https://doi.org/10.1051/e3sconf/202235603045

Simulation study on indoor thermal environment improvement in multi-story buildings assisted by natural ventilation

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Abstract. Buoyancy-driven natural ventilation has the potential to improve the indoor thermal environment without any energy consumption. In this study, the applicability of the dimensionless area design method was studied, and the airflow rate and excess temperature deviation of rooms on different floors were verified. The results demonstrate that the airflow rates on the first, second and third floors are 887.68, 861.84 and 820.93 m^3/h, respectively, and the corresponding airflow rates per capita are 88.77, 86.18 and 82.09 m^3/h, respectively. In addition, the average indoor temperatures on the first, second and third floors are 298.78, 299.05 and 299.58 K, respectively, with corresponding excess temperatures of 5.72, 5.99 and 6.52 K. The deviation of airflow rate in the room is within the range of 0.59%-4.2%, indicating that the dimensionless area design method is suitable for designing naturally ventilated buildings.

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1 Introduction

Buildings account for approximately 40% of total energy consumption and 30% of all greenhouse gas emissions [1]. The carbon dioxide emissions of China's construction industry reached 221 million tons in 2018, accounting for 21.7% of the total emissions [2]. To maintain the indoor environment, the daily energy consumption of heating, ventilation, air conditioning, lighting, and other building operations accounts for the vast majority of the building use stage [3][4]. With the deterioration of the world's energy situation and climate environment, sustainable development and energy conservation have become the focus of worldwide attention. Natural ventilation is considered to be beneficial in providing fresh air and helping to meet the cooling load of the building, effectively reducing energy consumption [5].

Buoyancy-driven natural ventilation has received considerable attention due to its great potential for energy saving and improvement of indoor thermal environment [6,7,8]. Yang et al. found that when the heat source is placed at a lower position, the greater the airflow rate, the smaller the vertical temperature difference, resulting in better thermal comfort [9]. Linden et al. [10] mathematically derived that the thermal stratification height is independent of the heat source intensity, heat source location, and heat source area, and is only related to the effective ventilation area of the ventilated room. Kaye and Hunt [11] proposed that natural ventilation simulations driven by uniformly distributed heat sources are equivalent to those driven by multiple local heat sources. Andrew Acred, Gary R. Hunt [12] studied the airflow rate of each floor under buoyancy-driven natural ventilation. The study proposed a dimensionless design method for natural ventilation, under which the airflow rate of each floor of the building with dimensionless design can be kept consistent.

Based on the research of Andrew Acred and Gary R. Hunt, the dimensionless design method is used to design a buoyancy-driven natural ventilation building, and the applicability of the design method is verified in this paper. In addition, the indoor thermal environment is explored as well.

2 Methodology

2.1 Geometrical model

In order to simplify the calculation, the building in this paper is simplified to a two-dimensional model, and the uneven distribution of physical quantities such as airflow rate, temperature, and pressure in the width direction of each point in the flow field is ignored. It is considered that at the same height, each point on a line parallel to the width direction has the same physical quantity and the same unit width value. Heat transfer between atrium and floor is not considered, and solar radiation and internal radiation heat transfer are not considered, which means only convective heat transfer is performed.

The designed building is a three-story building, and the of each room is 10 m × 3 m (Depth × Height). The total height of the building is 9 m, and the height of the ventilation shafts is 12 m. The designed geometric model is shown in Fig. 1. In addition, the floor of the room is uniformly provided with heat sources, and it can be approximated that a surface heat source is provided at the bottom of the room [11]. To study the buoyancy-driven natural ventilation characteristics, air inlets are placed at the bottom of the room.

The inlet and outlet area plays a significant role in the airflow rate of the room. In this paper, different inlet and outlet areas are set for different floors by using the dimensionless area design method to achieve the purpose of approximating the airflow rate of each floor, and are given in Table 1. The airflow rate can be calculated as

$$Q = A^{*}(g'H)^{\frac{1}{2}} \tag{1}$$

Where g' is deceleration gravitational acceleration, m/s^2; H is the total height of the building, m.

The dimensionless per capita ventilation area can be calculated as

$$A = \frac{1}{E^{\frac{3}{2}}} \tag{2}$$

where E is ventilation shaft enhancement factor.

The dimensionless effective area can be evaluated as

$$A^{*} = n\lambda AH^{2} \tag{3}$$

where n is the number of people; λ is dimensionless ventilation performance index.

The inlet and outlet area can be calculated as

$$a = \frac{A^{*}}{C_d} \tag{4}$$

where C_d is vent hole flow coefficient.

According to Eq. 1, the airflow rate is only related to the room height. The dimensionless area design method overcomes the negative impact of uneven airflow by changing the effective ventilation area of different floors. Using dimensionless area design method, the inlet and outlet areas of the first floor, the second floor and the third floor are 0.262 m^2, 0.320 m^2 and 0.450 m^2, respectively.

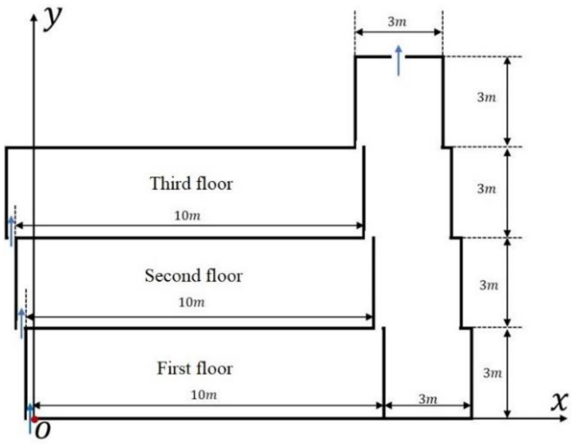

Fig. 1. Two-dimensional building model

2.2 Setup of simulation

In natural convection, common air models include the Boussinesq assumption and the incompressible ideal gas model. Both models consider only the effect of temperature on fluid density. Compared to the ideal incompressible model, the Boussinesq assumption is easier to converge, but has limited applicability and is mainly used for fluid densities that vary less than 20%. The incompressible ideal model is more applicable. Considering that the operation under variable heat sources may cause large temperature variations, the incompressible ideal model gas model is chosen in this paper.

$RNG\ K-\varepsilon$ model is adopted. This is because buoyancy is the main driving force in natural ventilation, and the influence of buoyancy must be considered in solving the model. The boundary condition settings of the model are shown in Table 1.

2.3 Boundary conditions

In this paper, a design condition of constant heat flux density is set up. Under the design conditions, there are 10 people on each floor with a per capita heat dissipation of 200 W, and the total heat per floor is 2000 W. Converting the heat source intensity into two-dimensional heat flux density is 50 W/m^2 per floor. The outdoor ambient temperature is 293.15 K, and the excess temperature ΔT is 7 K. The excess temperature is defined as the difference between the average air temperature in the room and the air temperature at the air inlet.

Table 1. Settings of the model

Number	project	Subitem	Setting
1	Inlet and outlet area	——	First floor: 0.262 m^2 Second floor: 0.320 m^2 Third floor: 0.450 m^2
2	Flow field material	——	Incompressible ideal gas
3	Solution method	——	Coupled
4	Boundary condition	External process	Constant temperature : 293.15K
		Room floor	Fixed non slip wall with constant heat flux
		Other wall surfaces	Adiabatic fixed non slip wall

3 Results and discussions

Fig. 2 shows that the temperature variation in most areas of the room does not exceed 0.25 K. This is due to the presence of uniform heat sources. In addition, the temperature variation in the working area ranges within 1.25 K. The most drastic temperature change is located at the air inlet, which is due to the large temperature difference between the inlet air and the heat source, resulting in entrainment phenomena.

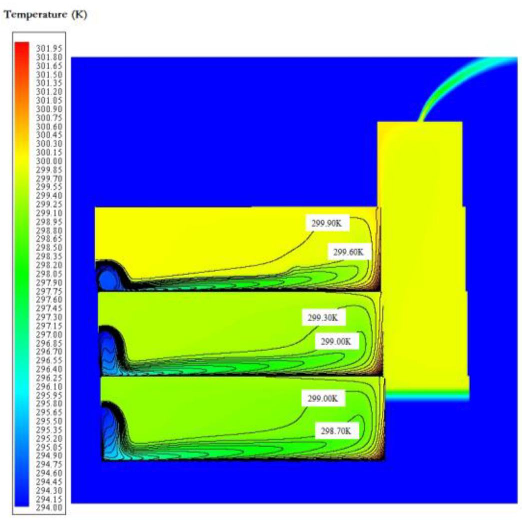

Fig. 2. Temperature nephogram of design condition

Fig. 3 shows the trend of temperature variation along the vertical height at different depths. According to the temperature trend, the room can be divided into three areas :

(1) Entrainment zone: The depth ranges from 0 m to 0.8 m. Due to the high wind speed and low air temperature at the air inlet, the air is strongly entrained and mixed, resulting in a large range of temperature drop in the vertical direction of the room.

(2) Mixed zone: The depth ranges from 0.8 m to 8.0 m. Since the air that has been entrained and mixed has not reached the heat balance, it will be further mixed along the depth of the room, and the temperature will drop at a certain height.

(3) Uniform zone: The depth ranges from 9.0 m to 10.0 m. The temperature decreases slowly in the vertical direction and tends to be stable. This is because the air has been fully mixed and the heat tends to balance, forming an air with a relatively uniform temperature. It can be seen that the uniform zone occupies the majority of the room.

It can be seen from Table 2 that the airflow rate of the three floors has reached 800 m^3/h. The average airflow rate is 856.82 m^3/h, and the airflow rate deviation of the room is within the range of 0.59%-4.2%. The average value of the excess temperature is 6.08 K, and the excess temperature deviation of the room is in the range of 1.5%-7.2%. The airflow rate of different floors is basically the same, which means that the dimensionless area design method is applicable to design naturally ventilated building.

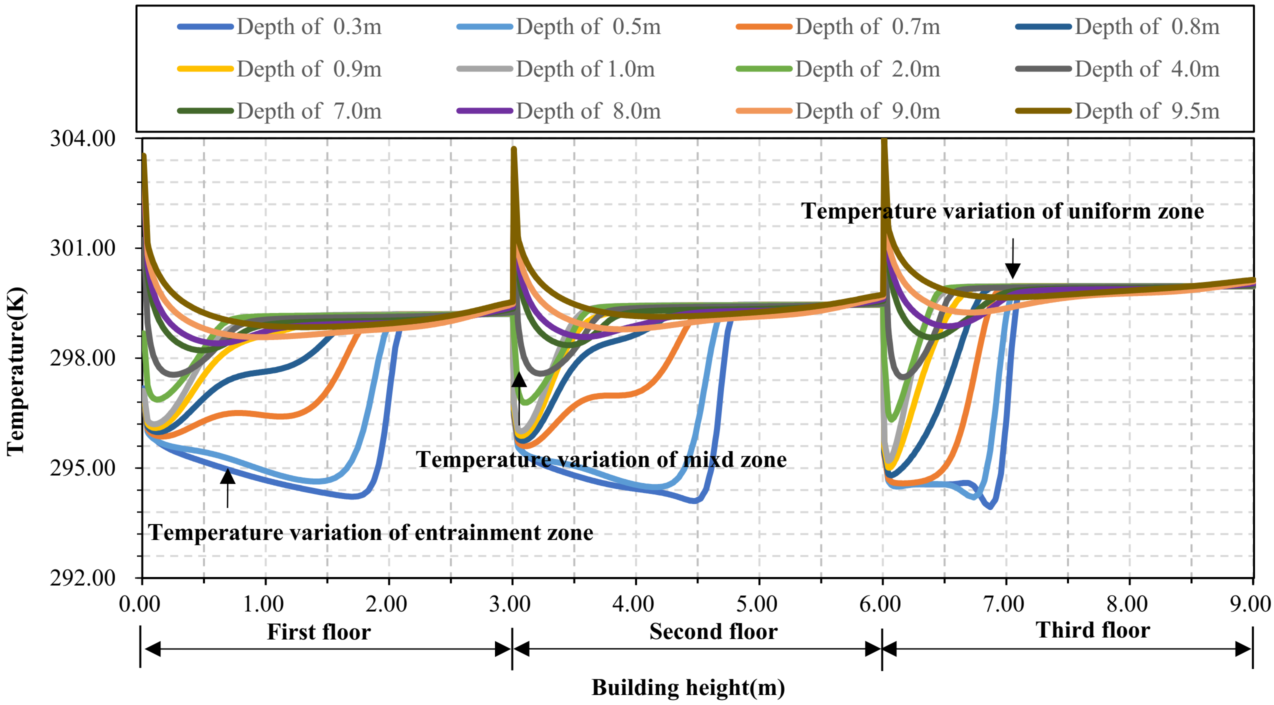

Fig. 3. Temperature variation of different depth along vertical height

Table 2. Indoor parameters of each floor

Floor	Airflow rate (m^3/h)	Average indoor temperature (K)	Excess temperature (K)
1	887.68	298.78	5.72
2	861.84	299.05	5.99
3	820.93	299.58	6.52

4 Conclusions

This study verifies the suitability of the building designed using the dimensionless area design method under design conditions, and uses computational fluid dynamics software to study the indoor thermal environment in the designed building, including airflow rate, indoor temperature variation, and excess temperature. The main conclusions are as follows:

(1) The building designed by the dimensionless area design method can meet the indoor fresh air requirements under the design conditions. The airflow rate of the first, second and third floors is 887.68, 861.84 and 820.93 m^3/h, respectively.

(2) The buoyancy-driven natural ventilation driven by buoyancy is beneficial to improve the indoor thermal environment. The average indoor temperatures on the first, second and third floors are 298.78, 299.05 and 299.58 K, respectively, with corresponding excess temperatures of 5.72, 5.99 and 6.52 K.

(3) According to the temperature distribution of the room, the room can be divided into three zones: the entrainment zone, the mixed zone and the uniform zone. The uniform area occupies most of the room, which means the room is in a comfortable and homogeneous thermal environment.

Acknowledgments

The authors acknowledge support from the National Natural Science Foundation of China (NSFC) under Grant No. 52078075 and 51708054.

References

1. E. Solgi, Z. Hamedani, R. Fernando, H. Skates, N.E. Orji, A literature review of night ventilation strategies in buildings, Energy and Buildings, **173**: 337-352 (2018)
2. Ma M, Ma X, Cai W. Low carbon roadmap of residential building sector in China: Historical mitigation and prospective peak[J]. Appl Energy, **273**:115-247 (2020)

3. Fan C, Sun Y, Shan K, Xiao F, Wang J. Discovering gradual patterns in building operations for improving building energy efficiency[J]. Applied Energy, **224**: 116–123 (2018)
4. Hacker JN, De Saulles TP, Minson AJ, Holmes MJ. Embodied and operational carbon dioxide emissions from housing: A case study on the effects of thermal mass and climate change[J]. Energy Building, **40**: 375–384 (2008)
5. Hawendi S, Gao S, Impact of an external boundary wall on indoor flow field and natural cross-ventilation in an isolated family house using numerical simulations [J]. Journal of Build Engineering, **10**: 109–123 (2017)
6. M. Prabhakar, M. Saffari, A. de Gracia, L.F. Cabeza, Improving the energy efficiency of passive PCM system using controlled natural ventilation, Energy and buildings, **228**: 110483 (2020)
7. M. Gil-Baez, Á. Barrios-Padura, M. Molina-Huelva, R. Chacartegui, Natural ventilation systems in 21st-century for near zero energy school buildings, Energy, **137**: 1186-1200 (2017)
8. Z. Gou, W. Gamage, S.S.-Y. Lau, S.S.-Y. Lau, An investigation of thermal comfort and adaptive behaviors in naturally ventilated residential buildings in tropical climates: A pilot study, Buildings, **8(1)**: 5 (2018)
9. X. Yang, K. Zhong, Y. Kang, T. Tao, Numerical investigation on the airflow characteristics and thermal comfort in buoyancy-driven natural ventilation rooms, Energy and Buildings, **109**: 255-266 (2015)
10. Linden P F, Laneserff G F, Smeed D A. Emptying filling boxes: the fluid mechanics of natural ventilation[J]. Journal of Fluid Mechanics, **212**: 309-335 (1990).
11. Kaye N B, Hunt G R. Heat source modelling and natural ventilation efficiency [J]. Building and Environment, **42(4)**:1624-1631 (2007).
12. Andrew Acred, Gary R. Hunt. Stack ventilation in multi-storey atrium buildings: A dimensionless design approach[J]. Building and Environment, **72**: 44-52 (2014).