Exergetic evaluation of high-temperature radiative cooling combined with natural ventilation

T. Iwamatsu, Y. Hoshino, E. Kataoka, M. Shukuya
Musashi Institute of Technology, Japan

ABSTRACT

This paper describes the possibility of high-temperature radiative cooling combined with natural ventilation. We set up two small wooden experimental buildings: one has a radiative-cooling system on the ceiling; and the other has a conventional convective-cooling system. In the room with radiative cooling, we examined three patterns of cooling and ventilation: the first is radiative cooling without ventilation; the second is radiative cooling with natural ventilation; and the third is no radiative cooling but natural ventilation. The ceiling surface temperature of the radiative cooling was controlled at approximately 26^{O}C, which is much higher than conventional radiative cooling panels.

We calculated exergetic quantities using the measured data: cool/warm radiant exergies emitted from indoor wall surfaces, cool/warm and wet/dry exergies contained by room air. The order of the cool radiant exergy emitted from the interior wall surfaces in the case of radiative cooling with natural ventilation was 10 to 80 mW/m^2, and the cool/wet exergies contained by room air were 14 J/m^3 and 8 J/m^3, respectively. These were much smaller than those in the case of radiative cooling without natural ventilation. If the room air temperature and relative humidity were controlled at 26^{O}C; 50 % with a convective cooling system under the outdoor condition of 32.5^{O}C; 61 %, the cool/dry exergies contained by room air would turn out to be 88 J/m^3 and 366 J/m^3, respectively. The result obtained from this experimental research suggests that the exhaustion of indoor moisture by natural ventilation is of vital importance to realize high-temperature radiative cooling systems, namely low-exergy cooling system.

1. INTRODUCTION

Conventional convective-cooling systems such as a packaged heat-pump air conditioner have been spread dramatically in hot and humid regions over the last couple of decades. There are some trials of radiative cooling as another cooling measure, but most of them make the surface temperature of the radiative cooling panels well below the dew-point temperature to dehumidify the room air. If the radiative cooling systems require the low surface temperature, we need to supply a lot of electricity as we do for conventional convective cooling. A previous research suggests that high-temperature radiative cooling may be possible if solar heat gain is minimized very much (Mori et al 2001). Therefore we focus on the feasibility of high-temperature radiative cooling without dehumidification but with moist-air exhaustion by natural ventilation. The development of such a system aims not only at reducing fossil fuel consumption but also at mitigating so-called heat-island phenomena, and avoiding “space-cooling syndrome” without sacrificing thermal comfort.

We investigated the thermal environments of two identical experimental buildings mainly from the viewpoint of “exergy” and their relation to thermal comfort. Exergy is one of the thermodynamic concepts to indicate the ability of energy or matter to disperse into its environmental space. We calculated exergetic quantities relating to the thermal environments using the measured data to find a new knowledge to develop “low-exergy cooling system”.

2. EXPERIMENTAL SET-UP

We used two identical wooden buildings prepared for experiment in Tsukuba: one has a radiative cooling panel on the ceiling (Bldg. RC); and the other a convective cooling unit (Bldg. CC). *Figure 1* shows the floor plan of Bldg. RC. *Photo 1* shows the appearances of Bldgs. RC and CC, respectively.

Over-all heat loss coefficient of Bldgs. RC and CC are 3.0 and 3.1W/(m^{2}K), respectively. Bldg. RC has an external shading device as shown in Photo 1 and Bldg. CC has an ordinary internal white curtain. The reason why the shading devices are different in both buildings is that external shading is regarded as a radiative cooling panel to make the window surface temperature lower than that with internal shading. The south-facing window of Bldg. RC is equipped with a fixed sash and a rotating sash so that the window can function for ventilation of air and prevention of crime. The north-facing door has several small slits to let the air in and out while being closed. Bldg. CC has sliding sashes on the south-facing window and no slit on the north-facing door.

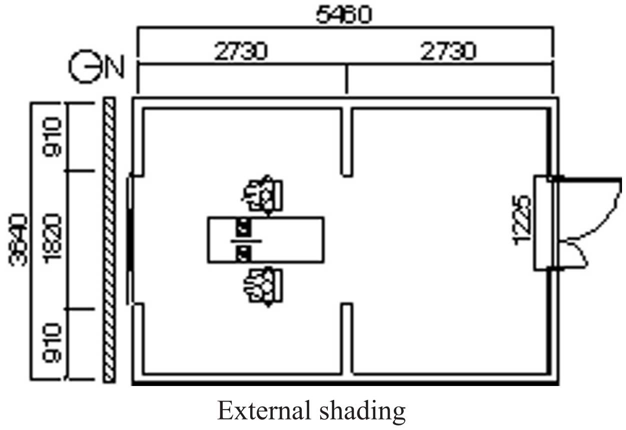


Figure 1: Floor plan of Bldg. RC

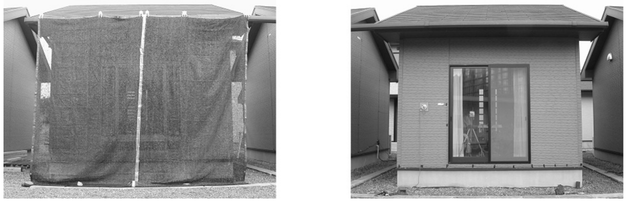


Photo 1: Two experimental buildings with radiative cooling (Bldg. RC, left) and convective cooling (Bldg. CC, right)

The experiment was made from 15th to 26th of August, 2005. In Bldg. RC, three cases of cooling and ventilation were examined: the first is radiative cooling without ventilation for two days (15th and 26th); the second is radiative cooling with natural ventilation (22th and 25th); and the third is no radiative cooling but natural ventilation (18th and 19th). The ceiling surface temperature was controlled at approximately 26^{O}C for all of those three cases. In Bldg. CC, on the other hand, the room air was conditioned aiming at the set-point temperature of 28^{O}C. *Figure 2* shows one unit of the whole experimental schedule. Two subjects stayed in one of the buildings for one hour; that is, four subjects simultaneously in two buildings. After one hour of the experiment, the four subjects took a rest for thirty minutes and then they experienced the other building. Thirty-five subjects participated in this series of experiment. During the experiment, the subjects wore light cloths and were seated. We asked each subject to choose one of the following four votes: "feel air current and comfortable", "feel air current but not comfortable", "feel no air current but comfortable" and "feel neither air current nor comfortable" whenever they perceived any change in either air current or comfort. These four votes were indicated by a dial shown in Figure 1, whose signal was recorded at one-second intervals. We also asked the state of thermal comfort and perspiration at fifteen-minute intervals. Measured environmental quantities were wall surface temperature, air temperature, relative humidity, air-current velocity, transmitted solar irradiance and others.

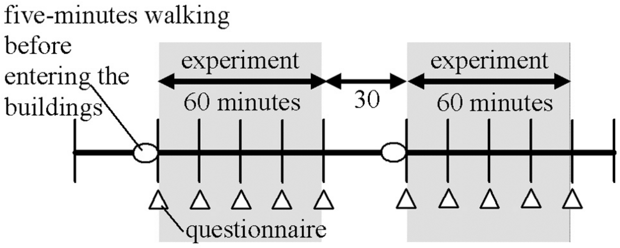


Figure 2: One unit of experimental schedule

3. EXPERIMENTAL RESULTS

Figure 3 shows the relationship between room air temperature and mean radiant temperature (MRT). In Bldg. RC, MRT is lower than room air temperature in any of three cases. The maximum difference between MRT and room air temperature is 1.3^{O}C. The fact that MRT was lower than room air temperature in the case of ventilation only in Bldg. RC is due probably to the effect of cool storage within the floor and the walls because of nocturnal ventilation. In Bldg. CC, MRT is usually higher than room air temperature. The maximum difference between MRT and room air temperature is 1.7^{O}C.

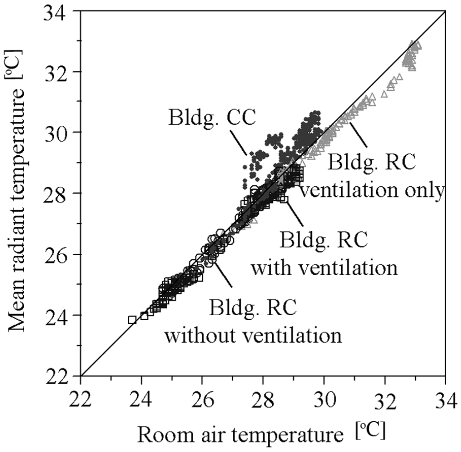


Figure 3: The relationship between room air temperature and mean radiant temperature

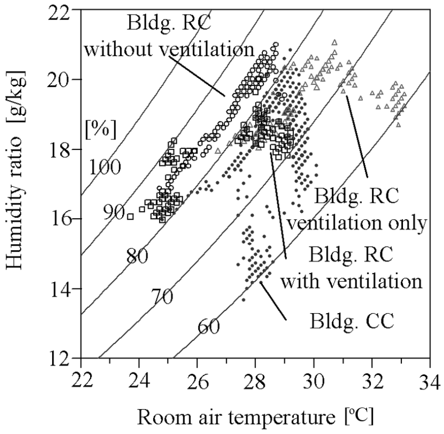


Figure 4: The relationship between room air temperature and

absolute / relative humidity

Figure 4 shows the relationship between room air temperature and humidity. The vertical axis shows the humidity ratio and the horizontal axis room air temperature. The solid lines indicate relative humidity. The relative humidity in Bldg. RC ranges from 59 to 90 %, while that in Bldg. CC from 59 to 82 %. The relative humidity in Bldg. RC was over 70 % during the period of more than three-forth of total experimental hours. The relative humidity in the case of Bldg. RC without ventilation was mostly over 80 % for the most of the time. The air current nearby the subjects were always still, namely less than 0.1 m/s, even in the case with natural ventilation in this series of experiment. The reason for this is due mainly to the fact that the effective opening area of the windows in Bldg. RC was very small.

4. DESCRIPTION OF THERMAL ENVIRONMENT BY EXERGY CONCEPT

4.1 Radiant exergy emitted from wall surfaces

The rate of thermal radiant exergy emitted from a square meter of wall surface can be calculated from the following equation.

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

where:

Overall emittance of the wall surfaces [-]

Stephan-Boltzman constant [W/ (m^2·K^4)]

Wall surface temperature [K]

Environmental temperature [K]

According to one of our previous researches (Shukuya et al. 2006), we found a relationship between thermal radiant exergy and thermal comfort under the condition of no perceived air current in naturally ventilated rooms as follows. The rate of "cool" radiant exergy of 20 mW/m^2 brings a condition that most of the subjects voted for comfort. Although, the same rate of "warm" radiant exergy brings an opposite result. This suggests that it is important to investigate the thermal environment from the viewpoint of radiant exergy.

Figures 5 and 6 show the variation of radiant exergy emitted from the wall surfaces. Looking first at Figure 5 for Bldg. RC, we find a large amount of cool radiant exergy ranging from 100 to 400 mW/m^2 is emitted from the wall surfaces in the case without ventilation. On the other hand, in the case of ventilation only, there is very small rate of cool radiant exergy available.

Looking next at Figure 6, we find that 10 to 80 mW/m^2 of cool radiant exergy is emitted in the case of Bldg. RC with ventilation. The order of cool radiant exergy is much larger than the cool radiant exergy rate of 20 mW/m^2, a critical value according to previous research. In the case of Bldg. CC, both cool and warm radiant exergies emerged. They stay much below the cool radiant exergy available in Bldg. RC. The emergence of warm radiant exergy in Bldg. CC is due to insufficient solar control over window with internal white curtain.

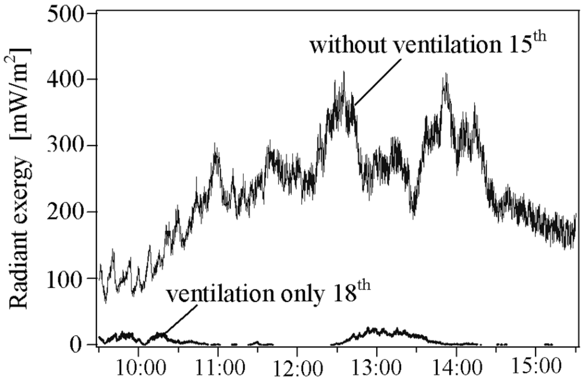


Figure 5: Cool radiant exergy rate in Bldg. RC on 15th and 18th of August

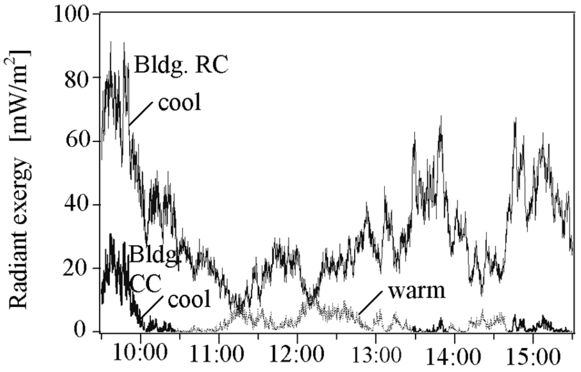


Figure 6: Radiant exergy rate of wall surfaces on 22nd of August

4.2 Exergy contained by room air

The room air whose temperature and humidity are different from those of outdoor air contains warm or cool exergy and wet or dry exergy. In terms of warm/cool exergy, if the room air temperature is higher than the outdoor air temperature, the room air contains "warm" exergy, otherwise "cool" exergy. In terms of wet/dry exergy, if the vapor pressure of room air is higher than that of outdoor air, the room air contains "wet" exergy, otherwise, "dry" exergy.

One of the merits of exergy concept is that exergy allows us to quantify the ability of dispersion of energy and matter on equal basis. Since warm/cool exergy and wet/dry exergy have the same unit, they can be compared directly, though the units of energy and matter themselves are different from each other; the former is Joule and the latter is gram.

Warm or cool exergy contained by a cubic meter of room air can be calculated from the following equation.

$$X_h = (C_{pa}m_a + C_{pv}m_w)\left\{(T_r - T_o) - T_o \ln\frac{T_r}{T_o}\right\} \qquad (2)$$

where:

C_{pa} Specific heat of dry air (=1.005) [J/(g·K)]

C_{pw} Specific heat of water vapor (=1.846) [J/(g·K)]

m_a Mass of dry air [g/m^3]

m_w Mass of water vapor [g/m^3]

T_r Room air temperature [K]

Wet or dry exergy contained by a cubic meter of room air can be calculated from the following equation.

$$X_d = T_o\left(\frac{m_a}{M_a}R\ln\frac{p_a}{p_{ao}} + \frac{m_w}{M_w}R\ln\frac{p_v}{p_{vo}}\right) \qquad (3)$$

where:

p_a Partial dry-air pressure of indoors [Pa]

p_v Partial water-vapor pressure of indoors [Pa]

p_{ao} Partial dry-air pressure outdoors [Pa]

p_{vo} Partial water-vapor pressure outdoors [Pa]

M_a Molecular mass of air (=28.97) [g/mol]

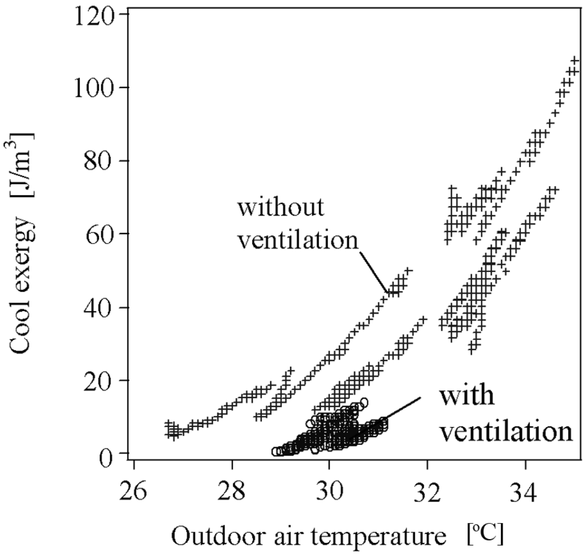
M_w Molecular mass of water (=18) [g/mol]

R Gas constant (=8.314) [J/(mol•K)]

Figure 7 shows the relationship between outdoor air temperature and cool exergy in Bldg. RC both without ventilation and with ventilation using all the measured data except 25th of August, whose outdoor temperature was lower than room air temperature and MRT.

As outdoor temperature increases, cool exergy contained by room air also increases, because the difference in temperature between indoor and outdoor becomes large. The maximum cool exergy is 107 J/m^3 in the case without ventilation and 14 J/m^3 in the case of ventilation. Looking at the range of outdoor temperature from 29 to 31^{O}C, cool exergy in the case with ventilation is smaller than that in the case without ventilation. The reason is that natural ventilation was quite effective in decreasing the difference between indoor and outdoor temperatures, though the rate of air exchange was considered to be very small, from 0.5 to 3 times per hour in this series of experiment, because of still air current.

Figure 8 shows the relationship between outdoor humidity ratio and wet exergy contained by room air in Bldg. RC. The maximum wet exergy is 62 J/m^3 in the case without ventilation and 8 J/m^3 with ventilation.



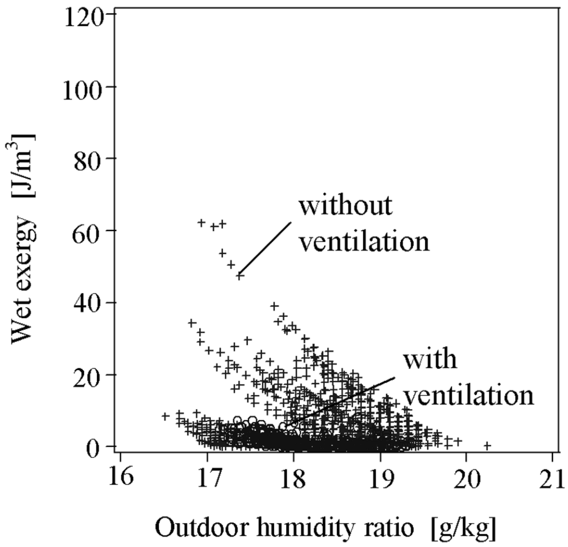


Figure 9: Percentage of thermal comfort votes

The wet exergy contained by room air with ventilation at the range of outdoor humidity ratio from 17 to 19 g/kg is much smaller than that without ventilation. The reason is the same as discussed above.

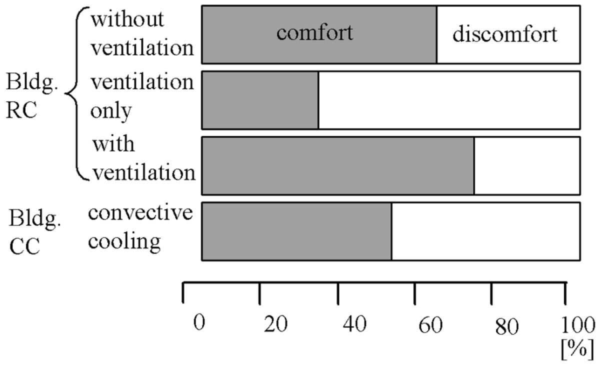
In Bldg. CC, dehumidification did not occur very much because the set-point air temperature in this experiment was relatively high at 28^{O}C. If the room air temperature and relative humidity were controlled at 26 ^{O}C; 50 % with a convective-cooling system under the outdoor condition of 32.5 ^{O}C; 61 %, the average outdoor temperature and humidity during this experiment, the cool/dry exergies to be contained by room air would be 88 J/m^3 and 366 J/m^3, respectively. They are much larger than those values shown in Figures 7 and 8. It implies that a large amount of cool exergy and an even much larger amount of dry exergy must be supplied to the room space by a conventional convective cooling system.

4.3 Exergetic evaluation of thermal comfort

Figure 9 shows the percentage of comfort in all subjective votes obtained from each case of experiment. The votes of "feel air current and comfortable" and "feel no air current and comfortable" are merged into "comfort vote", and also "feel air current but not comfortable" and "feel neither air current nor comfortable" are merged into "discomfort vote".

The largest percentage, 72 %, of comfort was obtained in the case of Bldg. RC with ventilation. The second largest, 62%, is the case without ventilation. As shown in Figure 7, the cool exergy contained by room air in Bldg. RC with ventilation are smaller than that in Bldg. RC without ventilation so that the presence of a large amount of cool exergy did not contribute to higher percentage of comfort. One may imagine that large air velocity indoors due to natural ventilation should contribute to higher percentage, but the air current was still as described above. The wet exergy contained by room air in the case with ventilation in Bldg. RC was also smaller than that without ventilation as shown in Figure 8. This must have contributed to higher percentage of comfort. In other words, the extraction of indoor moisture contained by room air must have played a key role in raising the percentage of comfort vote in Bldg. RC with ventilation together with a moderate rate of cool radiant exergy as shown in Figure 6.

The percentage of comfort vote in Bldg. RC with ventilation only and Bldg.CC with convective cooling are 31 % and 50 %, respectively. These percentages of comfort vote are smaller than those of the other two cases discussed above. This is because the cool radiant exergy emitted from the wall surfaces in Bldg. RC with ventilation only and in Bldg. CC was quite small as shown in Figures 5 and 6.



5. CONCLUSION

We conducted an experiment using two small identical wooden buildings to investigate the feasibility of high-temperature radiative cooling.

In the case of radiative cooling with natural ventilation, cool radiant exergy ranging from 10 to 80 mW/m^2 was emitted from the wall surfaces, while on the other hand, in the case of convective cooling much smaller cool radiant exergy and occasionally warm radiant exergy was emitted from the wall surfaces because of insufficient solar control over the window.

Cool and wet exergies contained by room air in the case of radiative cooling with natural ventilation were smaller than those in the case without natural ventilation. This difference is brought by natural ventilation which makes the indoor air temperature and humidity closer to those outdoors.

The percentage of comfort votes in the case of radiative cooling with natural ventilation is slightly larger than that in the case of radiative cooling without natural ventilation. This is because wet exergy contained by room air was decreased by natural ventilation and thereby provide the subjects with a room for sweat evaporation.

High-temperature radiative cooling systems can be realized provided that natural ventilation extracts the indoor moisture effectively.

ACKNOWLEGDEMENT

We are very grateful to Mr. Isao Ishizaki and Mr. Hirotsugu Yamada, Sumitomo Forestry Co., Ltd for their constant support for conducting the whole of this experiment.

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