

Case	Date	Air conditioner in the attic space	Window	Humidity values
1	8/22	ON*	Close	Measured
2		OFF	Close	Calculated
3		OFF	Open	Calculated
4	8/25	ON*	Open	Measured
5		OFF	Close	Calculated
6		OFF	Open	Calculated

*set-point temperature was 26℃.

where T is room air temperature [K]; T_o is outside temperature [K]; p_{vo} is outdoor water vapor pressure [Pa]; p_v is indoor water vapor pressure [Pa]; P is atmospheric pressure [Pa](=101325); R os gas constant [J/ (mo K)](=8.314). The values of p_v and p_{vo} are relative calculated with measured air temperature an relative humidity.

For a better understanding of wet/dry exergy, we picked up four additional cases to the two cases that we made our experiment. *Table 1* summarizes all cases. Cases 2 and 5 assume the air change rate of 0.5 times per hour, which corresponds to the room space with closed windows, and cases 3 and 6 the air change rate of 5 times per hour, which corresponds to the windows open. In these four cases 2, 5, 3, and 6, room air temperature is assumed to be the same as measured case 1 or 4, and room air humidity was calculated from the mass balance equation in term of water vapor.

Figure 6 shows the results of wet/dry exergy calculation. Vertical axis indicates wet or dry exergy. Exergy values above the horizontal axis corresponding to the exergy value of zero is "dry" exergy and below "wet" exergy. There is dry exergy in case 1 and case 3, and wet exergy in case 2. Since case 3 assumes no air conditioning in the attic space, the difference in dry exergy between cases 1 and 3 is considered to be given from the ceiling surface made of wooden frameworks with Japanese paper material, "Washi". In case 2 that the windows are assumed to be closed, there is always wet exergy in the room space, the radiant cooling system with the air conditioner in the attic space provides the room space with dry exergy in addition to cool radiant exergy.

Wet exergy is also available in case 5 whose assumption is the same as case 2. In cases 4 and 6, wet exergy is smaller than that in case 5. There is almost no dry exergy available in case 4, through the radiant cooling system is on. The dry exergy given to the room space must have been consumed immediately as it flowed out from the ceiling due probably to the immediate mutual dispersion with a portion of the room air being naturally ventilated. There are some occasional changes in wet exergy in case 4. It is due probably to the intermittent operation of the air conditioner in the attic space.

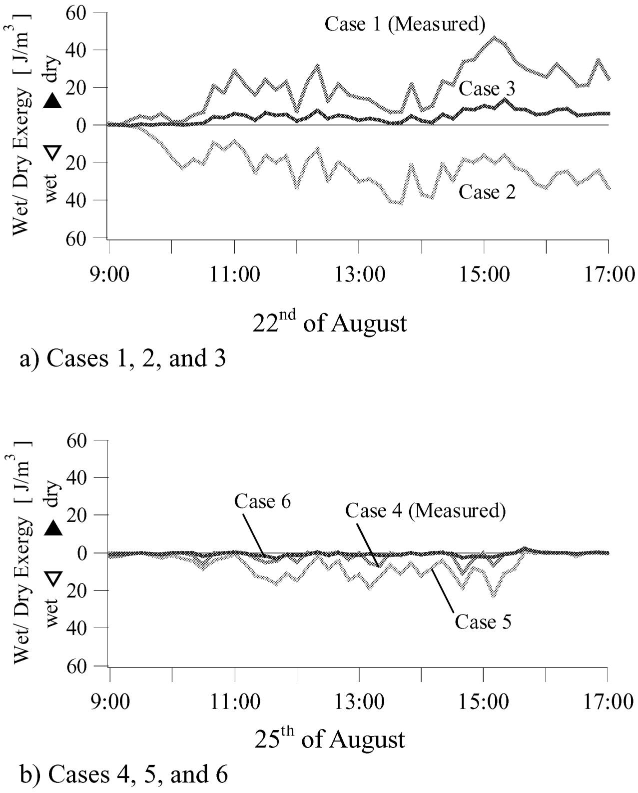


Figure 6: Comparison of wet/dry exergy calculated

6. CONCLUSION

Dry exergy in the room space is supplied by an air conditioner in the attic space. The boundary surface made of Washi with wooden frameworks allows dry exergy to transmit the ceiling into the room space together with cool radiant exergy to decrease mean radiant temperature in the room space. The removal of moisture from the room space by natural ventilation together with the supply of dry exergy available from the ceiling could allow the radiant cooling to be in the primary position for conditioning the built environment in summer.

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