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Development of a nodal model for predicting the vertical temperature profile in a stratum-ventilated room

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ABSTRACT

This paper presents the development and validation of a simplified nodal model that predicts the vertical temperature profile in a stratum-ventilated room. With full consideration of the mechanism of stratum ventilation and the effects of envelope heat transmission, the vertical temperature profile in a stratum-ventilated room could be predicted. The proposed model was validated through nine experiments of different scenarios. Generally good agreements between the model-predictions and measurements were achieved on the vertical air temperature profile, vertical temperature differences and area-weighted mean surface temperatures of different room enclosures. The agreements were also good for the volume-weighted mean temperatures of the core zone and breathing zone. Therefore, this nodal model can be used for energy calculation and practical engineering design.

1. Introduction

Nowadays, the problems with regard to energy, health and environment are growing rapidly in the world. It has already raised considerable concerns over the dilemma between a healthy and comfortable indoor environment and a healthy and comfortable global environment [1,2]. To reduce building energy consumption, a number of governments in East Asia have made proactive legislations on elevating the room temperature in summer [3,4]. This makes the discussion of acceptable velocity of airflow in an office environment attract substantial attention. Air movement is a major parameter related to human thermal comfort and also a simple and effective approach to improve thermal sensation at a relatively high room temperature [5]. According to this view, stratum ventilation was proposed by Lin et al. and has been considered as a solution to the new warm condition [6,7].

Stratum ventilation system aims to achieve a good indoor air quality (IAQ) in the breathing zone of occupants, with little consideration of the IAQ in the upper zone (above 1.4 m level for sedentary occupants) and the lower zone (below 0.8 m level). In a room with stratum ventilation (as show in Fig. 1), the fresh air is directly delivered to the breathing zone from the air supply terminal located at the middle of the front wall (typically at a cavity wall), with ambient fluid entrainment along its trajectory. When the supply air jet flows into the occupied zone, especially near the occupants and other internal heat sources, some of the supply airflow is driven upwards due to buoyancy and the sink (exhaust air terminal) on the ceiling, and then merges with the updraft induced by convection due to heat transmitted via the building envelope. Finally, a portion of the uprising airflows is vented outside while the other flows back into the supply jet as recirculating air. On the other hand, a portion of the cool supply airflow in the occupied zone dips due to buoyancy and the human obstacle, with heat exchange with the surrounding air. The downdraft bifurcates into two parts when its temperature is the same as that of the ambient air, one part is entrained into the boundary layer near the exterior wall as a wall-attached flow while the other recirculates back to be entrained into the supply airflow. Under stratum ventilation, the indoor thermal comfort is provided efficiently by elevating simultaneously the room temperature and air movement. This is different from the conventional mixing ventilation (MV) and displacement ventilation (DV). For MV, the contaminated room air is diluted by the mixing of outdoor fresh air with indoor air, and the indoor environment is considered as uniformly distributed [8]. For MV, the increase in air movement for thermal comfort, which aims to offset the elevated room temperature, would inevitably result in more energy consumption; For DV,

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Nomenclature

m_s	Supply airflow rate (kg/s)
m_{out}	Mass flux of the updraft induced by convective heat from the exterior wall (kg/s)
m_j	Airflow rate of the ambient air entrainment (kg/s)
t_f	Area-weighted mean temperature of the floor surface (°C)
t_c	Area-weighted mean temperature of the ceiling surface (°C)
t_{ln}	Air temperature near the floor (°C)
t_{hn}	Air temperature near the ceiling (°C)
t_b	Mean temperature of the plane in breathing zone(°C)
t_n	Volume-weighted mean temperature of the core zone of the room (°C)
t_{nw}	Air temperature near the exterior wall (°C)
t_w	Area-weighted mean inner surface temperature of the exterior wall (°C)
t_i	Area-weighted mean inner surface temperature of the interior partition
Q_{rf}	Heat radiation between the floor and the other enclosures (°C)
Q_{cf}	Heat convection between the floor and nearby air (W)
Q_{hf}	Radiant heat absorbed by the floor from the internal heat sources (W)
Q_{rc}	Radiant heat between the ceiling and the other enclosures (W)
Q_{cc}	Convective heat between the ceiling and nearby air (W)
Q_{hc}	Radiant heat absorbed by the ceiling from the internal heat sources (W)
Q_{ri}	Radiant heat between the interior partition and the other enclosures (W)
Q_{ci}	Convective heat between the interior partition and the indoor air (W)
Q_{hi}	Radiant heat absorbed by the interior partition from the internal heat sources (W)
Q_{rw}	Radiant heat between the exterior wall and the other enclosures (W)
Q_{cw}	Convective heat between the exterior wall and indoor air (W)
Q_{hw}	Radiant heat of the exterior wall absorbed from the internal heat sources (W)
Q_{ew}	Heat gain from the outdoor ambience (W)
Q_{dd}	Net convection of the air flowing into the near-floor zone from the core zone (W)
Q_{ec}	Net convection of the air flowing into the near-ceiling zone from the core zone (W)
Q_{wh}	Heat exchange rate of the updraft caused by the convective heat from the exterior wall (W)
Q_{nw}	Heat gain due to the air flowing into the boundary layer of the exterior wall (W)
Q_{sn}	Heat exchange between the cool supply air and indoor air (W)
Q_{hn}	Convective heat absorbed by the indoor air from the internal heat sources (W)
Q_{lnn}	Net convection between the indoor air and lower circulating flows (W)
Q_{hnn}	Net convection between the indoor air and upper circulating flows (W)
A_w	Surface area of the exterior wall (m^2)
A_c	Surface area of the ceiling (m^2)
A_i	Surface area of the interior partition (m^2)
A_f	Surface area of the floor (m^2)
h_{rf}	Heat transfer coefficient between the floor and the inner surface of any other enclosure ($W/(m^2K)$)
h_{cf}	Convective heat transfer coefficient of the floor ($W/(m^2K)$)
h_{rc}	Radiant heat transfer coefficient of the ceiling ($W/(m^2K)$)
h_{cc}	Convective heat transfer coefficient of the ceiling ($W/(m^2K)$)
h_{ri}	Radiant heat transfer coefficient of the interior partition ($W/(m^2K)$)
h_{ci}	Convective heat transfer coefficient of the interior partition ($W/(m^2K)$)
h_{rw}	Radiant heat transfer coefficient of the inner surface of the exterior wall ($W/(m^2K)$)
X	Radiation view factor between any two surfaces
F_{ln}	Fraction of the cooling energy from supply air that mixes into the near-floor zone
d_0	Hydraulic diameter of the air terminal (m)
x	Distance from the air jet to the air terminal (m)
δ	Average percentage error (%)
Avg.Dif.	Average temperature difference (°C)
R	Percentage error (%)
SD_r	Standard deviation of r (%)
Sim	Simulated data (°C)
Meas	Measured data (°C)
i	Serial number of the test cases
j	Serial number of a sample point in a test case

the contaminated room air is displaced by supplying fresh air at the floor level, the indoor airflow is largely governed by thermal buoyancy and a stratified environment is typically formed [9]. When the room temperature is elevated, if the air movement is strengthened to improve the cooling effect on occupants, the buoyant plume around occupants would be disrupted by the enhanced horizontal flow, which is in conflict with the principle of displacement ventilation.

Further studies through experiment and simulation were conducted by Tian et al. to investigate the thermal comfort and indoor air quality under stratum ventilation [10,11]. The results indicated that stratum ventilation can provide satisfactory thermal comfort as well as good IAQ for occupants in an energy-efficient way. A range of contrastive analyses were also carried out by several researchers. Fong et al. found that stratum ventilation performs well in thermal comfort with significant higher thermal neutral temperature than that of mixing ventilation or displacement ventilation [12]. The energy consumptions under different ventilation systems were subsequently investigated by Lin et al. The results demonstrated that the annual energy saving of stratum ventilation were at least 25% and 44% against displacement ventilation and mixing ventilation, respectively [13,14]. The distributions of droplets coughed by occupants under different ventilation methods were examined. The droplets concentration in the breathing zone under stratum ventilation is significantly lower than that under displacement ventilation [15]. Cheng and Lin carried out an experimental study on the airflow characteristics of different ventilation methods in a multi-occupant room, and found that stratum ventilation could provide satisfactory thermal comfort for occupants at higher room temperature and lower energy consumption in comparison with mixing ventilation and displacement ventilation [16].

The indoor temperature distribution plays an important role in the performance of an air-conditioning system [17]. A proper ver-