Multi-nodal model for predicting vertical temperature profile in the stratum-ventilated large retail facility

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ABSTRACT

Stratum ventilation (SV) is an energy-efficient solution to provide thermal comfort and improve air quality. The air distribution in rooms with SV depends on the room layout, location of supply and exhaust grills and indoor heat gains. Therefore, the commonly used methods to predict air temperatures in the occupied zone do not usually fit the indoor temperature distribution. At the same time, detailed simulations of indoor air distribution are still mainly used in complicated room layouts and research. Thus, a simplified but accurate model is needed to calculate air temperatures in stratum-ventilated rooms. Previous studies primarily focused on modelling in low-ceiling rooms with ceiling exhaust. This paper presents the development of a multi-modal model for vertical air temperature prediction in the stratum ventilated high-ceiling room with high internal heat gains. The CFD model investigated the large retail facility's air movement and temperature profile. In the simulated cases, the effects of the exhaust location on vertical temperature distribution were studied in detail. The proposed model was validated against the CFD-model results. The presented multi-modal model demonstrates good agreement between the proposed multi-nodal model predictions and CFD results in the occupied zone temperatures. The proposed model can be applied for energy and pre-design calculations.

KEYWORDS

Stratum ventilation, air distribution, ventilation modelling, nodal model, CFD model.

1 INTRODUCTION

Building ventilation systems are responsible for indoor air quality and thermal comfort, and they consume a significant proportion of building energy consumption (Chenari et al., 2016).
Stratum ventilation (SV), an advanced air distribution strategy, aims for better air quality in a breathing zone and lower annual energy consumption (Melikov, 2016). Stratum ventilation supplies fresh cool air horizontally to the breathing zone and usually removes the air at the ceiling level. Therefore, SV is effective in spaces with high internal heat gains, such as lecture halls, theatres or retail shops with a high density of internal heat sources (Lin, 2017).
The vertical air temperature profile is a critical factor in SV performance regarding thermal comfort and energy consumption. Therefore, the conventional assumption of uniform room air temperature is inadequate for the performance evaluations of stratum ventilation. This section provides an overview of existing approaches to study and calculate the air distribution parameters with SV.

The physical models to calculate the vertical temperature gradient in ununiformed indoor environments include experimental studies, computational fluid dynamics (CFD) simulations, zonal models and lumped parameter (nodal) models (Yu et al., 2019).
Measuring the data related to indoor airflow and contaminant diffusion directly provides first-hand and reliable information, including air temperature, air velocity and contaminant concentration. Moreover, the measured data can also validate the mathematical models applied to similar situations (Yao and Lin, 2014). Generally, an environmental chamber can minimise the influence of the outdoor environment on the measured indoor parameters, but it could be expensive, and its physical size is limited. Furthermore, during the measuring process, the supply airflow rate, temperature and envelope temperature should remain steady, which is not an easy task due to the variation of the outdoor environment. In addition, the measuring points need to be up to specific numbers to get detailed information about the flow field and temperature distribution (Lin et al., 2011).
On the other hand, the airflow can be determined by computationally solving a set of conservation equations describing the flow and energy in a system. CFD simulation is the most precise technique to study indoor air distribution giving whole flow field airflow patterns, air velocity and temperature distributions. It is a microscopic three-dimensional approach, dividing the room volume into several control volumes. Due to the limitations of the experimental method and the increase in performance and affordability of high-speed computers, CFD models can produce room airflow case studies for the various ventilation strategies and complicated room configurations (Sun and Wang, 2010).
Zonal modelling is a two-dimensional course-grid CFD technique where the entire room space is divided into several subzones of the room space. Additional information about the room airflow patterns is usually needed to solve mass and energy conservation equations throughout these subzones. These models are typically applied in large volumes and ununiformed boundary conditions at the building envelope (Megri and Haghighat, 2007).
The lumped-parameter nodal models consider each building zone as a uniform volume characterised by consistent state variables. These models represent room air as the assembly of air nodes connected by airflow elements (Foucquier et al., 2013). These models are widely applied in engineering design and simplified building energy calculations. Since ventilation design focuses mainly on room temperature and air quality distributions, airflow transport is represented as a one-dimensional flow from inflow to outflow openings (Kato, 2018). Nodal models of stratum ventilation will be addressed in section 2.3.
The current study aims to analyse the airflow distribution in a stratum-ventilated room with measurements, CFD simulations and nodal models. The modified nodal model is proposed to calculate the vertical temperature gradients in rooms with stratum ventilation.

2 METHODS

This section describes the case study in the retail shop with SV and calculation methods to calculate the vertical temperature gradient. The structure and principle of the models and the parameters involved are discussed in the following subsections.

2.1 Case studies

This section represents the stratum ventilation case study in a Kuala Lumpur retail shop. Partly illustrated in Figure 1, a retail shop facility with a 345.95m^2 covered area and 2.74 m height is considered a case study building in this study. It comprises 30% of the ground floor of a 13-story virtual office building in Petaling Jaya, Kuala Lumpur, Malaysia. Based on the critical features of the building, the thermal parameters of the building envelope, heat gains, and internal loads are shown in Table 1.

The total sensible cooling load was 21.16 kW, and the latent cooling load was 3.28 kW for the retail shop building. The indoor space is set to 55% RH and 24°C. The outdoor design conditions were selected as 35 °C and 27.7 °C. The retail shop is operated for 10 hours from 10:00 am until 08:00 pm on weekdays.
The modelled stratum ventilation with a total airflow rate of 3.6 m^3/s consisted of the 5 exhaust grilles (538x538 mm) at the ceiling and 16 wall-mounted supply air diffusers (301x301 mm) at the walls at the height of 1.9m from the floor.

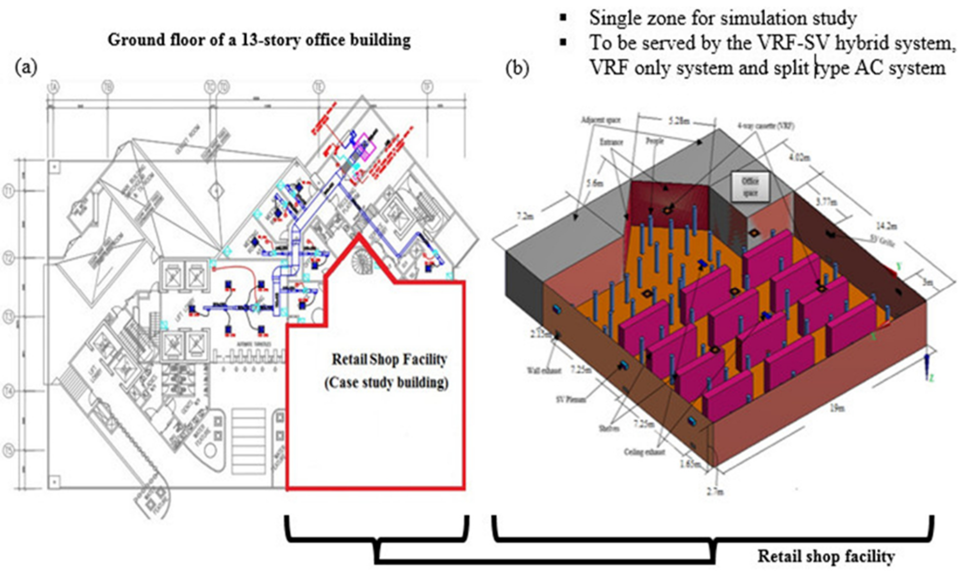

Figure 1: Overview of the ground floor of a virtual office building (left) and description of the simulation model geometry (right)

Table 1: Building structures and internal heat gains

Building structures			Internal heat gains		
Structure	**Area (m^2)**	**U-value (W/m^2K)**	**Item**	**Heat gains**	**Units**
Exterior wall-a	52.06	0.54	Lighting load	34	W/m^2
Exterior wall-b	38.90	0.54	Equipment load:	17	W/m^2
Exterior wall-c	19.73	0.54	Desktops	130	W
Exterior wall-d	49.86	0.54	Monitors	140	W
Roof	345.97	0.38	Laptops	165	W
Floor	345.97	2.89	Refrigerators	5740	W
Exterior windows	0.099	1.48	Occupancy (number)	56	persons
Glass doors	13.2	0.71	Occupancy (sensible heat gains)	73.2	W/person

2.2 CFD study

This study applied the turbulence k-ε (2-equation) model to predict the detailed indoor airflow distribution. The computational fluid dynamics (CFD) code, Ansys Fluent 20.1, was used to solve the governing equations using a segregated scheme numerically. The pressure and velocity were coupled and controlled by the SIMPLE algorithm. The governing equations have been discretised using a second-order upwind scheme for non-linear terms and a central scheme for viscous terms. RNG k-ε turbulence model was implemented for numerical simulations of the studied cases. The mesh sensitivity analyses were also carried out to obtain the results

independent of grid sizes. Yau and Rajput presented a detailed description of the CFD model in the previous studies (Yau et al., 2022; Yau and Rajput, 2022).
The numerical model has been extensively verified and validated for stratum ventilation in various environments (Lin et al., 2011; Yao and Lin, 2014; Liu et al., 2015). This study is further validated for the studied cases. Figure 2 demonstrates the numerical model's validity by comparing the results in terms of velocity and temperature at the selected locations.

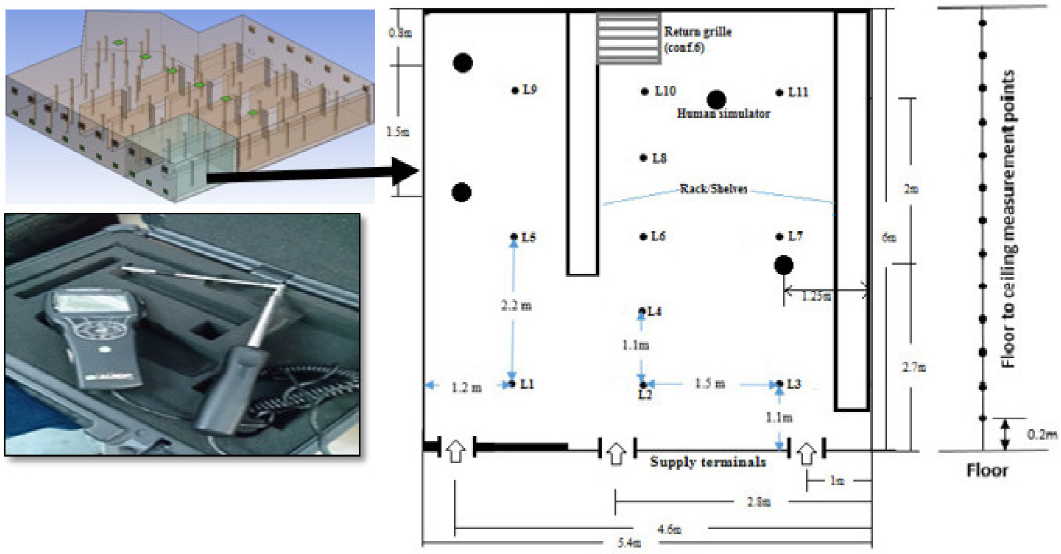

Figure 2: Simulation domain and measuring locations in the experimental facility

2.3 Nodal models

A typical characteristic of stratum ventilation air distribution is both vertical and horizontal temperature profiles distributed in the space (Cheng and Lin, 2015). The cooler air jects from the supply grilles spread into the occupied zone and gradually flows downward due to buoyancy. At the same time, the indoor heat gain sources cause upstream thermal plumes due to natural convection. Thus, in spaces with SV, the lowest temperature in the occupied and breathing zone (0.5m–1.7m) where the air stream passes is lower than in upper regions (Zhang et al., 2013). Therefore, for stratum ventilation, the air temperatures in the breathing and lower and upper zones are critical factors of the vertical temperature profile. These critical factors are addressed in simplified nodal models usually applied for coupling with building simulation software and predesign.
The nodal model for simulating vertically thermal stratified conditions, such as displacement and stratum air distribution, represents a set of heat balance equations for several vertical zones. The air nodes are connected using linearised approximation. As a result, the ratio of convective and radiant heat gains from internal heat sources is half to half (i.e., 50%convection and 50% radiation). Mass balance and airflow distribution in nodal models are considered with predefined empirical coefficients based on measurements, visualisation and CFD studies of airflow patterns or jet models. Thus, nodal models for stratum ventilation differ in the number of nodes and how the heat and mass balances are distributed between them.
The multi-node model for stratum and displacement ventilation proposed by Zhang et al. (Zhang et al., 2018) calculates air temperatures in three vertical zones using three constant coefficients of each zone determined by experiments and CFD simulations through multiple regression. On the other hand, Huan et al. (Huan et al., 2018) approach applied a jet model that calculates the vertical temperature gradient at different distances from the air supply and the effect of convection from a heated vertical surface. However, validated in the case with high

momentum flows only in the occupied zone, rather convective flows in upper room zones and low internal heat gains. At the same time, the cooling effectiveness of SV allows for using it in spaces with high cooling loads. It leads to higher inflow rates and, therefore – higher momentum forces. The following section describes the development of the modified modal model of SV.

2.4 Nodal models for stratum ventilation

The air distribution in a typical office environment with SV (Lin et al., 2011) is shown in Figure 3(a). Based on Huan's model, the sketch diagram of the auxiliary temperature nodes and energy balances is shown in Figure 3 (b). The initial airflow can be described as the fraction of supply air (F_{ln} m_s) that goes directly to the near-floor zone, and the remaining part (1- F_{ln})m_s goes towards the core zone of the room, where the core temperature is T_n. Then the fraction of the inflow that comes to the near-floor zone (F_{ln} m_s) circulates back to the core zone of the room. Then the combined air moves upward toward the exhaust grill at T_{ex}. With the help of the moderate convective flows from the heated sources (people, equipment, and lighting). In this case, the air in the upper zone moves instead by natural convective sources than by strong momentum flows. As a result, the vertical air temperature gradient is developed from the temperature near the floor that is cooled by the fraction of the supply air (80%).

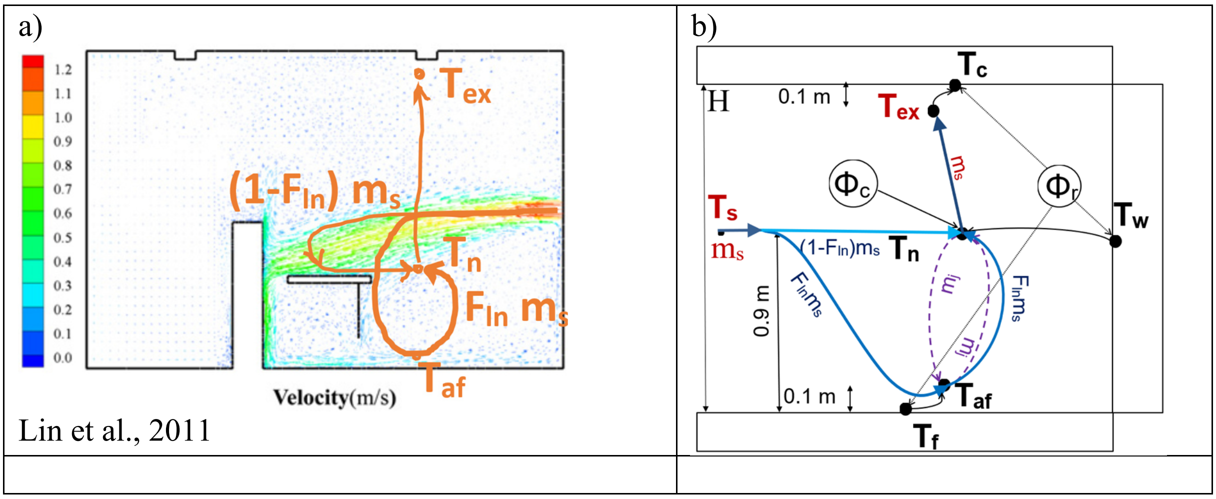

Figure 3: The air distribution in a typical office environment with SV (Lin et. al, 2011) (a) and Sketch diagram based on Huan's model (b)

In the modified Huan model, the initial airflow division is the same as in the reference model. As shown in Figure 4(a,b), the fraction (F_{ln} m_s) is going to the near-floor area and the remaining part (1- F_{ln})m_s towards the core zone of the room where the temperature is T_n. Then the fraction of the inflow air that comes to the near-floor zone (F_{ln} m_s) is lifted by the strong convective flows from the heat sources up to the ceiling exhaust level T_{ex}. Then this flow circulates to the core zone of the room at T_n.

In this air-distribution case, the temperature near the floor T_{af} is not cooled by the supply air. That is why it is estimated to be the same floor temperature. This case is characterised by high momentum flows (Ar = 4.103, 10 times lower than in Huan's measurements) and high internal heat gains. It causes intensive up flowed air towards the ceiling. Since the ceiling height is comparatively low (2.7 m), the flows return down to the core zone of the room. In this case, the temperature near the floor T_{af} is not cooled by the supply air due to the numerous obstacles and strong upward air flows that omit the zone near the floor. Therefore, the temperature T_{af} is estimated to be the same as the floor temperature T_f. In this case, the temperature gradient is developed from the core zone of the room. Since the room air is well-mixed, the air temperature can be estimated to be the same upper the floor zone (from 0.5m height) to the near-ceiling zone at the height (H-0.1) m.

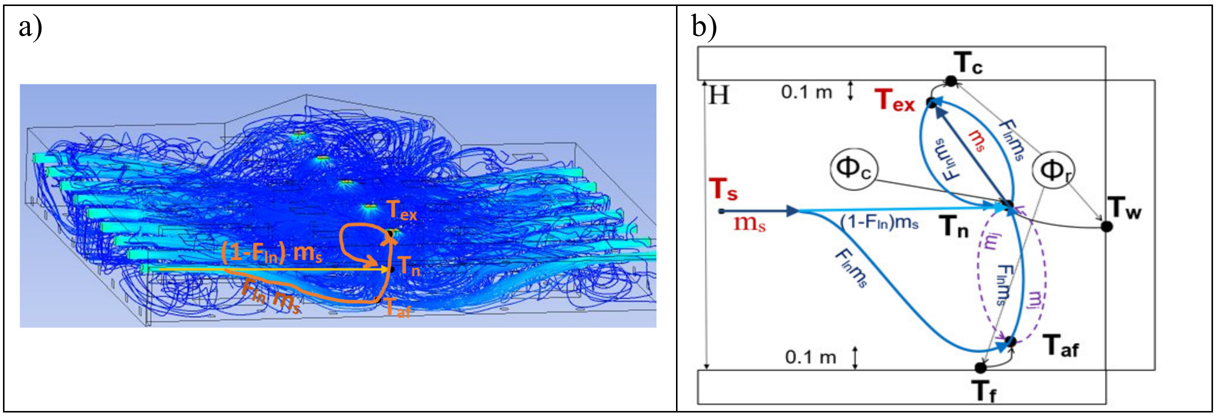

Figure 4: The air distribution in a case study in a retail shop (a) and Sketch diagram based on the modified Huan's model (b)

Table 2: Nomenclature

Nomenclature	
Φ_r	Radiative component of total heat gains (W)
Φ_c	Convective component of total heat gains (W)
A_t	The total area of the room surfaces (m^2)
A_f	Floor area (m^2)
A_w	Area of the walls (m^2)
A_c	Ceiling area (m^2)
T_{af}	Air temperature along the floor (°C)
T_n	Air temperature at the core zone of the room (°C)
T_{ex}	Exhaust air temperature (°C)
T_f	Area-weighted mean temperature of the floor surface (°C)
T_w	Area-weighted mean inner surface temperature of the walls (°C)
T_c	Area-weighted mean temperature of the ceiling surface (°C)
c_p	Specific heat capacity of indoor air (J/(kg K))
ρ	Air density (kg/m^3)
q_s	Supply airflow rate (m^3/s)
m_s	mass airflow rate (kg/s), $m_s = q_s \rho$
$\alpha_{c,f}$	Convective heat transfer coefficient of the floor ($W/(m^2K)$)
$\alpha_{c,w}$	Convective heat transfer coefficient of the walls ($W/(m^2K)$)
$\alpha_{c,c}$	Convective heat transfer coefficient of the ceiling ($W/(m^2K)$)
$\alpha_{r,f}$	Radiant heat transfer coefficient of the floor ($W/(m^2K)$)
$\alpha_{r,w}$	Radiant heat transfer coefficient of the walls ($W/(m^2K)$)
$\alpha_{r,c}$	Radiant heat transfer coefficient of the ceiling ($W/(m^2K)$)
m_j	Mass airflow rate of the recirculating air generated by the entrainment of the supply airflow (m^3/s) (Huan,)
F_{ln}	Fraction of the cooling energy from supply air that mixes into the near-floor zone (Huan)

The detailed descriptions of the energy equation established in this model to describe the energy transfer process are presented here.

The general convective heat balance for the room air can be expressed as:

$$\Phi_c = m_s\, c_p\, (T_{ex} - T_s) \tag{1}$$

The energy conservation near-floor zone (at the height of 0.1m from the floor) can be illustrated by Eq. (2):

$$A_f\, \alpha_{c,f}\, (T_f - T_{af}) + m_j\, c_p\, (T_n - T_{af}) + F_{ln}\, m_s\, c_p\, (T_s - T_n) = 0 \tag{2}$$

The energy balance at the core zone of the room (at the height of 0.9m) can be expressed as in Eq. (3):

$$A_w\, \alpha_{c,w}\, (T_w - T_n) + m_j\, c_p\, (T_{af} - T_n) + F_{ln}\, m_s\, c_p\, (T_{ex} - T_s) + m_s\, c_p\, (T_s - T_n) + \Phi_c \tag{3}$$

The energy conservation equation of the near–ceiling zone (at the height of 2.6m from the floor) can be expressed as:

$$\alpha_{c,c}\, A_c\, (T_c - T_{ex}) + m_s\, c_p\, (T_n - T_{ex}) + F_{ln}\, m_s\, c_p\, (T_n - T_{ex}) = 0 \tag{4}$$

The energy balance at the surfaces can be expressed by equations (5), (6), and (7).
The energy balance on the floor:

$$\alpha_{c,f}\, (T_f - T_n) + \alpha_{r,f}\, (T_f\, (F_{f-w} + F_{f-c}) - (F_{f-w}\, T_w + F_{f-c}\, T_c)) = \Phi_r / A_t \tag{5}$$

The energy balance at the walls:

$$\alpha_{c,w}\, (T_w - T_n) + \alpha_{r,w}\, (T_w\, (F_{w-f} + F_{w-c}) - (F_{w-f}\, T_f + F_{w-c}\, T_c)) = \Phi_r / A_t \tag{6}$$

The energy balance at the ceiling:

$$\alpha_{c,c}\, (T_c - T_{ex}) + \alpha_{r,c}\, (T_c\, (F_{c-f} + F_{c-w}) - (F_{c-f}\, T_f + F_{c-w}\, T_w)) = \Phi_r / A_t \tag{7}$$

3 RESULTS

3.1 Validation of the developed nodal model

The simulations and model calculation results were compared and analysed in this section. The model predicted results are compared with the simulation results obtained at the locations marked in Figure 5(a).

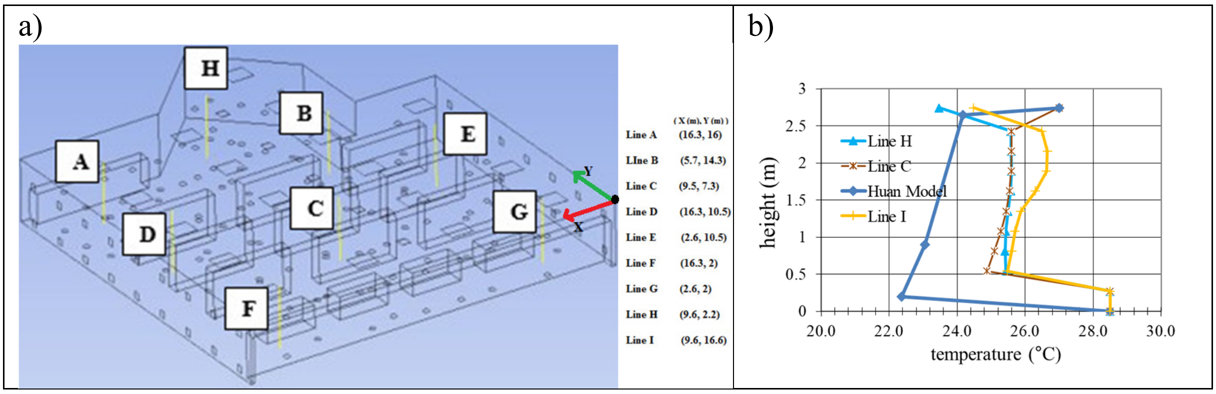

Figure 5: Simulations with measuring locations(a) and nodal modelling predicted vertical temperature profile(b)

One of the main applications of the developed model is to be coupled with an energy simulation tool to improve the accuracy of the energy calculation for buildings with stratum ventilation. Therefore, the mean temperature crossing a plane (horizontal section), which is relevant to energy consumption, was examined in this study. Figure 5 (a) compares the calculations and simulation predictions of the reference model (Huan's model). A significant difference can be observed, which indicates the model's inaccuracy in temperature profile prediction for large SV applications. A good match in the simulated and modified nodal model calculations is shown in Figures 6 (b) and (c).

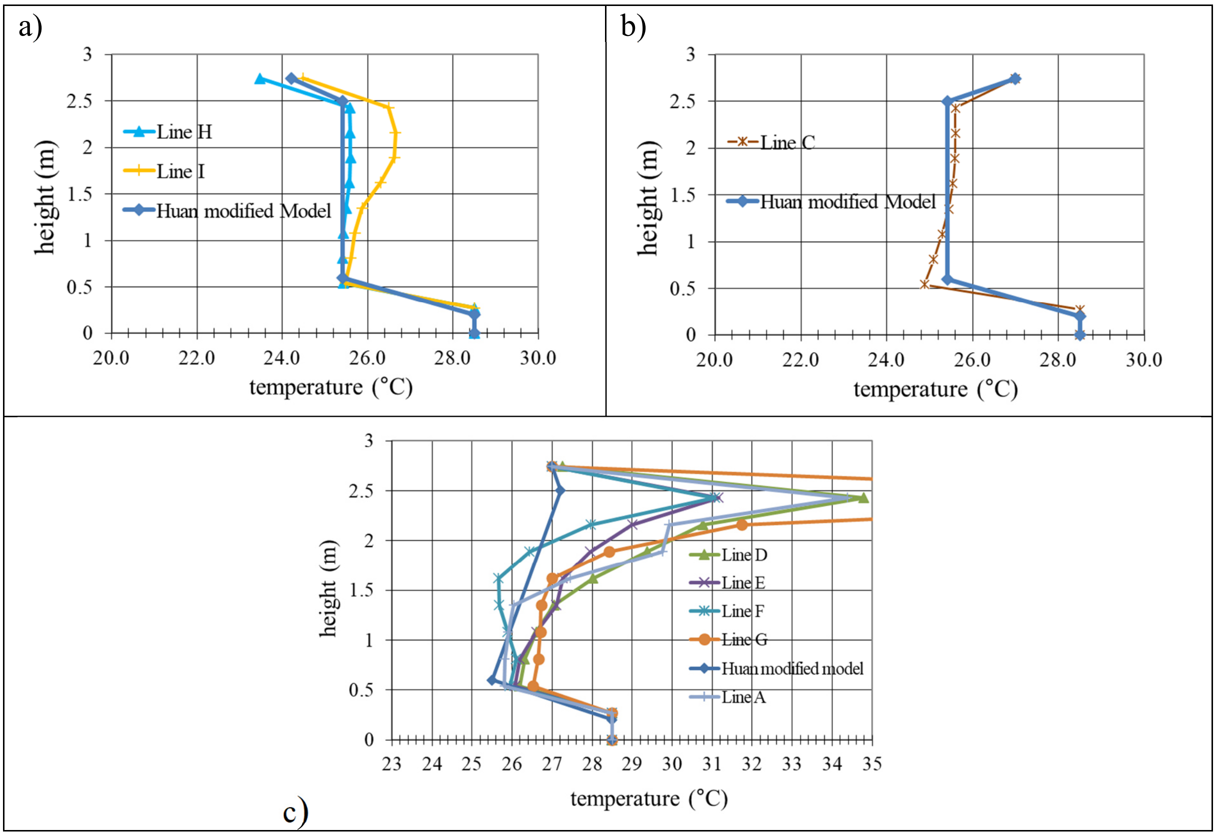

Figure 6: Simulated results comparison with reference model and modified model

4 DISCUSSIONS

The simplified nodal models do not contain the heat transfer calculation caused near local heat gain sources. In addition, nodal models are not universal in predicting the temperature gradient since they cannot count all the factors affecting indoor airflow. For example, when internal heat gains split into several highly asymmetric plumes, it may generate a stratification profile with several neutral levels. The simplified nodal model does not cover this complicated indoor temperature distribution. However, the temperature gradient in this zone is out of the occupied area. In many cases, these local heat gains do not significantly affect the occupied zone temperature.

The model is also inapplicable when internal heat gains are predominately radiative or placed out of the occupied zone. In that case, convective heat transfer in the room surfaces heated by the radiative gains can compete with the convective heat gains in the occupied area, creating a close to linear temperature gradient without an identifiable neutral level.

In practical applications, the room air temperatures are affected by the variation of heat gains in operation time and thermal mass effect, which are not considered in the steady–state models. Besides, most dynamic calculation methods assume complete mixing of zone air or linearised temperature gradient. Therefore, the dynamic analysis of temperature gradient development would benefit future studies in this direction.

5 CONCLUSIONS

Calculating indoor air temperatures in the occupied zone is essential in thermal comfort estimation, especially in high internal heat gains. In addition, indoor air temperature is a critical parameter for building energy calculations. The paper revised different approaches to studying air flows and vertical temperature distribution with stratum ventilation.

The nodal model was developed based on Huan's model (Huan et al., 2018) for the target building under ceiling exhaust configurations. The modified model can be applied in cases with high internal heat gains and airflow rates that cause higher momentum flows. The modified nodal model was validated in the retail shop case, which is characterised by high momentum flows throughout the room and high internal heat gains.

The nodal modelling results showed that more accurate predictions of the vertical temperature profiles were obtained through modified models compared to the reference model.

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