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Evaluating Effects Of Building Envelope Thermal Loads On Energy Use And Thermal Comfort for A Bedroom TAC System

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Abstract

There has been an increasing concern on thermal comfort in sleeping environments and its associated energy use in the past few years. To improve the thermal environment and reduce energy use of air conditioning in bedrooms, task/ambient air conditioning (TAC) can be applied and was studied previously. Due to the variation of the envelope thermal loads in a bedroom during night, it is necessary to study the thermal environment inside the bedroom and the energy use of a TAC system for the bedroom at varying envelope thermal loads. Therefore, this paper reports on a numerical study on a TAC system applied to a bedroom with different envelope heat gains. PMV and EUC (energy utilization coefficient) values were evaluated, respectively. The study results indicated that when envelope thermal loads was higher, the advantage of the TAC system in energy saving was greater for the same thermal comfort level. However, it should be noted that a higher envelope thermal load could also resulted in the non-uniformity in air flow and air temperature distributions, leading to a possible uncomfortable micro environment.

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Keywords: Thermal comfort; energy saving; task/ambient air conditioning (TAC); envelope thermal load

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1. Introduction

There has been an increasing interest in using TAC systems, due to their better performance in terms of energy saving and flexible control over thermal environments [1, 2]. Also, a limited number of studies have been carried out on the operating performances of TAC systems applied to sleeping environments [3, 4] and the study results indicated that a TAC system can be integrated with a bed for use in sleeping environments with appropriate operating parameters [3]. On the other hand, the appropriate ranges for operating parameters in various TAC systems have been investigated. These parameters included supply air temperature, supply air velocity, supply air direction and envelope heat gain, etc.

At night, due to solar energy, envelope heat gain varies greatly. Lin and Deng [5] investigated the rooms equipped with nighttime operating mode air conditioner during night. The results showed that the total cooling load peaks at 22:00, decreases rather quickly over the next 2 h, and then decreases relatively slowly between 0:00 and 6:00. Besides, the outdoor air temperature decreased during the period from 22:00 to 6:00 at the second day. In other studies, the variations of outdoor air temperature or cooling load were also reported [6, 7]. Due to the heat transfer through the envelope, on one hand, the heat gain brings about the ununiformity of temperature and air flow field inside the bedroom [8], on the other hand, the variation of outdoor air temperature results to the change of indoor air temperature [5]. Many different conditions were investigated with this change, such as operating air conditioners to maintain the indoor air temperature [5], it can be seen that, the air conditioner can weaken the variation of indoor air temperature. Therefore, for a bed TAC system, it is necessary to study the effect of the external wall heat gain on the indoor air temperature.

In this paper, a bed-based TAC system was developed in a bedroom in subtropics. With the variation of outdoor air temperature, the indoor thermal environment was studied and analyzed using CFD method.

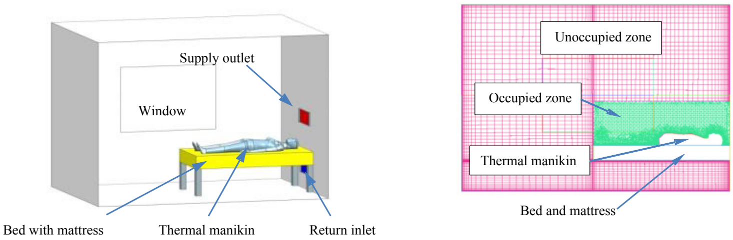
2. CFD method

2.1 Geometry model and mesh generation

According to the experimental bedroom in previous related studies [8-11], a geometry model was established, as shown in Fig. 1, with a physical dimension of 3.62 × 2.6 × 2.53 m [3]. The TAC system used in the experimental bedroom and modelled in the CFD method was bed-based, consisting of a supply air outlet, a return air inlet and a bed with mattress where a thermal manikin was placed [12, 13]. A supply air outlet (0.57 × 0.21 m) was placed at 1.1 m above the floor level immediately above the bed, and a return air inlet (0.37 × 0.16 m) at 0.32 m above the floor level, as shown in Fig. 1. A cuboid (1.84 × 0.92 × 0.6 m) immediately above the bed with mattress was designated as an occupied zone in this study for the purpose of results analysis, and the rest of the space inside the bedroom an unoccupied zone, as shown in Fig. 1(b). Grids used in the CFD method were separately generated for the occupied zone and the unoccupied zone [14]. The sectional view of the mesh for the computational domain for both the occupied and the unoccupied zones can also be seen in Fig. 1 (b).

2.2 Numerical model

A commercial CFD code was used to compute the air flow field and heat transfer inside the bedroom. The air flow field was calculated by the three-dimensional and steady-state Reynolds averaged Navier-Stokes (RANS) equations, combined with continuity and energy equations. The SIMPLE algorithm was used with a second order scheme for the convective terms. The SST turbulence model [16], which takes advantages of both the k-ε model and the k-ω model and displays the best performance when predicting air velocity and temperature distributions inside a room [17, 18], was used for modelling the turbulent flow. Therefore, the surface-to-surface (S2S) radiation model was used to compute the radiation heat exchange among the surfaces in the bedroom. Details of the surface-to-surface radiation model can be found in previous related studies [19, 20].



(a) Simulated bedroom (b) Mesh of computational domain

Fig. 1 Geometry and the mesh for the experimental bedroom

2.3 Boundary conditions

(1) Skin surface temperature

Mean skin surface temperature, t_{sk}, was an important factor influencing human's thermal sensation. The linear regression equation [21], t_{sk}=35.7-0.0275(M-W), was used to evaluate the value of t_{sk}:

The metabolic rate (M) of a sleeping person is 40 W/m^2, and the workload (W) is zero, therefore, the mean skin temperature would be 34.6 ºC.

(2) Moisture diffusion

To predict the moisture transfer between the surface of the thermal manikin and the surrounding environment, air moisture content was taken as 10 g/kg air at the surfaces of the thermal manikin according previous studies [22, 23]. The gradient of air moisture content at the all other solid surfaces was taken as zero [22, 23].

2.4 Simulation cases

To evaluate the effects of different envelope heat gain on the indoor environment, six different outdoor temperatures were selected: 25, 27, 29, 31, 33, 35 ˚C.

3. Results and analysis

3.1 Evaluation index

The energy use by the experimental bed-based TAC system under study was indirectly evaluated using energy utilization coefficient (EUC) which relates to the temperature difference between the occupied zone and the unoccupied zone [3, 24], as follows:

$$EUC=\frac{(t_{uz}-t_s)}{(t_{oz}-t_s)} \tag{1}$$

When the average air temperature in the occupied zone is lower than that in the unoccupied zone, EUC value will be greater than 1. The greater the EUC value, the greater the energy saving.

Fig. 2 shows the EUC values, t_{uz} and t_{oz} at different envelope heat gains. It can be found out that when the envelope heat gain was increased, the averaged air temperature t_{uz} and t_{oz} were gradually increased. Due to the cooling air was directly delivered into the occupied zone, a lower t_{oz} was resulted in, as shown in Fig. 2. Moreover, with the same increased envelope heat gain, a higher difference between t_{uz} and t_{oz} was found out. It suggested a deeper influence of the envelope heat gain on the unoccupied zone. Meanwhile, a slight increase of EUC values was shown in the Fig. 2, which was caused the different influences of envelope heat gain on occupied and unoccupied zones. This phenomenon also indicates that the TAC system can be more effectively energy saving if the outdoor environment is hotter.

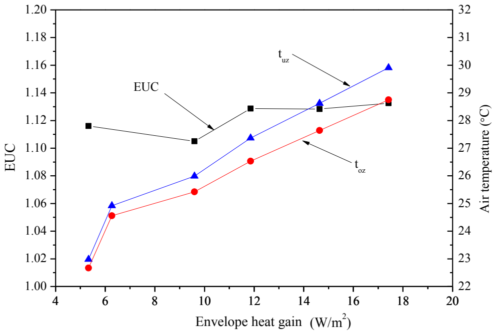


Fig. 2 EUC values at different envelope heat gains

Based on the well-known Fanger's thermal comfort model [21] and considering the heat generation and balance for a sleeping person, Lin and Deng [25] developed an equation to evaluate the PMV index in sleeping environments:

$$PMV=0.0998[40-(C+R+E_{sk}+C_{res}+E_{res})] \quad (2)$$

In Equation (7), C+R is the total heat flux generated from a human body. In this study, the CFD method provided the numerical value of C+R, as part of the simulation outputs.

Evaporative heat loss from skin, E_{sk}, depended on the amount of moisture on skin and the difference between the water vapor pressure at the surface of a human body and that in the ambient environment, and was evaluated by:

$$E_{sk}=\frac{i_m L_R w(p_{sk,s}-p_a)}{R_t}=0.06h' i_m L_R(P_{sk,s}-P_a) \quad (3)$$

Respiratory heat loss, q_{res}, is often expressed in terms of sensible heat loss, C_{res}, and latent heat loss, E_{res}. Sensible loss (C_{res}) and latent loss (E_{res}) due to respiration can be estimated, respectively, by the following equations [23, 24]:

$$C_{res}=0.0014M(34-t_a) \quad (4)$$

$$E_{res}=0.0173M(5.87-p_a) \quad (5)$$

Fig. 3 shows the PMV values at different envelope heat gain. As seen, when the envelope heat gain was increased, the air temperature in the occupied zone was increased and the PMV values was correspondingly increased. This suggested that different supply conditions should be set for a specified envelope heat gain to maintain a suitable comfortable environment.

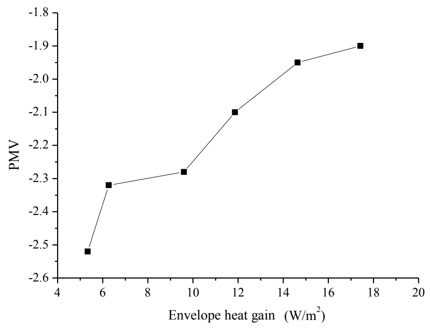


Fig. 3 PMV values at different envelope heat gains

3.3 Nonuniformity of temperature distribution

Seven sectional planes were obtained at seven different distances from the external wall: 8, 408, 808, 1300, 1700, 2100, 2592 mm. The air temperature in each plane was averaged and shown in Fig. 4. Reductions were observed with the increased distance from the external wall while this distance was lower than around 400 mm. When the distance was enlarged continuously, the temperatures seemed constant. To compare the nonuniformity of the temperature at different distances, the variances were calculated and shown in Fig. 5. It can be seen that with the increase of envelope heat gain, a higher temperature variance was resulted in. This suggested that a higher envelope heat gain brought about a more serious temperature nonuniformity, which may affect the thermal comfort of the sleeping person.

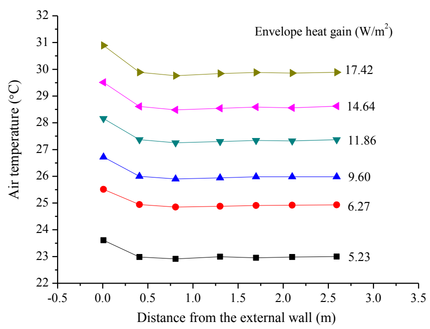


Fig. 4 Averaged air temperature with varied distances from the external wall

Air temperatures were averaged at four different heights from the floor level: 100, 600, 1100, 1700 mm. As shown in Fig. 6, with the increase in height, the air temperatures were raised continuously at the five envelope heat gains. This suggested that the cooling effect was better in the lower height. To compare the nonuniformity of the temperature at different heights, the variances were calculated and shown in Fig. 7. It can be seen that with the increase of envelope heat gain, a higher temperature variance was resulted in. This suggested that a higher envelope heat gain brought about a more serious temperature nonuniformity, which may affect the thermal comfort of the sleeping person.

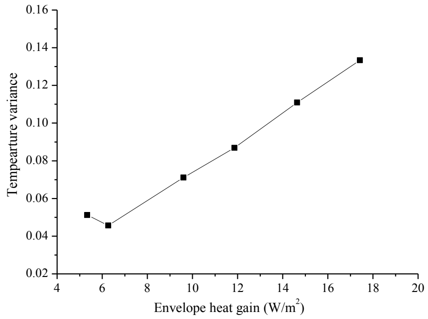


Fig. 5 Variance of air temperature at different envelope heat gains

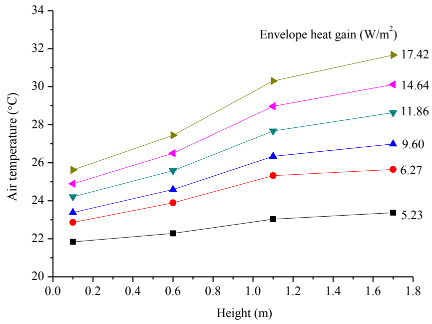


Fig. 6 Averaged air temperature with varied height from the floor level

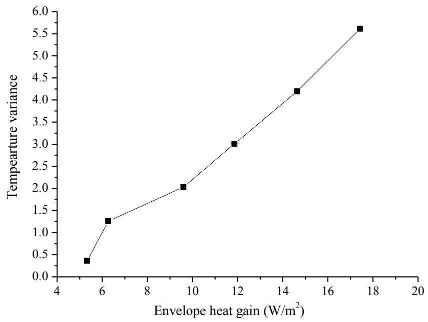


Fig. 7 Variance of air temperature at different envelope heat gains

4. Conclusions

In this paper, different envelope heat gains were studied for a bedroom equipped with a TAC system. The PMV values, EUC values and air temperature distributions along two directions were calculated and analyzed at different envelope heat gains. The research results demonstrated that the increased envelope heat gain influences both the energy saving performance and the thermal comfort level. Besides, it resulted in the nonuniformity of air temperature distributions inside the bedroom, especially for a higher envelope heat gain. Therefore, during night, when the outdoor air temperature varies, the indoor thermal comfort level, energy saving of the TAC system and the uniformity of air temperature distributions inside the room will varies correspondingly. To improve this phenomenon, further research should be carried out on the optimization of the TAC system and operating strategy of the air conditioning.

Acknowledgements

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Biography

MAO Ning, PhD, lecturer at China University of Petroleum (East China). His main research areas include thermal comfort, air conditioning, indoor air quality, heat pump, building energy saving, and thermal energy recovery.