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Yanping Xie, Yabin Wu, Zhi Zhao, Hui-hua Xiong

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# The numerical simulation of thermal environment of high-rise buildings based on Rosseland radiation model

Yanping Xie

Department of Architecture,
Hunan Urban Construction College,
Xiangtan 411101, China
Email: 147125532@qq.com

Yabin Wu*

Changsha Institute of Mining Research Co., Ltd.,
Changsha 410012, China
Email: wyb@cimr.com.cn
*Corresponding author

Zhi Zhao

College of Architectural Engineering,
Wenzhou Polytechnic,
Wenzhou 325035, China
Email: 1050371261@qq.com

Hui-hua Xiong

School of Architecture and Urban Planning,
Hunan City University,
Yiyang 413000, China
Email: 248134266@qq.com

**Abstract:** Aiming at the problem of thermal environment numerical simulation of buildings, this paper proposes a new research method of thermal environment numerical simulation of high-rise buildings based on Rosseland radiation model. First of all, analyse the wind flow characteristics of the thermal environment around the building to obtain the total heat value. Secondly, the energy conservation law equation, momentum conservation law equation and mass conservation law control equation of hot gas fluid flow are constructed. Finally, Rosseland radiation model is introduced to obtain heat flux and output the numerical simulation results of thermal environment. The results of performance comparison show that the proposed simulation method can get accurate thermal environment simulation results without being affected by seasonal temperature changes.

**Keywords:** Rosseland radiation model; high rise building; thermal environment; numerical simulation.

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**Biographical notes:** Yanping Xie received his Master's in Architectural Design and Theory from Hu Nan University in 2015. Currently, he is a Lecturer at the Hunan Urban Construction College. The main research direction is the architectural design and its theory.

Yabin Wu received his Doctor's in Safety Science and Engineering from Central South University in 2022. Currently, he is a Professor at Changsha Institute of Mining Research Co., Ltd. His research interests include hydrodynamics theory and the method of numerical simulation

Zhi Zhao received his Master's in Architectural Design and Theory from Hu Nan University in 2010. Currently, he is a Lecturer at the Wenzhou Polytechnic. His research interests include architectural design and urban design.

Hui-hua Xiong received his Master's in Architecture and Civil Engineering from Hu Nan University in 2015. Currently, he is a Senior Engineer at the Hu Nan City University. His research interests include architectural design and urban design.

## 1 Introduction

People's work, study and life are inseparable from architecture (Wang et al., 2021), so people put forward higher requirements for building comfort and air quality (Yang et al., 2021a). Building thermal environment is the basis for creating comfortable environment. The thermal environment is the performance of the thermal field in the building space environment, but it is not only affected by temperature, but also related to the degree of air pollution, building density, water body, vegetation and other factors (Chang et al., 2021; Ekici et al., 2021; Cheng et al., 2021). A good building thermal environment is an important symbol of ecological human settlements. It is of great significance to master the spatial distribution of various influencing factors of the building environment for promoting sustainable development.

Yang et al. (2021b) proposed a research method for numerical simulation of thermal environment of high-rise buildings based on UAV thermal infrared. This method uses UAV equipped thermal infrared imager to collect the temperature and data of building surface, and uses ENVI-met and PALM-4U models to simulate the temperature of building surface. According to the type and characteristics of building surface, the numerical simulation results of thermal environment are obtained. However, this method can only be used to simulate the thermal environment in summer. In cold winter, the acquisition results of the infrared imager will be biased, leading to the deviation of the thermal environment numerical simulation results. In Su et al. (2022), a CFD-based numerical simulation research method for building thermal environment was proposed, and the building temperature field data were collected. The RNG k-ε calculation model was constructed by using the basic governing equation and the turbulence hierarchy model, and the temperature and pressure gradient was calculated to complete the simulation study. However, this study only considers the influence of one factor on the temperature field, resulting in insufficient simulation accuracy. Ou et al. (2020) proposed a thermal environment simulation method based on the radiation heat transfer model, input the thermal environment temperature value into the radiation heat transfer model, and display the thermal environment numerical results of the building through CFD software. The calculation of this method is easy to be affected by seasonal temperature changes. When the temperature changes greatly, large numerical simulation errors will occur.

Aiming at the problem of insufficient accuracy of existing simulation methods, the Rosseland radiation model is proposed to simulate the thermal environment of buildings. The implementation scheme is as follows:

1. Extract the thermal air flow characteristics of the thermal environment, and calculate the total heat of the thermal environment on the building surface in combination with the comprehensive value of heat transfer per unit area and temperature radiation.
2. Based on the calculated total heat data, combined with the heat transfer principle of the thermal environment, the relevant control equations of hot gas fluid flow are constructed. Under the constraint of thermal environment temperature slip boundary, Rosseland radiation model is used to calculate the heat flux and output the final simulation results.
3. The accuracy of thermal environment simulation of high-rise buildings in winter and summer is verified by experiments.

## 2 Thermal environment data

With the increase of population, people's housing demand continues to rise. In order to meet the needs of the population and save land area, high-rise buildings are gradually popularised with the support of modern building technology (Oliveira and Vasconcelos, 2021). However, because the general floors of high-rise buildings are more than 17 floors, in hot or cold environments, the changes in the building's temperature environment make it difficult for people to adapt, because the building air flow will roll at a certain height and transmit the air flow to the ground. The schematic diagram of air flow change is shown in Figure 1.

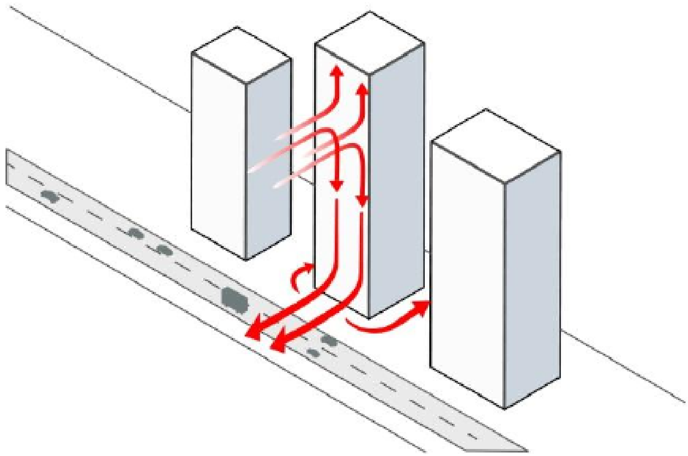
With the goal of obtaining accurate thermal environment numerical simulation results, the thermal environment data of the building is collected. The specific process is as follows:

The calculation formula of heat transfer per unit area of building surface is:

$$q = \alpha_{out}\left[\left(t_w + \frac{q_s + q_r}{\alpha_{out}} - \frac{q_e}{\alpha_{out}}\right) - t_{wb}\right] \tag{1}$$

In the formula, $t_w$ represents outdoor temperature, $t_{wb}$ represents fence temperature, $\alpha_{out}$ represents the heat transfer coefficient of the fence, $q_r$ represents the ground reflection heat value, $q_e$ represents the atmospheric radiation heat, and $q_s$ represents the solar radiation heat (Wells and Spewak, 2019).

**Figure 1** Characteristics of hot air flow in high-rise buildings (see online version for colours)



The disturbance factors of building thermal environment are relatively complex. In order to simplify the simulation process, the outdoor temperature radiation comprehensive action value is directly used to replace the outdoor air temperature, which can also comprehensively reflect the building thermal environment data. The calculation formula for the comprehensive results of outdoor temperature radiation is:

$$t_z = t_a + \frac{q_s + q_r}{\alpha_{out}} - \frac{q_e}{\alpha_{out}} \tag{2}$$

Solar radiation will produce temperature effect on the external surface, and the external surface will absorb solar radiation energy (Tan and Moinuddin, 2019). This part of energy can be regarded as the added value of outdoor temperature of high-rise buildings. Therefore, the calculation result of temperature radiation can be expressed by the following formula:

$$t_z = t_a + \frac{q_s + q_r}{\alpha_{out}} \tag{3}$$

In the process of thermal environment simulation, the calculation of indoor heat source does not consider artificial lighting and human body heat, but only focuses on outdoor convective heat transfer and radiant heat.

The calculation formula of unit heat transfer of surface heat source of high-rise building is:

$$q_c = \alpha_c (t_b - t_n) \tag{4}$$

In the formula, $\alpha_c$ represents the convection heat transfer coefficient, $t_b$ represents heat source temperature, $t_n$ represents indoor temperature (Bak and Yoon, 2021).

The calculation formula of unit radiation of surface heat source of high-rise building heat source is:

$$q_r = C\left[\left(\frac{T_b}{100}\right)^4 - \left(\frac{T_n}{100}\right)^4\right] \tag{5}$$

In the formula, C represents the thermal radiation coefficient, $T_b$ and $T_n$ denote heat source temperature and ambient temperature respectively.

Air volume of building gaps and doors and windows:

$$L = a\Delta p^{b} l \tag{6}$$

In the formula, l represents the length of the gap or door and window, a represents the air tightness parameter of the door and window, and $\Delta p^b$ represents the indoor and outdoor thermal pressure difference (Fathi and Kavoosi, 2021).

Air volume of vent:

$$G = A^{\frac{2}{3}}\left[2B_0\left(H - Z_s\right)\right]^{\frac{1}{3}} \tag{7}$$

In the formula, A is the ventilation area, $B_0$ is the buoyancy, $Z_s$ is the thermal stratification height, and H is the vertical height of the vent.

The calculation formula of total heat can be expressed as:

$$Q = c_\rho \rho G_w\left(t_n - t_{out}\right) n \tag{8}$$

In formula (8), $c_\rho$ is the specific heat capacity of external ambient air, ρ is the air density, $G_w$ is the air quality, and n is the air change rate.

## 3 Simulation research based on Rosseland radiation model

The thermal environment is easy to be affected by the underlying surface (building surface, pavement, vegetation and water body), so the underlying surface and the surrounding air together form a thermal environment system when conducting thermal environment simulation research. The whole thermal environment system includes three processes: convection, radiation and heat conduction (Saroglou et al., 2019; Sun et al., 2019). The schematic diagram of heat exchange process in the thermal environment of high-rise buildings is shown in Figure 2.

The flow of hot gas fluid shall conform to the law of conservation of energy, constant momentum and the law of conservation of mass. The simulation equation of hot gas flow in high-rise buildings shall be constructed according to the three laws:

The mass conservation equation is:

$$\frac{\partial\left(\rho u_i\right)}{\partial t} + \frac{\partial\left(\rho u_i u_j\right)}{\partial x_j} = 0 \tag{9}$$

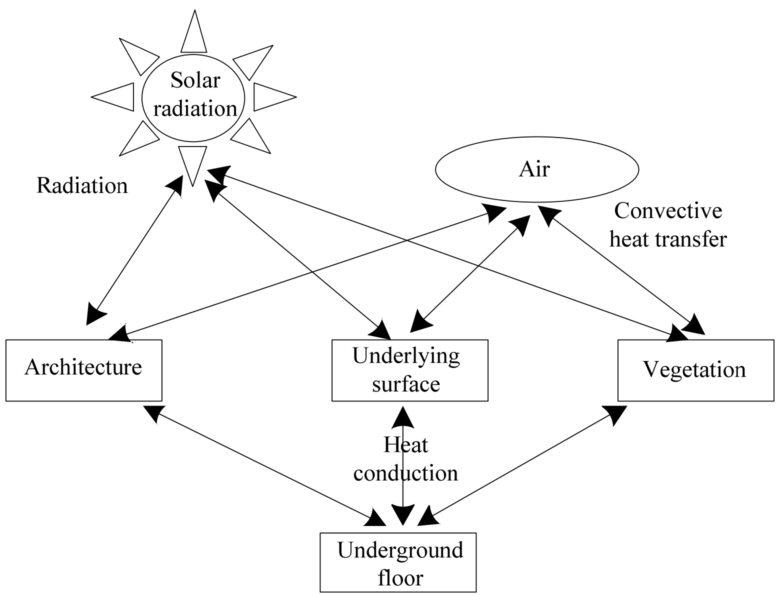
In the formula, $u_i$ and $u_j$ represent internal energy and external energy respectively, and $x_j$ represents the direction of hot gas fluid.

The momentum conservation equation is:

$$\frac{\partial\left(\rho u_i\right)}{\partial t} + \frac{\partial\left(\rho u_i u_j\right)}{\partial x_j} = \frac{\partial}{\partial x_j}\left\{\mu \frac{\partial u_i}{\partial x_j}\right\} - \frac{\partial p}{\partial x_3} - \beta\left(T - T_{ref}\right) g + S_{u_3} \tag{10}$$

In the formula, T represents temperature, $\beta$ represents extinction coefficient, $T_{ref}$ represents buoyancy reference temperature, g represents buoyancy parameter and $S_{u_3}$ represents momentum parameter.

**Figure 2** Schematic diagram of heat exchange process in thermal environment




The energy conservation equation is:

$$\frac{\partial(\rho T)}{\partial t}+\frac{\partial(\rho u_i T)}{\partial x_i}=\frac{\partial}{\partial x}\left(\frac{k}{c_v}\frac{\partial T}{\partial x}\right)-\frac{\partial}{\partial y}\left(\frac{k}{c_v}\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(\frac{k}{c_v}\frac{\partial T}{\partial z}\right)+S_T \tag{11}$$

where $c_v$ is constant pressure ratio, k is the thermal conductivity coefficient, x, y, z represent the direction, and $S_T$ represents the temperature coefficient.

Unify the above equations to get the expression shown in formula (12):

$$\frac{\partial(\rho\phi)}{\partial t}+\operatorname{div}(pu\phi)=\operatorname{div}(\Gamma\operatorname{grad}\phi)+S \tag{12}$$

Build the radiation heat transport equation, introduce the radiation diffusion coefficient, and build the radiation flux expression:

$$q_\sigma=-\int_{-\infty}^{\infty}\frac{4}{3\beta-AK_s}\nabla e_{bv}dv \tag{13}$$

In the formula, $K_s$ represents the radiation intensity and $\nabla e_{bv}$ represents the radiation energy.

In the equation shown in formula (13), Rosseland radiation model is introduced to combine the transfer term with the radiation term. Rosseland radiation model can directly calculate the radiation heat flux through the heat transfer coefficient, without considering the transportation of radiation intensity. It has the advantages of fast calculation speed and more memory saving, and can meet the requirements of this radiation heat flux calculation. A new calculation expression of radiant heat flux is constructed as follows:

$$q = q_\sigma + q_c = -\left(k + k_r\right)\nabla T \tag{14}$$

In the formula, $k_r$ represents the total radiation transfer coefficient, and its calculation formula is:

$$k_r = \frac{16\sigma n^2 T^3}{3\beta} \tag{15}$$

According to the above calculation results, the thermal environment heat flux calculation formula of high-rise buildings is constructed with the thermal environment temperature slip boundary as the constraint condition:

$$q_{r,w} = \frac{-\vartheta\left(T_w^4 - T_g^4\right)}{\Psi} \tag{16}$$

In the formula, $\Psi$ represents the slip coefficient, $T_w$ represents the wall temperature, and $T_g$ represents the surface gas temperature.

According to the calculation results of heat flux, the characteristics of the whole thermal environment can be clarified, and the simulation of the thermal environment can be completed.

## 4 Experimental verification

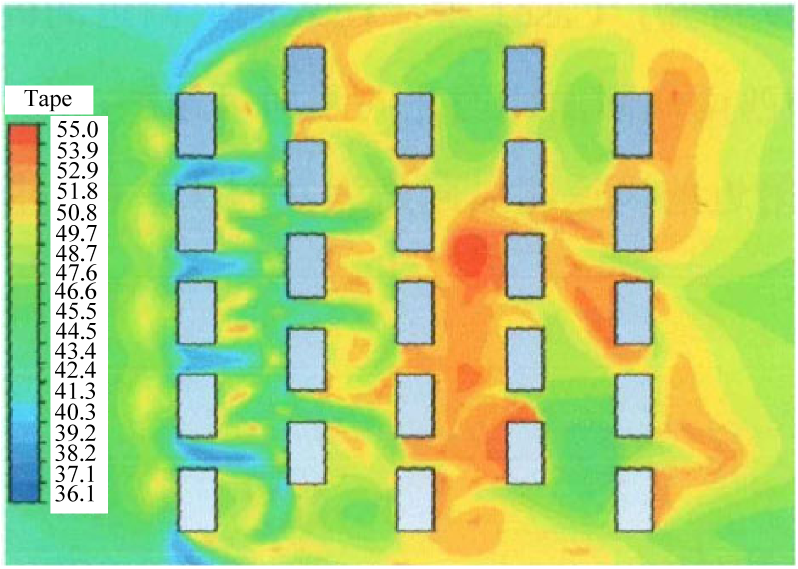
In order to verify the practical application effect of the proposed numerical simulation method for thermal environment of high-rise buildings based on Rosseland radiation model, comparative verification experiments are carried out.

### *4.1 Experimental data collection*

This study takes high-rise buildings in a community in this city as the research object. The community covers an area of 35,000 square metres. There are 25 buildings in the community, of which the maximum building height is 100 m and the total floor is 33 m. Therefore, the high-rise buildings in this community can meet the requirements of this thermal environment numerical simulation. The thermal environment diagram is as shown in Figure 3.

Collect the thermal environment data of the community as the sample data of this experiment. The data acquisition equipment consists of thermocouple, input terminal box, temperature patrol detector and PC. The thermal environment temperature value is collected by the T thermocouple on the building surface, and then the collected data is transmitted to the input terminal box. After signal conversion, it is transmitted to the PROCOS-VII digital temperature itinerant detector. After analogue-digital conversion in the instrument, the temperature signal is transmitted to the PC, which will store and display the data.

**Figure 3** Thermal environment simulation (see online version for colours)




## *4.2 Experimental scheme*

In order to obtain accurate experimental results and improve the universality of experimental results, the experimental scheme is set as follows: take the accuracy of thermal environment data collection, the accuracy of thermal environment numerical simulation, and the time consumption of thermal environment numerical simulation as the experimental comparison indicators, and compare and verify the methods in this paper with those in Yang et al. (2021b) and Su et al. (2022).

Thermal environment data acquisition accuracy: thermal environment data acquisition accuracy refers to the degree of consistency between the thermal environment data acquisition results of different methods and the actual thermal environment data. The higher the thermal environment data acquisition accuracy, the stronger the performance of the method is.

Thermal environment numerical simulation accuracy: thermal environment numerical simulation accuracy refers to the similarity between the thermal environment simulation results of different methods and the real thermal environment. The higher the numerical simulation accuracy, the stronger the simulation performance of the method is.

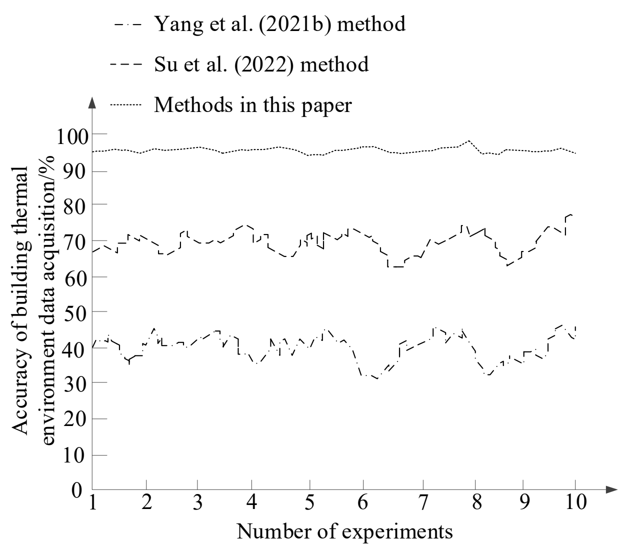
Time consuming of thermal environment numerical simulation: the time consuming of thermal environment numerical simulation refers to the time consuming of different methods to complete the thermal environment numerical simulation of high-rise buildings. The shorter the time consuming, the higher the simulation efficiency of the method is.

## *4.3 Experimental result*

### *4.3.1 Thermal environment data acquisition accuracy*

Thermal environment data is the key to the thermal environment simulation of high-rise buildings. If the thermal environment data of high-rise buildings cannot be accurately collected, the accuracy of numerical simulation will be seriously reduced. Therefore, it is necessary to compare and analyse the accuracy of thermal environment data collection of different methods. Taking the thermal environment data acquisition accuracy as the test index, the method in this paper is compared with the methods in Yang et al. (2021b) and Su et al. (2022). The comparison results of thermal environment data acquisition accuracy of high-rise buildings using the three methods are shown in Figure 4.

**Figure 4** Thermal environment data acquisition accuracy of high-rise buildings




It can be seen from the comparison results of the thermal environment data acquisition accuracy of high-rise buildings shown in Figure 4 that the thermal environment data acquisition accuracy of this method is significantly higher than that of Yang et al. (2021b) and Su et al. (2022) under multiple acquisition experiments. The highest data acquisition accuracy of this method reaches 99%, and can always maintain more than 95% of the data acquisition accuracy. Although the thermal environment data acquisition accuracy of the Su et al. (2022) method is higher than that of the Yang et al. (2021b) method, the highest data acquisition accuracy of the Su et al. (2022) method is only 80%. The thermal environment data acquisition accuracy of the method in Yang et al. (2021b) is the lowest among the three methods, and the highest data acquisition accuracy of the method in Yang et al. (2021b) is only about 50%. Therefore, this method can accurately collect the thermal environment data of high-rise buildings.

### 4.3.2 Winter thermal environment

The comparison results of numerical simulation accuracy of winter thermal environment by different methods are shown in Table 1.

**Table 1** Winter thermal environment

| *Number of experiments* | *Numerical simulation accuracy of thermal environment of motor/%* | | |
|---|---|---|---|
| | *Research method* | *Yang et al. (2021b)* | *Su et al. (2022)* |
| 1 | 90.20 | 80.12 | 77.56 |
| 2 | 96.23 | 80.50 | 78.56 |
| 3 | 94.20 | 82.20 | 79.85 |
| 4 | 99.25 | 86.52 | 77.52 |
| 5 | 97.12 | 81.25 | 78.36 |
| 6 | 92.34 | 80.45 | 79.11 |
| 7 | 99.63 | 85.62 | 77.52 |
| 8 | 93.25 | 84.26 | 71.25 |
| 9 | 91.25 | 86.26 | 70.15 |
| 10 | 93.25 | 85.21 | 72.30 |

From the comparison results of numerical simulation accuracy of winter thermal environment shown in Table 1, it can be seen that the simulation accuracy of this method is always higher than that of the two literature comparison methods in many simulation processes, and the maximum accuracy of numerical simulation of winter thermal environment of this method is 99.63%. Among the three methods, the numerical simulation accuracy of thermal environment in winter of the method in Su et al. (2022) is the lowest, and the lowest value is only 70.15%. Although the accuracy of numerical simulation of winter thermal environment of the method in Yang et al. (2021b) is slightly higher than that of the method in, it is still lower than that of the method in this paper, and the accuracy of numerical simulation of winter thermal environment of the method in Yang et al. (2021b) is up to 86.52%. The above experimental results show that this method can accurately simulate the thermal environment of high-rise buildings in winter.

### 4.3.3 Numerical simulation accuracy of thermal environment in summer

In the hot summer environment, test the thermal environment numerical simulation performance of the research method, Yang et al. (2021b) and Su et al. (2022). The comparison results of numerical simulation accuracy of the three methods for summer thermal environment are shown in Figure 5.

It can be seen from the comparison results of thermal environment numerical simulation accuracy shown in Figure 5 that the thermal environment numerical simulation accuracy of this method is much higher than that of the two literature comparison systems, and the simulation accuracy of this method always remains above 90%. However, the maximum simulation accuracy of the Yang et al.'s (2021b) method is less than 50%. Although the simulation accuracy of the Su et al.'s (2022) method is higher than that of the Yang et al.'s (2021b) method, the maximum value is still less than 90%. Therefore, the text method can accurately simulate the thermal environment of high-rise buildings.

**Figure 5** Thermal environment in summer (see online version for colours)

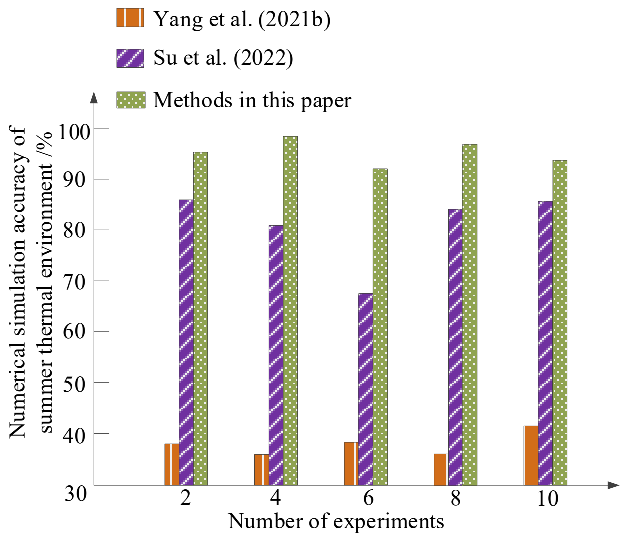
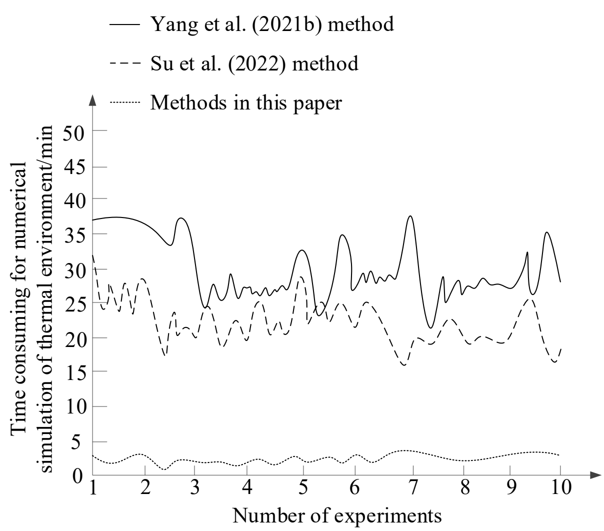



**Figure 6** Time consuming for numerical simulation of building thermal environment by different methods




### *4.3.4 Time consuming for numerical simulation of thermal environment of high-rise buildings*

Because the thermal environment data of high-rise buildings are abundant and need to be simulated for different seasons, the numerical simulation method of thermal environment of elevation buildings is required to have high efficiency. Taking the time consumption of numerical simulation of thermal environment of high-rise buildings as the test index, the method in this paper is also compared with the methods in Yang et al. (2021b) and Su et al. (2022). The time consuming comparison results of the three methods for numerical simulation of thermal environment of high-rise buildings are shown in Figure 6.

It can be seen from the time consuming results of the numerical simulation study of the building thermal environment shown in Figure 6 that, under multiple comparative experiments, the maximum time consuming for the numerical simulation study of the thermal environment in this method is not more than 5 min, while the maximum time consuming for the numerical simulation of the thermal environment in Yang et al. (2021b) and Su et al. (2022) is more than 30 min. Therefore, the proposed method can shorten the time consumption of building thermal environment numerical simulation and improve the efficiency of thermal environment numerical simulation.

## 5 Conclusions

In order to accurately simulate the thermal environment of buildings, a numerical simulation research method of thermal environment based on Rosseland radiation model is proposed. In the process of thermal environment simulation, this method has high simulation reliability in winter and summer. Specifically, compared with the method based on UAV thermal infrared, the simulation accuracy of winter thermal environment of the method studied reached 99.63%; for the CFD-based method, the simulation accuracy of the summer thermal environment of the studied method is always above 90%.

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