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Effect of the night ventilation rate on the indoor environment and air-conditioning load while considering wall inner surface moisture transfer

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ABSTRACT

Night ventilation may improve the indoor air temperature and reduce the cooling load. However, the effects of different night ventilation rates on the indoor air relative humidity, wall inner surface temperature, inner surface moisture flux, sensible heat load, latent heat load and total load are rarely studied in terms of the inner surface moisture transfer. The present paper aims to investigate the effect of different night ventilation rates on the above items in a hot-humid climate in China. The results show the following: when the moisture absorption–desorption process at the wall inner surface is not considered, the air-conditioning load of the night ventilation at 15ACH is approximately 5% lower than that at 5ACH. When the moisture absorption–desorption process is considered, the night ventilation rate has a smaller impact on the indoor air temperature and has a larger impact on the indoor air relative humidity during the night. The night ventilation rate negatively correlates with the sensible heat load and positively correlates with the latent heat load due to the increased amount of moisture that is absorbed or desorbed at the interior wall surface. The total air-conditioning load of Case B.1, which featured a 15ACH night ventilation rate, was approximately 8% higher than that of Case A.1, which featured a 5ACH night ventilation rate.

1. Introduction

Night ventilation is a low-cost passive cooling technique that may contribute to reducing the cooling load of buildings and to improving the thermal comfort of occupants. At present, many scholars have used important experimental and theoretical studies to investigate the efficiency of night ventilation [1–5].

Wang used the whole energy-consumption analysis software EnergyPlus to simulate the indoor thermal environment and energy consumption of typical office buildings with night mechanical ventilation in three cities in northern China. The results show that the night ventilation operation time is closer to the active cooling time and longer as the efficiency of night ventilation increases [6]. G. Carrilho da Grac-a et al. used a coupled model of computational fluid dynamics (CFD) and building thermal analyses to simulate the heat transfer and airflow in apartments in Beijing and Shanghai. Two passive cooling strategies, daytime ventilation and night cooling, have been evaluated based on the occupant's thermal comfort [7]. Sreshthaputra et al. coupled DOE-2 and 3D transient CFD simulations for an unconditioned 100-year-old Buddhist temple in an urban area of Bangkok, Thailand. Several remedial changes for improving the poor indoor thermal conditions were proposed, including applying a low absorption roof coating, adding ceiling insulation, increasing the sunshade at the building's exterior surfaces and nighttime-only ventilation [8].

Wang et al. investigated the impacts of various ventilation strategies and facade designs on the indoor thermal environment for naturally ventilated apartments in Singapore. The study concluded that night ventilation is not as effective as full-day ventilation with low thermal conductance or little thermal inertia. However, the indoor conditions with night ventilation are slightly better than those with full-day ventilation when the heat conductance is high and the thermal inertia is adequate [9]. Artmann et al. studied the effect of building construction, heat gains, the air change rate, the heat transfer coefficient and climatic conditions on the performance of building cooling due to night-time ventilation [10]. Kubota et al. compared the indoor air temperature and humidity of night ventilation with those of daytime ventilation, no ventilation and full-day ventilation in Malaysia. He also showed that night ventilation would not be superior to other techniques in

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providing daytime thermal comfort, mainly due to the high humidity conditions. Dehumidification was necessary during the daytime [11].

However, scholars have mainly focused on the effect of night ventilation on the indoor air temperature and sensible heat load in these studies. The effects of different night ventilation rates on the relative indoor air humidity, the wall inner surface temperature and latent heat load have rarely been considered with respect to the vapor absorption–desorption at the wall inner surface. In fact, insufficient air relative humidity may result in dry skin and mucous membranes and sensory irritation of the eyes and upper airways [12], as well as affect the static electricity levels [13,14]. The higher air relative humidity leads to serious moisture problems for the building envelope and indoor climate due to the development of microorganisms and house dust mites [15]. Moreover, the moisture transfer and heat transfer processes are coupled on the wall inner surface, and moisture transfer can change the inner surface temperature. Furthermore, any required reduction in the cooling load during the daytime air-conditioning period due to an increased night ventilation rate in a hot-humid climate requires investigation. Therefore, the moisture transfer process at the wall inner surface should be studied as a function of the night ventilation rate, and the effect of this process on the indoor thermal environment and cooling load is also researched in this paper.

In this paper, a whole-building hygrothermal model that considers the moisture transfer at the wall interior surface is presented and subsequently validated with an analytical solution. The model is applied to investigate the effect of different night ventilation rates on the indoor air temperature and relative humidity, inner surface temperature, inner surface moisture flux, sensible heat load, latent heat load and total load in a hot-humid climate in China. Detailed discussions and analyses are presented in the following sections.

2. Modeling of heat and moisture transfer for building envelope

Previous studies have mainly focused on the heat transfer of building envelopes, and the moisture transfer process is often ignored. In fact, the moisture migration process significantly impacts the heat transfer, especially in humid climates. Therefore, the coupled heat and moisture transfer equations for a building envelope are presented in the following sections while considering the absorption–desorption process at the wall interior surface in order to accurately calculate and analyze the effect of the night ventilation rate on the indoor environment and air-conditioning load.

2.1. Governing equations of moisture transfer

The total moisture flux consists of vapor flux and liquid flux. More complicated descriptions of the total moisture flow have also been suggested [16,17]. However, the required material parameters are difficult to determine. Furthermore, the vapor flow and liquid flow usually occur in the same direction and cannot be easily separated in an experiment. For the isothermal case, a simple description of the total moisture flow, J_m, proposed by Nilsson [18], is adopted in this research that neglects some thermodiffusion:

$$J_m = J_v + J_l = -\delta_v \frac{\partial P_v}{\partial x} - D_l \frac{\partial P_l}{\partial x} = -\left(\delta_v + \delta_l\right) \frac{\partial P_v}{\partial x} = -{\delta_v}' \frac{\partial P_v}{\partial x} \qquad (1)$$

where J_m is the total moisture flux in kg/m^2 s; J_v is the vapor diffusion flux in kg/m^2 s; J_l is the liquid conduction flux in kg/m^2 s; δ_v is the vapor permeability in kg/Pa m s; D_l is the liquid water transmission coefficient in kg/Pa m s; P_v and P_l are the vapor pressure and the suction pressure in Pa; ${\delta_v}'$ is the equivalent total moisture diffusion coefficient.

The suction pressure can be expressed as a function of the relative humidity and temperature by using Kelvin's equation,

$$P_l = \left(\rho_l RT/M_l\right) \ln\left(P_v/P_{v,\text{sat}}\right),$$

where T_k is the thermodynamic temperature in K; ρ_l is the density of water in kg/m^3; M_l is the molar mass of water in g/mol; R is the universal gas constant in J/kg K; $P_{v,\text{sat}}$ is the saturated vapor pressure in Pa.

Because the main gradients for both temperature and relative humidity are in the direction of the x-axis, the 1-D modeling hypothesis is considered in this paper. The coupled heat and moisture transfer equations are given based on the Philip and De Vries theory [19].

The moisture composition equilibrium equation in the porous material can be expressed by the following:

$$\frac{\partial w}{\partial t} + \nabla\left(J_v + J_l\right) = 0 \qquad (2)$$

Or

$$\frac{\partial w}{\partial t} = \frac{\partial}{\partial x}\left({\delta_v}' \frac{\partial P_v}{\partial x}\right) \qquad (3)$$

where w is the volumetric moisture content in kg/m^3.

Theoretically, all the moisture component parameters can be used as the moisture driving potential, such as the moisture content, vapor pressure and absolute humidity, etc. As shown in Eq. (3), w is used as the storage quantity and P_v is used as the only driving potential according to Eq. (1). For the convenience of calculations, w and P_v can be expressed in terms of the relative humidity. The relative humidity is continuous at the interface of different materials that have different moisture storage properties. According to Eq. (4), $\partial P_v/\partial x$ can be transformed into a function of relative humidity and temperature. According to the definition of the slope of the moisture retention curve, $\partial w/\partial t$ in Eq. (3) can be transformed into $\xi\left(\partial\varphi/\partial t\right)$ in Eq. (6). Therefore, the relative humidity is chosen as the moisture driving potential.

The vapor pressure gradient, $\partial P_v/\partial x$, is expressed as a function of the relative humidity and saturated vapor pressure as follows:

$$\frac{\partial P_v}{\partial x} = \frac{\partial\left(\varphi P_{v,\text{sat}}\right)}{\partial x} = \varphi\frac{\partial P_{v,\text{sat}}}{\partial x} + P_{v,\text{sat}}\frac{\partial \varphi}{\partial x} = \varphi\frac{\partial P_{v,\text{sat}}}{\partial T}\frac{\partial T}{\partial x} + P_{v,\text{sat}}\frac{\partial \varphi}{\partial x} \qquad (4)$$

where T is the temperature in °C; $P_{v,\text{sat}}$ is expressed as a function of the temperature [20]:(5)$P_{v,\text{sat}}(T) = 610.5\exp\left(\frac{17.269T}{237.3+T}\right)$

Therefore, substituting the above equations into Eq. (3) allows the moisture transfer process to be expressed as follows:

$$\xi\frac{\partial\varphi}{\partial t} = \frac{\partial}{\partial x}\left({\delta_v}'\left(\varphi\frac{\partial P_{v,\text{sat}}}{\partial T}\frac{\partial T}{\partial x} + P_{v,\text{sat}}\frac{\partial\varphi}{\partial x}\right)\right) \qquad (6)$$

$$\xi\frac{\partial\varphi}{\partial t} = \frac{\partial}{\partial x}\left(D_\varphi\frac{\partial\varphi}{\partial x}\right) + \frac{\partial}{\partial x}\left(D_T\frac{\partial T}{\partial x}\right) \qquad (7)$$

where $\xi = \partial w/\partial\varphi = \rho\left(\partial u/\partial\varphi\right)$ is the slope of the moisture retention curve; u is the qualitative moisture content in kg/kg. $D_\varphi = {\delta_v}' P_{v,\text{sat}}$ and $D_T = {\delta_v}'\varphi\left(\partial P_{v,\text{sat}}/\partial T\right)$.

2.2. Governing equations of heat transfer

The phase change that occurs within porous materials acts as a heat source or sink, which results in the coupled relationship