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Optimization of room air temperature in stratum-ventilated rooms for both thermal comfort and energy saving

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HIGHLIGHTS

- An optimization method is proposed on room air temperature.
- Energy consumption for air conditioning with stratum ventilation is minimized.
- Intended thermal condition based on modified PMV is provided.
- Modified PMV is validated by subjective surveys.

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ABSTRACT

Elevated room air temperature is normally accompanied by elevated room air velocity to provide thermal comfort and save energy. One problem is that an excessively high room air temperature would deteriorate the energy performance of the air conditioning system due to the increased energy consumption of the ventilation fans. Another problem is that existing thermal comfort evaluation models in the field of building energy performance may fail because most of the building simulation tools/building management systems cannot provide accurate information on the elevated room air velocity. This study proposes a room air temperature optimization method to achieve intended thermal condition and to minimize energy consumption of the air conditioning system with stratum ventilation simultaneously. Firstly, the PMV model for thermal condition evaluation is modified by representing the room air velocity in the original PMV model given in ASHRAE 55-2013 using the room air temperature and supply airflow rate. Secondly, with the modified PMV, one supply airflow rate is quantified for one room air temperature to achieve the intended thermal condition (i.e., the intended PMV value); and the energy consumptions of different room air temperatures are evaluated using building energy simulations. Objective measurements and subjective surveys in a typical classroom in Hong Kong validate the modified PMV with a mean discrepancy of 0.14 scale from the thermal sensation vote. TRNSYS simulations demonstrate the effectiveness of the proposed method that the energy consumption of the air conditioning system is reduced by 7.8% while satisfying the intended thermal comfort.

1. Introduction

People spend more and more time conducting indoor activities (around 80–90%) [1]. Indoor thermal comfort conditions can significantly affect health (e.g., the sick building symptom) and productivity of the building occupants [2–4]. Thermal comfort is the condition of mind that expresses satisfaction with the thermal environment [5]. To provide a thermally comfortable indoor environment, the air conditioning system with mechanical ventilation is popularly installed in buildings [6]. While buildings consume about 40% of the primary energy worldwide, air conditioning systems account for the majority of the building energy consumption [6]. For energy saving of air conditioning systems, the room air temperature is required/recommended to be elevated by governmental guidelines [7–9]. An appropriate increment in the room

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Nomenclature

ACH	air change per hour (–)	Q_c	cooling load of chiller (kW)
c	specific heat capacity of air (kJ/(kg °C))	Q_{cl}	room cooling load (kW)
COP_{nom}	nominal COP of chiller (–)	T_e	exit air temperature (°C)
EC	energy consumption (kJ/h)	T_R	room air temperature (°C)
FFLP	fraction of full load power (–)	T_s	supply air temperature (°C)
$\dot{m}_{wat}$	water flowrate (kg/s)	v_R	room air velocity (m/s)
n	room occupants number (–)	*V*	room volume (m^3)
N	supply airflow rate (ACH)	ρ_{air}	air density (m^3/kg)
PMV	predicted mean vote (–)	ρ_{wat}	water density (m^3/kg)
PMV_{ASHRAE}	original PMV given in ASHRAE 55-2013 (–)	ΔP_{air}	pressure drop of airflow (Pa)
PMV_m	modified PMV (–)	ΔP_{wat}	pressure drop of water flow (Pa)
Pow_{chi}	chiller power (kW)	η_{fan}	fan efficiency (–)
Pow_{fan}	fan power (kW)	η_{pum}	pump efficiency (–)
Pow_{pum}	pump power (kW)	δ	ventilation effectiveness (–)
PPD	predicted percentage dissatisfied (%)		

air temperature was found to save energy by about 6%/°C [10,11]. The effect of the elevated room temperatures on the thermal condition could be offset by elevated room air velocities to provide a thermally satisfactory indoor environment, because an elevated room air velocity could increase the body heat loss by convection [12,13]. However, an excessively high room air temperature would deteriorate the energy performance due to the increased energy consumption by ventilation fans to provide the required room air velocity [14,15].

Stratum ventilation is a sustainable mechanical ventilation mode for the small-to-medium sized space for accommodating elevated room air temperatures [16–19]. The fresh air is horizontally supplied to the breathing zone, reaching the head level of the occupants with a relatively short distance. The horizontal supply airflows at the head level form the breathing zone of lower temperature, higher velocity and younger air age compared with those at the other levels in the room. Therefore, the occupants could be efficiently cooled, and provided with high quality inhaled air [20,21]. The neutral room air temperature under stratum ventilation is about 2 °C higher than that of mixing ventilation (a conventional air distribution), and saves energy by at least 37.7% [19,20,22]. A life cycle analysis demonstrated that compared with mixing ventilation, stratum ventilation reduced CO_2 emission up to 31.7% and saved life cycle cost up to 23.9% for a service span of 20 years [23]. To achieve a high performance of stratum ventilation, the room air temperature needs to be properly set [24,25]. Environment chamber experiments on stratum ventilation showed that under a supply airflow rate of 10 air change per hour (ACH), a room air temperature of 27 °C provided a thermally neutral environment while a room air temperature of 24/29 °C resulted in the percentage of subjects feeling comfortable obviously less than 80% [24]. However, the existing studies did not provide insights into the effects of the room air temperature on the energy performance of the air conditioning system with stratum ventilation. Thus, it calls for optimization of the room air temperature for simultaneous energy saving and thermal comfort under stratum ventilation.

Also, it becomes a crucial issue that how to provide thermal comfort with an elevated room air velocity for the optimization of room air temperature. The PMV model, a thermal condition prediction method, is widely employed for mechanically ventilated buildings in the field of building energy performance [4,26–28]. This model predicts the mean thermal sensation of a group, and relates the result to the percentage of dissatisfaction with the thermal environment [5]. To achieve a thermally acceptable indoor environment, the PMV value should be constrained within a certain range [5,29]. Sensitivity analysis revealed that the PMV value heavily related to the room air velocity and temperature [30,31]. Moreover, the standard effective temperature based on PMV is particularly proposed to evaluate the cooling effect of the elevated room air velocity for thermal comfort, and it also requires the exact value of room air velocity [5]. On the other hand, it is common to adopt building simulation tools/building management systems to identify the room air temperature with minimal energy consumption. However, most of the popularly used building simulation tools (e.g., TRNSYS [32] and EnergyPlus [33])/building management systems could not provide accurate information on room air velocity [34,35]. When the room air velocity is lower than 0.2 m/s, the operative temperature, which is simplified from the PMV model, is allowed to be used for thermal condition evaluation [5,36–41]. Actually, even with a room air velocity below 0.2 m/s, the operative temperature risks to inaccurately predict the three thermal comfort levels stipulated by EN 15251 [40]. However, in a stratum-ventilated room, the mean room air velocity is typically higher than 0.2 m/s [24,42]. The existing thermal comfort evaluation methods used in building simulations/building management systems could not accurately predict the thermal condition of a stratum-ventilated room. As a result, it could be a problem that the selected room air temperature based on the conventional thermal comfort evaluation methods fails to fulfill the thermal comfort requirement [43]. It is noted that some advanced thermal comfort models are available such as models for local comfort and overall comfort evaluation developed by Zhang et al. in the field of thermal comfort [44,45], but they are too complex to be employed in the field of building energy performance at present. These models require detailed inputs of room air flow parameters (e.g., room air velocity) and occupants' responses (e.g., skin temperatures), but tools used for building energy performance studies cannot provide such information. There is a gap between the fields of thermal comfort and building energy performance, which deserves immediate attentions and efforts as both thermal comfort and energy performance are two main concerns of modern building development. This paper could be regarded as an effort contributing to narrowing the gap.

Therefore, this paper proposes a method for optimizing the room air temperature for minimal energy consumption and satisfactory thermal condition under stratum ventilation. Firstly, the PMV model is modified by representing the room air velocity in the original PMV formula given in ASHRAE 55-2013 using the room air temperature and supply airflow rate. Then, with the modified PMV model, one supply airflow rate is determined for each potential room air temperature to achieve the intended thermal