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Performance evaluation of an air conditioning system with different heights of supply outlet applied to a sleeping environment

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ABSTRACT

Because of the increased expectations on thermal comfort and indoor air quality in sleeping environments at a low energy consumption, it is necessary to develop new air conditioning systems applied to sleeping environments. In recent years, a large number of studies on task/ambient air conditioning (TAC) have been carried out due to its excellent ventilation and energy saving performance. However, compared to full volume air conditioning (FAC), there exists an inadequacy on thermal control for TAC because cooled air is directly delivered to the space around a human body. Hence, the TAC and FAC systems have their own pros and cons in aspects of thermal, ventilation and energy saving performances, and the position of a supply outlet in an air conditioning (A/C) system significantly influences its operating performances. Therefore, a study on the performance evaluations of an A/C system installed in an experimental bedroom with its supply outlet positioned at five different heights has been carried out, and the study results are presented in this paper. The study results suggested that overall speaking, the A/C system performed the best at a supply air temperature of 23 °C, an air flow rate of 50 L/s and a fresh air flow rate of 13 L/s at H1100 setting, among all study cases. On the other hand, the A/C system performed the best at H800 setting among the five height settings.

1. Introduction

In the tropical or sub-tropical regions, where summers are hot and humid and may last for over 7 months in a year, room air conditioners (RACs) are widely used in residential buildings at not only daytime but also nighttime to maintain thermally comfortable sleeping environments. A survey on the use of air conditioning (A/C) in bedrooms in residential buildings in Hong Kong revealed that up to 68% of the respondents would leave their RACs on during sleep [1]. This can well be an important contributor to the annual electricity use for A/C in residential sector. For instance, in Hong Kong, residential A/C consumed 155 GWh of electricity in 1971, or 14.6% of the total residential electricity use. In 1996, this rose to 2467 GWh, or 30.4% of the total [2]. However, in 2011, residential A/C electricity consumption was increased to 4983 GWh, or 45% of the total residential electricity [3]. Hence, it has been always challenging to reduce residential A/C energy use while still maintaining a thermally comfortable and healthy indoor environment at both daytime and nighttime.

To reduce A/C energy consumption, TAC has been proposed and has found wide applications in office buildings at daytime [4–6]. However, intuitively, TAC may be best applied to a sleeping environment at nighttime since a sleeper is immobile and confined to a small space, or a bed. In view of this, Pan et al. [7] proposed a bed-based TAC system applied to a sleeping environment, and evaluated its thermal control and energy saving performances, using a full volume air conditioning (FAC) system as a basis. Mao et al. [8] further developed a simplified ductless bed-based TAC system so as to make it applicable to a real bedroom, and investigated its operating performance in terms of thermal control, ventilation effectiveness and energy saving. In this study [8], the supply outlet of the TAC system was placed at 1.10 m above floor level, and its operating performances were compared to that of an FAC system whose supply outlet was placed at 2.0 m above floor level. The results of this further study revealed that the TAC and FAC systems have their own pros and cons in aspects of ventilation, thermal and energy saving performances, and for an A/C applied to a sleeping environment the height of its supply outlet would significantly affect its operating performances. Hence, a follow-up study on the

Abbreviations: CN, Nondimensionalized CO_2 concentration; DR, Draft risk; EUC, Energy utilization coefficient; TEM, Nondimensionalized temperature; VE, Ventilation effectiveness.

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Nomenclature

C	CO_2 concentration at a measurement position (ppm)
C_{oz}	Mean CO_2 concentration in the occupied zone (ppm)
C_r	CO_2 concentration in return air (ppm)
C_s	CO_2 concentration in supply air (ppm)
D_{im}	Mass diffusion coefficient (m^2/s)
$D_{T,i}$	Thermal diffusion coefficient (m^2/s)
J_i	Diffusion flux of species i ($kg/(m^2/s)$)
Q_f	Fresh air flow rate (L/s)
Q_s	Supply air flow rate (L/s)
Sc_t	Turbulent Schmidt number
S_i	Rate of creation by addition of species i ($kg/(m^3/s)$)
t	Air temperature at a measurement position (°C)
t_{oz}	Average air temperature in an occupied zone (°C)
t_s	Supply air temperature (°C)
t_{uz}	Average air temperature in an unoccupied zone (°C)
T_u	Turbulence intensity
U	Nondimensionalized velocity
v	Air velocity at measurement position (m/s)
Y_i	Mass fraction of the species i
μ_t	Turbulent viscosity (Pa s)

A/C system to obtain the best performances considering the three aspects became necessary.

On the other hand, the use of CFD can simultaneously predict air flow, heat transfer and contaminant transportation in and around buildings [9–11]. The outcomes from a CFD-based study have been therefore used to evaluate the ventilation effectiveness, thermal control and energy saving performances for an A/C system. For instances, the air flow and CO_2 concentration distribution inside kitchens, offices and lecture rooms equipped with conventional A/C systems [12–14], and in offices equipped with personalized ventilation (PV) systems [15] or TAC systems [16], were numerically studied using CFD method. Furthermore, the air velocity and air temperature distributions around a thermal manikin [17,18], and the radiative heat transfer for a seated human body [17,19] were also numerically studied.

Therefore, a follow-up CFD study on evaluating the operating performances of an A/C system installed in an experimental bedroom with its supply outlet placed at five different heights has been carried out, and the study results are presented in this paper. The study was carried out in two steps: the numerical simulation using CFD method, and performance evaluations based on the CFD simulation results. First, the detailed distributions of air flow, temperature and CO_2 concentration inside the bedroom were simulated using CFD, when the A/C system was operated at different supply air temperatures, flow rates and fresh air flow rates, with its supply outlet placed at five different heights. Second, based on the simulation results, three performance evaluation indexes, i.e., ventilation effectiveness (VE), thermal control in terms of draft risk (DR) and energy saving in terms of energy utilization coefficient (EUC), for the A/C system operated at different operating conditions, were obtained and analyzed. Finally, in view of the inadequacy of using separately each of the three performance evaluation indexes, an evaluation tool called TOPSIS (Technique for Order Preference by Similarity to an Ideal Solution) was employed to evaluate the overall performance of the A/C system at various operating conditions, through integrating the indexes for ventilation effectiveness, thermal control and energy saving.

Table 1
Numbers of meshes for the computational domain at the five settings (million).

Settings	H 800	H1100	H1400	H1700	H2000
Occupied zone	1.43	1.48	1.48	1.48	1.48
Unoccupied zone	0.48	0.48	0.53	0.52	0.49
Total	1.91	1.96	2.01	2.00	1.97

2. Methodology

The methodology used in this study is shown in Fig. 1. As seen, there were two steps. In the first step, a CFD method for the A/C system and an experimental bedroom was first established and validated with experimental results. Then, the validated CFD method was used to numerically study air temperature, velocity and CO_2 concentration distributions inside the experimental bedroom when the A/C system was operated at different supply air conditions and with its supply outlet placed at five different heights. In the second step, based on the simulation results obtained in Step 1, the performance evaluations were carried out in two parts: performance evaluation for the A/C system using three separate indexes: ventilation effectiveness, thermal control and energy saving, and an overall performance evaluation using the TOPSIS method.

2.1. Numerical study using CFD method

2.1.1. Geometry model

A geometry model was built for an experimental bedroom, shown in Fig. 2, with its dimensions shown in Fig. 3. As mentioned, the operating performances of an A/C system applied to a sleeping environment were significantly affected by the height of its supply outlet. Therefore, in this study, the height of supply outlet was set at five different levels: 800, 1100, 1400, 1700 and 2000 mm above the floor level, as also shown in Figs. 2 and 3, respectively. These five heights were designated as the following five system settings: H800, H1100, H1400, H1700 and H2000. The detailed information of the experimental bedroom, thermal manikin and experimental measurements was presented in the previously reported experimental study [8]. For the purpose of results analysis, the modeled experimental bedroom was divided into two zones: an occupied zone, which was a cuboid (1.84 × 0.92 × 0.6 m) immediately above a bed with mattress, and an unoccupied zone for the rest of the bedroom, as shown in Fig. 3.

2.1.2. Mesh generation

When using CFD method, the mesh structure is very important for computational stability and results accuracy. For simulating airflow around complicated geometries, unstructured grids are more flexible in grid distribution and therefore often used. However, for simple geometries, structured grids can be easily generated with high mesh quality and a lower number of mesh elements. Therefore, grids were separately generated for the occupied zone and the unoccupied zone. The sectional view of the mesh for the computational domain including both the occupied and the unoccupied zones is shown in Fig. 4(a). In the occupied zone, due to the complex geometry of thermal manikin surface, unstructured grids (tetrahedral meshes) were generated and prism mesh was used for the entire wall representing the manikin surface. The height of the first layer for prism mesh from the surface of thermal manikin was set at 0.4 mm, and 10 layers of prism mesh were generated in wall-normal direction to guarantee $y+<1$ and to provide a better computational result [20], as shown in Fig. 4(c). In the unoccupied zone, structured grids were generated, as shown in Fig. 4(a). The numbers of meshes for the computational domain at the five settings are shown in Table 1.