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A numerical study on influences of building envelope heat gain on operating performances of a bed-based task/ambient air conditioning (TAC) system in energy saving and thermal comfort

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HIGHLIGHTS

- A numerical study was conducted on a task/ambient air conditioning system.
- The effects of envelope heat gain on energy consumption was studied.
- The effects of envelope heat gain on thermal comfort was investigated.
- Thermally neutral operating conditions were obtained.

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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 to reduce energy use of air conditioning in bedrooms, applications of task/ambient air conditioning (TAC) systems were proposed and studied previously. It's indicated that the TAC system can be well integrated with a bed. Due to the variation of the envelope heat gain in a bedroom during night, it is necessary to study the thermal environment inside a 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. The influences of envelope heat gain on energy consumption of the TAC system and the indoor thermal comfort were studied in this paper. The research results show that at supply air flow rate (Q_s) of 50 l/s, energy consumption was increased from 47.78 W to 213.11 W, and the PMV value was increased from −1.69 to −1.29 with the increase in envelope heat gain from 3.11 W to 155.6 W. To make PMV equal to zero under different envelope heat gains, linear regression models between supply air parameters and PMV were built and solved. The obtained values form curves where PMV = 0 and give a guide for operation of the TAC system. It was found that the calculation of energy consumption on these curves depends only on envelope heat gain.

1. Introduction

A building envelope which comprises of various components such as walls, fenestration, roof, foundation, thermal insulation, thermal mass, and external shading devices [1], separates the indoor and outdoor environments of a building. It is important to control the indoor conditions. In subtropics, during night, caused by the periodic solar radiation on earth, the outdoor air temperature varied through one day, especially at night [2]. Consequently, the heat gain through the building envelope varies correspondingly. Broadly speaking, there are three types of heat gain coming through the building envelope: wall conduction, window conduction and solar heat through the windows [3]. At nighttime, there

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Nomenclature

C	convective heat loss [W/m^2]
C_p	specific heat [J/kg K]
C_{res}	sensible heat loss due to respiration [W/m^2]
D_{im}	mass diffusion coefficient [m^2/s]
E	total energy [J]
E_{res}	latent heat loss due to respiration [W/m^2]
E_{sk}	evaporative heat loss from skin [W/m^2]
$\vec{g}$	gravitational acceleration [m/s^2]
h_j	enthalpy of specie j [J]
i_m	total vapor permeation efficiency [–]
$\vec{J}_j$	diffusion flux of species j [kg/(m^2 s)]
k_{eff}	effective conductivity [W/m k]
L_R	Lewis ratio [K/kPa]
M	metabolic heat production [W/m^2]
p_a	water vapor pressure in ambient air [(kPa)]
$P_{sk,s}$	water vapor pressure in saturated air [(kPa)]
Q_c	energy consumption of the TAC system [W]
Q_s	supply air flow rate [l/s]
R	radiative heat loss [W/m^2]
R_t	total equivalent uniform thermal resistance between body and environment including clothing and boundary resistance [m^2 K/W]
S_{ct}	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_a	ambient air temperature [°C]
T_{eo}	external wall outside surface temperature [°C]
t_r	return air temperature [°C]
T_s	supply air temperature [°C]
t_{sk}	mean skin temperature [°C]
t_{uz}	average air temperature in an unoccupied zone [°C]
t_{oz}	average air temperature in an occupied zone [°C]
v	air velocity at a measurement position [m/s]
w	skin wetness [–]
Y_i	mass fraction of the species i [–]
ρ	air density [kg/m^3]
$\bar{\bar{\tau}}$	stress tensor [Pa]
μ_t	turbulent viscosity [Pa s]

Abbreviation

CFD	computational fluid dynamics [–]
PMV	predicted mean vote [–]
TAC	task/ambient air conditioning [–]

are only conduction through wall and window. Therefore, the heat gain through the envelope is mainly affected by the outdoor thermal environment. Lin and Deng [4] investigated the rooms equipped with an air conditioner operated in nighttime mode 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. Furthermore, envelope heat gains accounted for more than 70% of the total cooling load for a bedroom [4]. Hence, the envelope heat gain also undergoes obvious variation during night. Other than the envelope heat gain, the outdoor air temperature decreased during the period from 22:00 to 6:00 at the second day. Wang et al. [5] studied a temporary prefabricated houses used in south China experimentally. The air temperature outside the house was found varying with time during night. Yang and Li's study also found the variation of outdoor air temperature [6]. Saffari et al. carried out study and found the variations of outdoor air temperature and cooling load [7].

Due to the heat transfer through the envelope, the variation of outdoor air temperature results to the change of indoor air temperature. Wang et al. [5] studied a temporary prefabricated houses used in south China experimentally. The air temperature inside and outside the house and wall surface temperature were measured. The results show that outdoor air temperature varied obviously during night, and the indoor temperature's variation trend agree well with the outdoor air temperature, suggesting the effects of outdoor thermal environment on indoor. Yang and Li [6] simulated the variation of cooling load of air conditioning for a whole day. Not only the variation of outdoor air temperature was studied, but different mean outdoor air temperatures were considered. Evola et al. [8] investigated the influence of outdoor environment on indoor thermal environment using different envelope insulations. On this base, night-time ventilation was proposed and studied to reduce the cooling load. Goia [9] evaluated the thermal comfortable level inside a test room. It was found that PMV (predicted meat vote) values underwent an obvious decrease during night. Ascione et al. [10] studied the thermal comfort level in residential buildings in Athens. The PPD (predicted percentage of dissatisfied) values were found increasing after 24:00 during night. These previous studies show that varying envelope heat gain through night affects the thermal comfort and cooling load.

To weaken the effect of varying envelope heat gain, two types of method were adopted: passive cooling/heating and active cooling/heating. The former includes using PCM (phase change materials), changing envelope insulation, and ventilation. Lei et al. [11] integrated the PCM materials into building envelope, and found that it reduce the change of indoor air temperature and cooling load. Huang et al. [12] investigated the thermal insulation of building, and found that employing thermal insulation can significantly reduce cooling load through the building external wall. Evola et al. [8] proposed night-time ventilation to reduce the cooling load. The typical method for the latter is using heat pumps in winter [13,14] or air conditioners [4] in summer. In subtropics, air conditioners have been widely used to maintain a suitable thermal environment [15]. Lin and Deng [4] investigated the rooms equipped with nighttime operating mode air conditioner during night. It can be seen that, the air conditioner can weaken the variation of indoor air temperature [4]. However, the wide spread use of air conditioning at both daytime and nighttime contributed to increased energy use in buildings [16–18]. Therefore, it's necessary to introduce novel air conditioning systems to reduce energy.

There has been an increasing interest in using task/ambient air conditioning (TAC) systems, due to their better performance in terms of energy saving and flexible control over thermal environments [19,20]. By allowing individual occupants to control their thermal environments, their individual thermal comfort preferences can be accommodated. Amai et al. [21] carried out an experimental study on four types of TAC systems installed in a climate chamber. It was found out that using TAC systems achieved better thermal comfort. A personal environmental module based TAC system was flexible and easy to control, therefore offered a significant potential to improve thermal comfort in workspaces [20]. On the other hand, the use of TAC systems also helped achieve energy saving. This was because when a full volume air conditioning (FAC) system was used, a comfortable indoor environment for everywhere in a room may be maintained. However, when a TAC system was used, only a comfortable indoor environment within an occupied zone would be maintained, but air temperatures outside the