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# An experimental study on moisture distribution and a way of mitigating condensation in a bedroom with a radiation-based task air conditioning system applied to sleeping environments

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## Abstract

Task/ambient air condition system (TAC) is an excellent air conditioning method because of good performance in thermal comfort, indoor air quality and energy saving, and can be best applied to sleeping environments due to the immobility of a sleeping person. Previously, an R-TAC system for sleeping environments was proposed to deal with the cold-draft problem encountered in C-TAC systems for sleeping environments. However, the potential risk of condensation should not be ignored when using R-TAC systems due to the cold radiant panel. Therefore, a follow-up experimental study on indoor moisture distribution and a way of mitigating condensation in a bedroom when using R-TAC systems was carried out, and are presented in this paper. Firstly, two different settings of the R-TAC system are described. Secondly, moisture distributions in the bedroom, and condensation thresholds of moisture content of the supply air are analyzed and compared at two settings. The experimental results showed that vertical and horizontal moisture distributions in the bedroom were not greatly affected by the height of the supply vent, however, the R-TAC system at Setting 2 performed better in reducing condensation risk as compared with Setting 1.

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*keywords:* Sleeping environments; Task/ambient air conditioning; Radiation based; Radiant panel; Moisture content; Condensation

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## Introduction

Due to the increased expectations on human thermal comfort in sleeping environments at a low energy consumption, task/ambient air condition system (TAC) can be the best air conditioning method when considering the immobility of a sleeping person. For the last two decades, TAC systems have been investigated in a number of previous studies [1-3]. For example, Amai et al. [1] compared four types of task conditioning systems and all of them were effective in providing thermal comfort; Pan et al. [2]

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demonstrated that personalized air conditioning systems can save up to 45% of the energy consumed by central systems; Zhang et al. [3] showed that air quality was significantly improved when task conditioning system was operated. However, the reported studies on the application of TAC to sleeping environments are limited. Lan et al. [4] proposed a bedside personalized ventilation system to improve occupant thermal comfort, but the ambient temperature also needed to be controlled. Pan et al. developed a bed-based TAC system [5] and then Mao et al. improved it by removing bulky air ducts and plenums [6-8]. Although the use of the TAC systems can efficiently reduce indoor contamination and energy consumption as compared to the use of a full volume air conditioning (A/C) system, cold drafts could hardly be avoided. It is because that the vents supplying air with a high velocity and a low temperature would have to be close to occupants when using convection-based TAC systems (C-TAC). As illustrated in a previous study [6], the values of draft risk in most of the measurement positions in an occupied zone were higher than 20%, which was the upper-limit value for acceptable cold draft as suggested in ASHRAE Standard 55 [9].

Therefore, to address the cold-draft issue encountered in the previously developed C-TAC systems applied to sleeping environments, a radiation-based TAC (R-TAC) system was developed and its operating performance experimentally studied in an experimental setup including an experimental bedroom and a thermal manikin [10]. In this R-TAC system, a small supply vent was used to provide the manikin with fresh air and a cold radiant panel to deal with indoor space load. Experimental results showed that, at the same thermal comfort level, draft risk in the occupied zone when using the R-TAC system was considerably lower than that when using the C-TAC system. However, when the temperature and relative humidity of fresh air are 23°C and 60%, respectively, condensation on the radiant panel was observed with a panel surface temperature of 17°C. Therefore, condensation might be a potential problem when using R-TAC systems.

In previous studies, some methods were proposed to prevent condensation on the cold radiant panel: Ge et al. [11] indicated the pre-dehumidification time is critical to prevent condensation on the radiant cooling surface; Song et al. [12] used the dehumidifying ventilation to avoid condensation on the radiant floor cooling system. Yin et al. [13] found out that gypsum radiant cooling panel performed better in avoiding water condensation as compared to the metal panel and the pure tube panel. However, there are limited studies on the effects of changing the height of the supply vent on moisture distribution in a bedroom and on mitigating condensation when using R-TAC systems.

Therefore, an experimental study on indoor moisture distribution in a bedroom when using the R-TAC system and a way of mitigating condensation was conducted. The organization of this paper is as follows. Firstly, the details of the experimental setup, measurement methods and experimental conditions are presented. Secondly, the moisture distributions in the bedroom at two different heights of the supply vent are reported. This is followed by identifying the condensation thresholds of moisture content of the supply vent at two different heights when using the R-TAC system. Finally, a conclusion is given.

## Experimentation

### 1.1. Experimental setup

The experiments in this study were carried out using an experimental setup, which consisted of three parts: an experimental bedroom, a plant room and a simulated outdoor space, as shown in a previous study [14]. The details of the experimental bedroom, the plant room and the simulated outdoor space were previously described [14].

A three-dimensional view and two sectional views of the experimental bedroom used in this experimental study are shown in Figure 1 and Figure 2, respectively. In the experimental bedroom, there was a simulated external wall with a simulated external window, through which heat transfer between the bedroom and the simulated outdoor space would take place. Except the simulated external wall and window, all the other five envelope surfaces of the bedroom can be regarded as adiabatic since they were well insulated. Inside the bedroom, a mattress bed was placed at 400mm above the floor level, and a cold radiant panel at a height of 1580 mm above the floor, as shown in Figs 1-3. Between the radiant panel and the mattress bed, a cuboid (2000 mm × 1200 mm × 1000 mm) above the mattress bed was designated as an occupied zone (OZ). The rest of the experimental room, on the other hand, was designated as an unoccupied zone (UZ). The thermal manikin, placed in a supine position on the mattress bed, was used to simulate a sleeping person, with two concentric thermal compartments, a core compartment and a skin compartment [15-17]. Also in the experimental study, the temperature for the core compartment was set at 36.4°C [18], but that for the skin compartment was left uncontrolled, and can therefore vary in response to ambient thermal environment. There was also a humidifier used to resemble human moisture dissipation, releasing water vapor at a constant value of 45 g/h, according to ASHRAE [19].

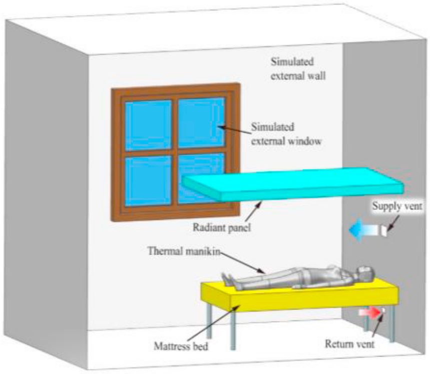


Figure 1 A 3-D view of the experimental bedroom and the prototype R-TAC system

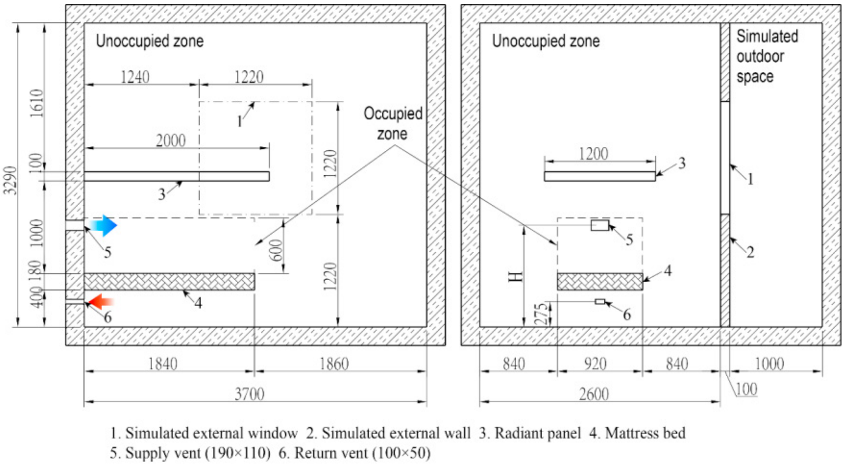


Figure 2 Sectional views of the experimental bedroom and the prototype R-TAC system (unit: mm)

A supply vent (190 mm ×110 mm) and a return vent (100 mm ×50 mm) were placed on the left-hand side wall, so that conditioned air from the neighboring plant room can be supplied to the occupied zone. For the supply vent, two heights (H), shown in Figure 2, were used: H=1100 mm and 1500 mm, regarded as Setting 1 and Setting 2, respectively; For the return vent, it was placed at a fixed height of 275 mm above the floor level.

### *1.2. The construction of the radiant panel*

The sectional view of the radiant panel and the details of the capillary tubes in the radiant panel are shown in Figure 3(a) and (b), respectively. For the panel, an aluminum foil adhered to the water pipes was used to increase heat exchange between the water pipes and an aluminum sheet in the lower part of the panel. On the other hand, in the upper part of the panel, a thermal insulation layer and an external aluminum foil were used to reduce conductive and radiative heat transfer, respectively. In Figure 3(b), the water flow from one main pipe was distributed into the branch pipes, then returned into the other main pipe. Four temperature sensors, A, B, C, D, were adhered on the radiant panel surface facing thermal manikin and their positions are shown in Figure 3(b).

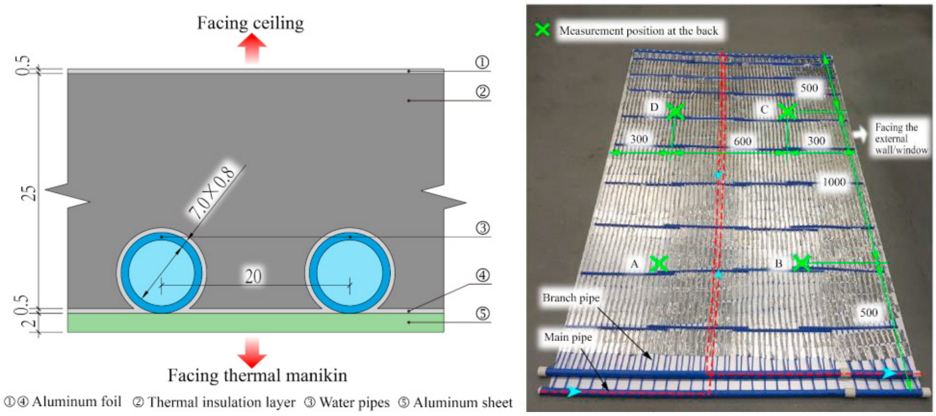


Figure 3 (a) Details of the radiant panel components (unit: mm) (b) The distribution of the capillary tubes and measurement positions for the radiant panel

### *1.3. Experimental conditions*

The temperature for the simulated outdoor space was set at a constant value of 30℃, which is the averaged outdoor air temperature at nighttime in Hong Kong according to ASHARE weather data [19]. Outdoor air flow rate supplied to the experimental bedroom from the plant room was set at 7.5 L/s, at a fixed temperature of 23°C and a fixed relative humidity of 50% (moisture content: 8.7 g/kg). The surface temperature of the radiant panel was fixed at 17°C. For the thermal manikin, its core temperature was set at 36.4°C and moisture dissipation at 45 g/h.

## **Experimentation**

### *1.4. Moisture distribution in the bedroom at two heights of the supply vent*

The averaged moisture contents in the occupied and unoccupied zones at different heights of the supply vent are shown in Figure 4(a) and (b), respectively. As seen, there was no significant variation of the moisture contents at different heights at two settings, ranging at 9.14~9.18 g/kg. Moisture content was obviously reduced along with the increased height in the occupied zone at setting 1 since the supply vent was closed to the measurement positions at the height of 1000 mm. In the unoccupied zone, affected by moisture dissipation from the thermal manikin, moisture content was increased at the height of 600 mm, then peaked at the height of 1100 mm, finally reduced at the height of 1700 mm at both settings. The horizontal distribution of moisture content in the experimental bedroom at two settings is shown in Figure 5. Basically, the moisture content was evenly distributed in the whole bedroom. However, the moisture content at left-hand side of the thermal manikin tended to be lower at Setting 1 compared with that at Setting 2. It was because that the direction of the supply air may not stay in the middle of the bedroom and tended to go towards the left-hand side of the thermal manikin due to the warm external wall on the right-hand side.

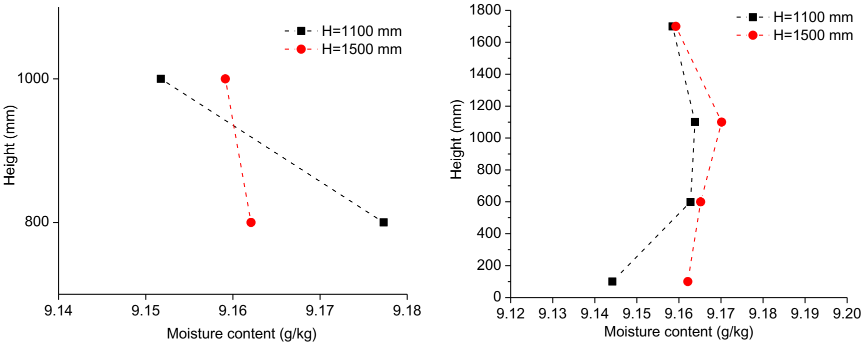


Figure 4 (a) Averaged moisture contents for different heights in the occupied zone at two different settings (b) Averaged moisture contents for different heights in the unoccupied zone at two different settings

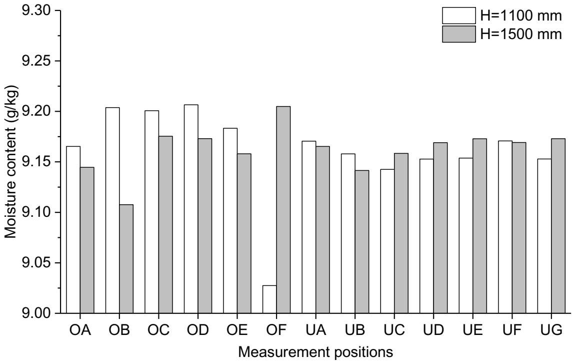


Figure 5 Averaged moisture contents of different measurement positions at two different settings

### *1.5. Non-condensation regions with different panel temperatures at two heights of the supply vent*

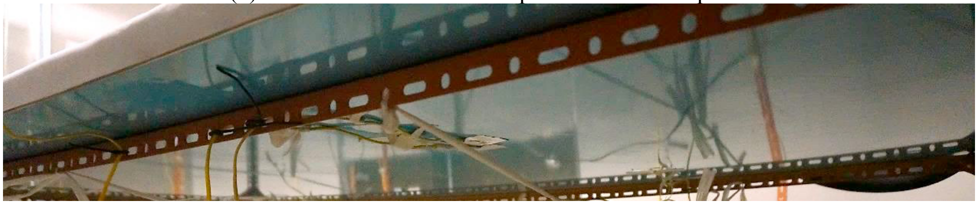
When applied the R-TAC system to the real world, especially in a hot and humid climate zone, the potential risk of condensation should be taken into consideration. Therefore, to avoid it, the temperature and humidity of the supply air should be limited to in a reasonable region in psychrometric chart for different panel temperatures.

Condensation occurred when the minimum temperature of radiant panel was lower than the dew point temperature of the ambient air. Although it was impossible to obtain the panel temperatures at all the points of the radiant panel, condensation can be observed during the experiments. Therefore, the lowest surface temperature among the four measurement positions on the radiant panel, defined as $t_{l\text{-}rp}$, was used and set at 15°C, 16°C, 17°C and 18°C. For each $t_{l\text{-}rp}$, the dry-bulb temperature (DBT), 20°C and 30°C, of the supply air was selected to find out the condensation thresholds of moisture content for the supply air, respectively. Hence, the critical lines of condensation in psychrometric chart can be obtained for each $t_{l\text{-}rp}$.

The way of identifying the condensation thresholds was to adjust the moisture content of the supply air from the plant room based on the air condensation situation. As seen in Figure 6, condensation occurred on most of the radiant panel and a small part of the radiant panel in Figure 6(a) and in Figure 6(b), respectively; without condensation, the radiant panel becomes reflective (see Figure 6(c)). The moisture content of the supply air was increased until condensation situation on the radiant panel was shown like Figure 6(a) or Figure 6(b). Then the moisture content of the supply air was reduced slightly until condensation situation on the radiant panel was changed as shown in Figure 6(c). When this situation did not change for 30 minutes, the moisture content of the supply air can be considered as the threshold for a fixed value of $t_{l\text{-}rp}$.

(a) Condensation on most of the radiant panel

(b) Condensation on a small part of the radiant panel



(c) No condensation on the radiant panel

Figure 6 Condensation situations on the radiant panel

Figure 7 (a) and (b) show the condensation thresholds of moisture content at Settings 1 and 2, respectively. For each $t_{l\text{-}rp}$ at both settings, when the supply air was 20°C and 30°C, the thresholds of moisture content were basically similar, with the former slightly higher than the latter. It was because that, when the dry-bulb temperature of the supply air was increased from 20°C to 30°C, heat exchange between the radiant panel and its ambient air was enhanced, which increased the nonuniformity of panel temperature and lowered the minimum surface temperature of the radiant panel in order to maintain a constant value of $t_{l\text{-}rp}$. Therefore, the condensation thresholds of moisture content with a supply air temperature of 30°C were slightly lower than those of 20°C. With a 1°C's increase in $t_{l\text{-}rp}$, the condensation threshold of moisture content of the supply air was increased about 1 g/kg.

When compared the thresholds between the two settings, the condensation thresholds at Setting 2 were significantly higher than those at Setting 1, indicating that the supply air can carry more moisture without condensation occurred on the radiant panel. It was because that a layer of drier air surrounding the radiant panel was formed at Setting 2 due to the shorter distance between the supply vent and the radiant panel. On the other hand, the effects of reducing condensation risk at Setting 2 may be explained by the nonuniform surface temperature of the radiant panel. Figure 8 shows Surface temperature of the radiant panel at different measurement positions at Setting 1. As seen, the surface temperatures at different measurement positions were different, reflecting surface temperature of the radiant panel was nonuniform. Furthermore, the panel temperature at the side with A and B measurement positions was greatly lower than that with C and D measurement positions. It may be affected by the distribution of the capillary pipes, as seen in Figure 3(b), the main pipe with colder water was placed at the side with A and B measurement positions. Therefore, supplying drier air from the colder side of the radiant panel was effective to reduce condensation risk when using the R-TAC system.

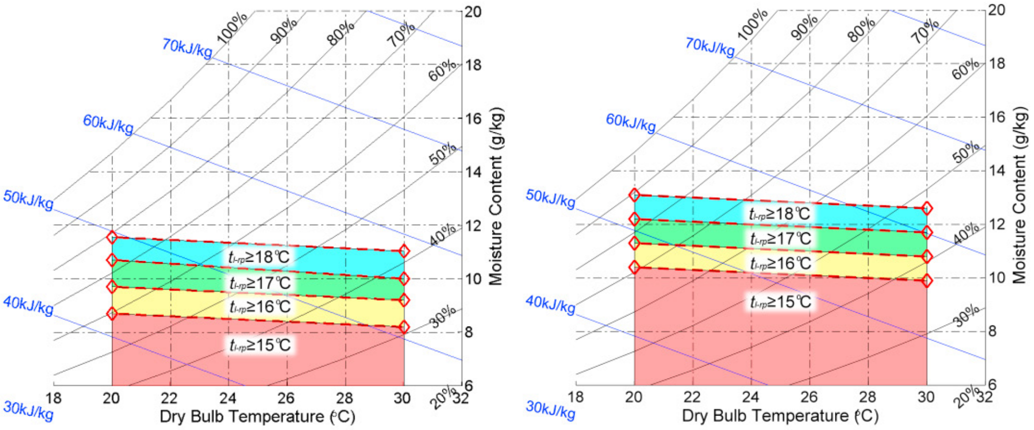
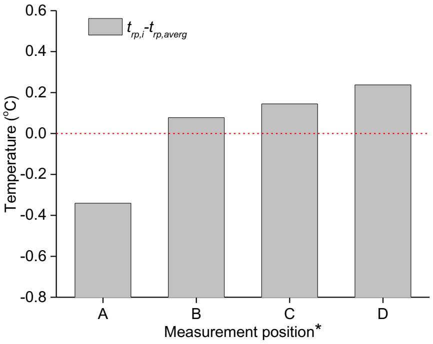


Figure 7 (a) Condensation thresholds of moisture content for each $t_{l\text{-}rp}$ at Setting 1 (b) Condensation thresholds of moisture content for each $t_{l\text{-}rp}$ at Setting 2



*Measurement positions are shown in Figure 5.

Figure 8 Surface temperatures of the radiant panel at different measurement positions at Setting 1 ($t_{rp,averg}$=17°C)

## Conclusions

This paper reports an experimental study on the moisture distribution and a way of mitigating condensation in a bedroom when using the R-TAC system. The moisture content distributions in the bedroom were investigated and the condensation thresholds of moisture content of the supply air at different panel temperatures were identified. The results showed that there was no obvious variation of moisture content vertically and horizontally in the bedroom. The moisture contents at the height of 600 mm and 1100 mm were slightly higher than those at the height of 100 mm and 1700 mm. The height of the supply vent had slight impacts on the distribution of moisture content in the bedroom. However, the condensation thresholds of moisture content of the supply air were greatly increased at Setting 2 as compared with those at Setting 1. It was because that, at Setting 2, the shorter distance between the supply vent and the radiant panel resulted in a layer of drier air formed around the colder side of the radiant panel.

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## Biography

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