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Heat removal efficiency based multi-node model for both stratum ventilation and displacement ventilation

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ABSTRACT

The non-uniform distribution of vertical air temperature helps stratum ventilation and displacement ventilation to save energy compared with mixing ventilation. To reasonably predict the vertical distribution of the non-uniform air temperature, the multi-node (nodal) model requires an in-depth understanding of the airflow pattern and is specific for different designs of ventilation, which challenges engineers/designers in practice. To be more practical, this study proposes a heat removal efficiency (HRE) based multi-node model. The proposed model employs HRE to conveniently represent the airflow pattern, requiring little understanding of the airflow pattern. Moreover, the proposed model is general for both stratum ventilation and displacement ventilation, and flexible to include heating/cooling devices. Experimental case studies show that compared with the conventional model, the proposed model is more accurate and robust. The proposed model reduces the overall mean absolute error in the temperature predictions of the nodes of the air and inner surfaces of the enclosure by 0.1°C (from 0.94°C to 0.84°C) for stratum ventilation, and by 0.08°C (from 0.33°C to 0.25°C) for displacement ventilation with floor heating; and reduces the associated overall standard deviation of errors by 0.14°C (from 0.55°C to 0.41°C) and 0.02°C (from 0.19°C to 0.17°C) respectively. Benefiting from its convenience, generality, flexibility, accuracy and robustness, the proposed model is practical and would contribute to the practical applications of the energy-efficient stratum/displacement ventilation strategies.

1. Introduction

Air conditioning systems are widely installed in modern buildings for indoor air quality and thermal comfort [1–3], but they account for a major proportion of building energy consumption [4,5]. One of the main reasons is that the conventional ventilation strategy, mixing ventilation, uniformly treats the entire room, resulting in energy waste for treating the upper zone without occupants [1,6,7]. To develop low energy buildings [8], there is an urgent need to shift the conventional ventilation strategy to advanced ones which focus on the occupied zone [1,6]. Stratum ventilation [9,10] and displacement ventilation [11,12] are two examples of such advanced ventilation strategies. Objective measurements and subjective surveys confirmed that compared with the neutral temperature of mixing ventilation (around 24.5°C), those of stratum ventilation and displacement ventilation were increased by 2.5°C and 0.5°C respectively [13]. At the neutral temperature, neutral thermal sensation can be achieved [2,13]. And the annual energy consumption of the air conditioning system with mixing ventilation was saved by at least 44.37% and 25.61% by stratum ventilation and displacement ventilation respectively [7].

Stratum ventilation supplies conditioned air horizontally to the breathing zone, forming a sandwich shape vertical air temperature profile with the lowest value at the head level (Fig. 1(a)) [14,15]. Displacement ventilation supplies conditioned air to the floor level, and then creates the upward convective flows (i.e., thermal plumes) due to heat sources (Fig. 1(b)) [16]. The vertical air temperature of displacement ventilation increases almost linearly with heights, or firstly almost linearly increases with heights till the neutral height and then keeps constant (i.e., two-layer theory) [17,18]. The vertical air temperature profile is a critical factor in the performances of stratum ventilation and displacement ventilation regarding thermal comfort and energy consumption [19–21]. The conventional assumption of uniform room air temperature is inadequate for the performance evaluations of stratum ventilation and displacement ventilation [6,22–26].

Technologies used to produce the vertical air temperature profile mainly include experiments, CFD simulations, zonal models and multi-

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Nomenclature

A	Area (m^2)
D	equivalent diameter (m)
h	heat transfer coefficient ($W/(m^2 \cdot °C)$)
k	constant coefficient
m	mass flow rate (kg/s)
Q	heat gain/loss (W)
t	temperature (°C)
X	radiation view factor
c_p	specific heat capacity of air ($J/(kg \cdot °C)$)
ε	surface emissivity
σ	blackbody radiation constant ($W/(m^2 \cdot K^4)$)

Abbreviations

ACH	air change rate
HRE	heat removal efficiency
MAE	mean absolute error
mea	measurement
pre	prediction
SD	standard deviation

Subscripts

a	room air/air of the core zone of room
ac	air layer near ceiling
af	air layer near floor
aw	air layer near exterior wall
c	convection/ceiling
e	from/to the ambiance
f	floor
i	interior partition
in	internal heat sources
j	Case j
n	number of cases
r	radiation/exit air
rs	radiation from internal heat sources
s	supply air
v	ventilation
w	exterior wall
1, 2	number of surfaces
0.1, 0.2, 0.3, 0.6, 0.9, 1.1, 1.4, 1.7, 2.0	height (m)

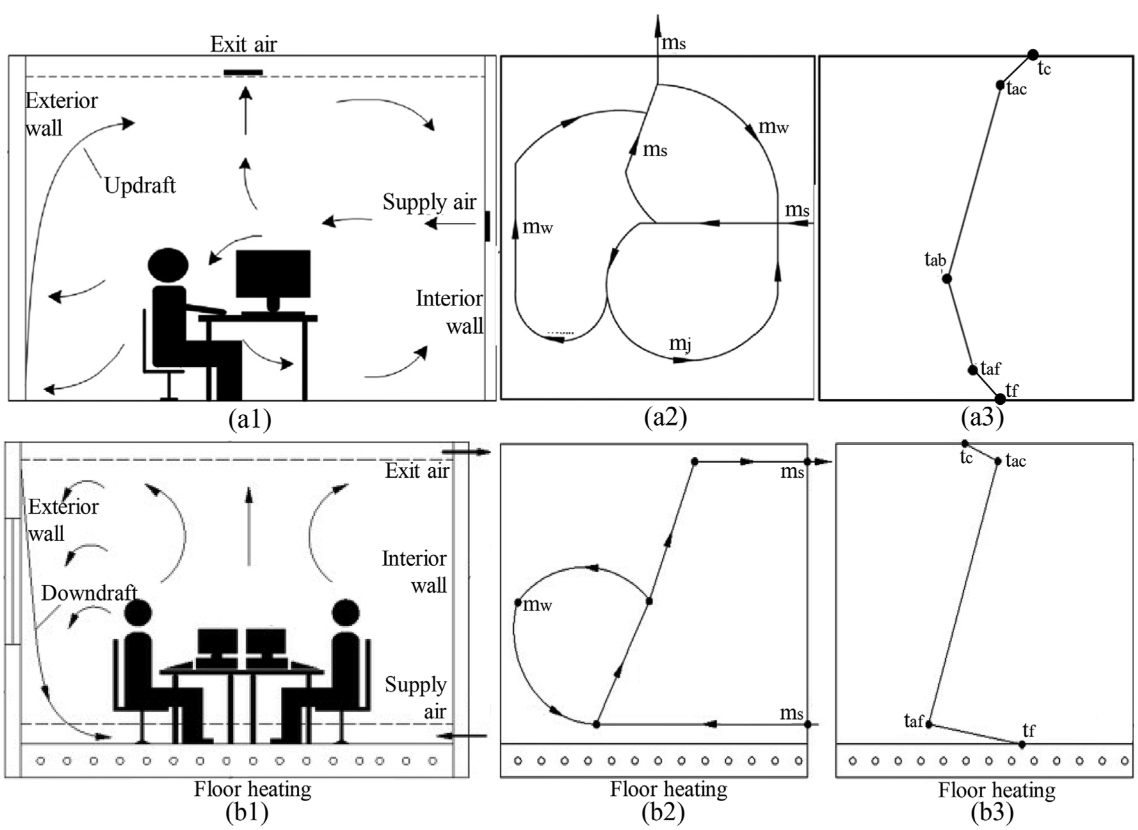

Fig. 1. Typical office with (a) stratum ventilation [27] and (b) displacement ventilation and floor heating [16]: (1) Room configuration; (2) vertical airflow pattern; and (3) vertical air temperature profile.

node models. Zonal models divide the entire room into several subzones and solve mass and energy conservation equations throughout these subzones [28]. Multi-node models (also termed as nodal models) introduce several nodes for temperature stratification [16,20,29]. For long-term performance evaluation (e.g., annual performance evaluation), experiments and CFD simulations are generally too time-consuming [30,31]. Although zonal models have been combined with multi-zone models for long-term performance evaluation [24], multi-node models are the most computation-efficient. The multi-zone model treats room air as a single node (i.e., assuming the room air temperature is uniformly distributed) [24,28], thus it is unable to take into account the non-uniform vertical air temperature distributions of stratum ventilation and displacement ventilation (Fig. 1). As revealed by Griffith and Chen [23], compared with the simple assumption of uniform air