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An enthalpy-based energy savings estimation method targeting thermal comfort level in naturally ventilated buildings in hot-humid summer zones

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HIGHLIGHTS

- Energy saving potential is assessed by energy balance and thermal comfort.
- Enthalpy change is used as the result of energy fluxes of a room in hot-humid zones.
- Thermal comfort index APMV is proper for naturally ventilated buildings.
- Steps are given to design a well-performed naturally ventilated building.

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ABSTRACT

This paper examines naturally ventilated buildings in hot and humid summer zones and proposes an air enthalpy-based energy conservation rating method with an emphasis on the combined thermal comfort-ventilation parameters, particularly the impact of humidity and human adaptations on thermal comfort. The new method starts with energy flow analysis to a naturally ventilated room and assessment of thermal comfort accounting for the humidity of the naturally ventilated room as well as the occupants' adaptability, differing from the PMV models and widely-used adaptive models adopted in existing rating methods. It contributes to designing a well-performed naturally ventilated building by analysing the interplay of climate elements, design features, indoor thermal comfort, and energy consumption for cooling in hot-humid climates. It also gives the access to rate the influence of an estimated energy saving due to natural ventilation on the energy system at a district or national scale. The proposed method is then applied to a naturally ventilated office located in three cities within this particular climatic region of China. The results indicate that natural ventilation is an effective way to improve thermal comfort while maintaining a low cooling energy consumption in hot-humid summer zones. Using natural ventilation could help reduce cooling energy demand by 10–30% compared to not using natural ventilation. Its energy saving potential is strongly affected by the enthalpy of outdoor air, followed by airflow rate. Then, a contrast comparison between the new method based on energy balance and Chinese indoor thermal comfort standard and the conventional method coupling adaptive ASHRAE standard-55 thermal comfort model with sensible heat balance model is carried out. The contrast results validate the considerable impacts of humidity on energy balance analysis and thermal comfort rating. It points out the new method makes improvement of the maximum energy saving potential of naturally ventilated buildings prediction.

1. Introduction

Due to the poor quality of the thermal environment in hot-humid climate zones, there is an increased demand for improvement of indoor thermal conditions [1]. Artificial cooling always

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results in increased energy usage and increased electricity cost to the occupants in a hot and humid climate [2,3]. Moreover, many studies reveal a statistically significant relationship in which buildings with air-conditioning, with or without humidification, are consistently associated with 30–200% higher incidences of sick building syndrome symptoms, compared to naturally ventilated buildings [4,5]. Considering such issues, natural ventilation in summer and transition seasons is a commonly used passive cooling technology to improve the indoor thermal comfort and air quality in such climate zones [6,7]. Determining whether natural ventilation would remain an acceptable means of indoor thermal comfort control requires prediction of the indoor conditions in the spaces when they are naturally ventilated. Consequently, the energy performance of natural ventilation should be assessed associated with the relation of climate, building design, and thermal comfort. A number of studies on cooling energy savings of using natural ventilation have considered the ventilation parameters, thermal comfort and energy savings together for various building types and climate zones [8–10]. Some research aimed at the natural ventilation performance of residential building designs by taking thermal comfort into account [11–14] while some were focused on hybrid ventilated buildings [15–17]. Some research discussed the link between the natural ventilation performance and urban environments [18]. Studies also covered various climates such as warm conditions [19], warm-humid conditions [20], and hot-dry summer climate [21–23].

Almost all of the aforementioned research took thermal comfort into account. The assessment of thermal comfort under naturally ventilated environment is mainly based on either PMV model [24–26] or adaptive models [27]. However, the PMV method, which is based on steady-state, human body heat balance theory [28] has been challenged by adaptive models [29]. The adaptive models adopted in existing methods are mainly based on four well-known and most widely accepted thermal comfort international standards: American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) standard-55 [30], the International Organization for Standardization (ISO) standard-7730 [31], the European standard EN15251 [32], and the Chartered Institution of Building Services Engineers(CIBSE) [33]. These international comfort standards are almost all based on North American and northern European subjects [31,34]. It has not been clarified in the aforementioned standards whether they are applicable to different environmental conditions [29]. Taking hot-humid summer zones of China as an example, studies broadly covering different types of buildings found that adaptive models adopted in aforementioned standards, such as the ASHRAE and ISO, are not suitable due to the different climatic characteristics, significant sensation variations and human adaptations in China [35–38]. These studies generally indicate that there are discrepancies between people's real thermal sensation and the predicted thermal sensation, especially for naturally ventilated buildings. Taking into account factors such as climate, social, psychological and behavioural adaptations of these regions, studies have been conducted within the context of thermal comfort, and Adaptive Predicted Mean Vote (APMV) model for China conditions has been proposed [29,39–40].

According to the China *"Standard of climatic regionalization for architecture (GB 50178)"* [41], hot-humid zones in China refer to the hot summer and cold winter climate zone, and the hot summer and warm winter climate zone. In other words, it contains the Yangtze River basin and Southern coastal regions. These areas are of important to the development of China due to the growth in population and the economy [42]. Natural ventilation is highly recommended in hot-humid zones in China [43,44]. Therefore, the objective of this work was to review existing methods for rating energy saving using natural ventilation, and then propose a new method to rate energy use in naturally ventilated buildings based on energy balance and thermal comfort in the hot-humid climate regions of China.

2. Rating energy savings with a consideration of thermal comfort using natural ventilation

To improve the estimation of energy benefits when deploying natural ventilation to achieve thermal comfort in a hot and humid environment, it is crucial to use a robust heat transfer model with appropriate thermal comfort criteria.

Energy embedded in the flowing material consists of internal energy, macroscopic kinetic energy, gravitational potential energy, and flow work. The internal energy and flow work embedded in the flowing material are regarded as "enthalpy" in thermodynamics because they depend on the thermal state of the flowing material. When analysing the heat transfer process of creating a thermal environment, the macroscopic kinetic energy and gravitational potential energy embodied in the air are not taken into consideration, and hence the value of enthalpy is the energy of air per unit mass. Among various thermodynamic parameters, "enthalpy" is the indicator used to analyse the energy balance of a room. Hence, thermal load changes including sensible heat changes and latent heat changes can be regarded as alterations of the air enthalpy in the room [45]. In other words, the total heat balance is expressed as enthalpy-based balance of a room. Homod et al. [25] proposed a control system by employing all factors affected by indoor air enthalpy to predict system deviations and generate control actions pertaining to mechanical ventilation time. Liu et al. [46] studied the control strategies at different conditions of indoor load, ventilation and indoor air temperature and humidity by analysing two control modes, enthalpy control and temperature control, in a hot and humid climate.

In practice, most studies described above simplify the heat balance as sensible heat balance, using the indoor temperature change as the result of energy fluxes, such as the multi-zone thermal and airflow model [19,47–48], BIN method [49] and CDD method [10,50]. Those methods have widely been used for predicting the cooling energy savings of using natural ventilation, neglecting the influence of latent heat on the total energy load. For instance, Florides et al. [15] reported ventilation in summer results in a maximum reduction of annual cooling load of 7.7% when maintaining the house at 25 °C. Taleb [21] investigated the potential energy saving prospects of integrating natural ventilation with air conditioning systems into the residential buildings of Dubai through the use of computer simulation. In distinction to these, however, latent heat cannot be neglected in high-humidity zones. Shin and Do [51] examined a building's cooling energy use as it is predicted with outdoor dry-bulb temperature versus outdoor enthalpy in a hot and humid climate. As a result, the comparison utilizing the enthalpy-based cooling degree-days method resulted in an error margin of approximately 2% less than that of the temperature-based cooling degree days method. In short, the analysis of total heat balance of a room is necessary in hot and humid climate zones.

Natural ventilation is an essential passive strategy to maintain indoor thermal comfort, therefore, the thermal comfort criteria is coupled to the existing energy-saving evaluation methods for using natural ventilation. As mentioned earlier, thermal comfort criteria can be classified into two categories: PMV model and adaptive models. PMV model [28] based on the human heat balance reveals a complex interaction of dry bulb temperature, mean radiant temperature, air velocity, relative humidity, clothing insulation and activity level. Although it is accepted as applicable to all conditions in occupied spaces [30,52–53], it has been very difficult