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Building Energy Consumption Prediction Model for Edge Effects in the Case of High-Rise Buildings

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ABSTRACT

Under the background of carbon neutrality, the energy-saving design of high-rise buildings has received widespread attention. And the differences in energy consumption in various parts of high-rise buildings have become an obstacle to energy-saving design. The edge effects is one of the main causes of the differences in energy consumption. The existing research lacks accurate quantitative assessment of edge effects, making it is difficult to guide the energy-saving design of high-rise buildings. Therefore, a modeling method for studying the distribution of building energy consumption is proposed, the edge effects energy consumption prediction model of building space is established by parametric technology, and CFD and energy simulation technology are used to carry out experiments. We conduct in-depth discussions on the influence areas of edge effects on different heights of plate and tower high-rise buildings, as well as the impact intensity of edge effects on energy consumption. In addition, an optimization strategy to reduce the impact of edge effects on the energy consumption of high-rise buildings is proposed.

Keywords: high-rise buildings, edge effects, computational fluid dynamics, energy simulation

NONMENCLATURE

Abbreviations	
CHTC	Convective Heat Transfer Coefficient
CFD	Computational Fluid Dynamics

1. INTRODUCTION

In recent years, carbon emissions have had a serious impact on the ecological environment. The construction industry is emitting more carbon emissions, accounting for around 40% of global carbon emissions[1]. Among the various building types, high-rise buildings have attracted widespread attention due to their high energy consumption and significant differences in energy consumption among rooms[2]. Therefore, it is of great significance for the construction industry to achieve the goal of carbon neutrality by balancing the energy consumption differences of various parts of high-rise buildings through refined energy-saving design, and reducing the total energy consumption of high-rise buildings[3].

Building energy consumption is subject to a variety of environmental factors[4], and changes in wind speed are one of the main reasons for the differences in energy consumption in various parts of high-rise buildings[5]. As the height increases, the wind speed of the façade generally increases in gradient, but the wind speed increases significantly on the windward side near the top and side of the building, which has been confirmed in many studies[6][7]. This phenomenon is known as the edge effects, and in the field of construction engineering, the edge effects refers to the separation of airflow at the edge of the building near the top of the building and the edges on both sides, forming a significant high-speed flow area[8], and the wind pressure will decrease. The sharp increase in wind speed caused by the edge effects will significantly change the CHTC of the envelope[9] and the air penetration of the room[10], which in turn affects the energy consumption of the building. A large number of

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studies have found that due to changes in wind speed, parts of high-rise buildings vary greatly[11], and the convective heat transfer coefficients near the edge of the building show a significant increasing trend[12]. Researchers at Western University found through experiments that the CHTC in the top corner area of the building is 24% higher than the average CHTC[13]. In view of the difference in energy consumption of high-rise buildings, scholars have carried out relevant research. Meseret T et al. developed a new CHTC model to evaluate building energy consumption in different locations, multi-objective optimization experiments based on the experimental results were carried out to obtain the optimal window size for rooms in different locations[14]. Girma T et al. compared the CHTC values of different heights and positions of buildings with or without facade components, and the results showed that the lateral edge positions of buildings showed higher CHTC values with or without facade components[15]. According to previous research, improving the overall thermal performance of high-rise building envelope structures is not economical and has a low cost-effectiveness. The energy-saving design trend of high-rise buildings is to further refine the design of buildings. To sum up, although predecessors have a certain understanding and research on the impact of edge effects on buildings, the current research lacks a clear quantitative assessment of the impact of edge effects on building energy consumption, and there is no universal strategy and method developed to guide building design.

On the basis of previous research, this paper hopes to establish the energy consumption prediction model of edge effects combined with parameterization technology, to quantitatively evaluate the degree of edge effects on building energy consumption. We explore the impact rules of edge effects on high-rise building energy consumption, and summarize universal rules to guide the energy-saving and refine design of high-rise buildings.

2. METHODOLOGY AND CASE STUDIES

2.1 Project profile

The engineering training center on the campus of Shenyang Jianzhu University is selected as the experimental object (Fig. 1), and the project is located in Shenyang, Liaoning Province, north China. The construction area is about 29,500m^2, the building has 12 floors, and the height is about 56m.

Fig. 1 Real photo of engineering training center

2.2 The influence of edge effects on facial wind speed

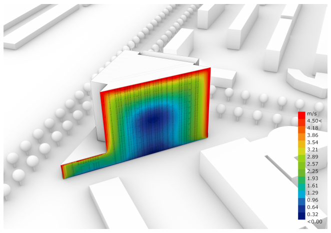
2.2.1 Geometric model building and parameter se tting

Based on the Rhino+Grasshopper platform, we establish a geometric model and use OpenFoam for wind environment simulation. A calculated wind field with the size of 20H × 10H × 6H is established, grids are divided according to the wind field, and the grids are encrypted near the buildings. The k-ε turbulence model is selected to solve the problem, the ground roughness is 0.25, and the inflow wind speed is respectively set to 2.73m/s and 2.97m/s in summer and winter.

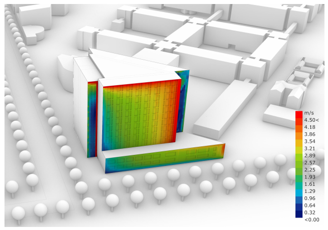
2.2.2 Facade wind speed simulation results

Under the dominant wind direction in winter, the wind speed on the windward side of the north side of the building increases with height. It can be observed in Fig. 2a that the wind speed near the top and side edge of the building presents an obvious increasing trend, which is much higher than the average wind speed, and an obvious high wind speed area is formed along the edge of the building. The closer the location is to the edge of the building, the more drastic the wind speed changes.

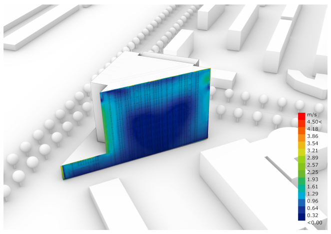
In the dominant summer wind direction, due to the small projection angle of the wind direction on the south windward side, the wind speed on the south windward side increases diagonally. Near the top and east edge, the wind speed showed an obvious increasing trend (Fig. 2b). The wind speed distribution on the leeward side in winter and summer shows no obvious regularities. The wind speed near the edge shows an increasing trend due to pressure changes, but this trend is not severe compared with that on the windward side (Fig 2cd).



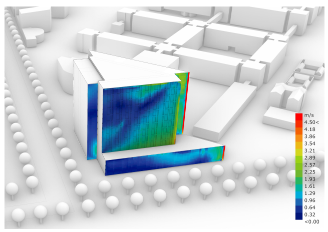
a.North windward side in winter



b.South windward side in summer



c.North leeward side in summer



d.South leeward side in winter

Fig. 2 Visualization of facade wind speed

This uneven distribution and change trend of wind speed is bound to cause differences in convective heat transfer and air penetration of the envelope structure in various parts of the building, and then affect the distribution of energy consumption in various parts of the building.

2.3 The influence of edge effects on energy consumption

2.3.1 Establishment of energy consumption information model

In order to further verify the influence of edge effects on energy consumption, based on the established geometric information model, the internal function room is delineated and the door and window openings are built. Honeybee is used to assign thermal parameters to the envelope structures at different levels (Table 1).

Building envelope level		**Insulation materials**	**K-value/[W/(m2 • K)]**	**R-value/[(m2 • K)/W]**
Opaque envelope	*External wall*	*rock wool board*	*0.37*	*2.55*
	Roof	*XPS*	*0.35*	*2.71*
	Floor	*XPS*	*0.34*	*2.79*
	Ground	*XPS*	*0.44*	*2.11*
Transparent envelope	*Curtain wall*	*Low-E*	*2.2*	*0.31*
	Windows	*-*	*2.2*	*0.31*
	Skylight	*Low-E*	*2.2*	*0.31*

Table. 1 Thermal parameters of envelope structure

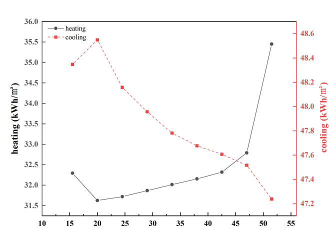
Then, technical indicators of operational Energy consumption are assigned to each type of room, and Energy Plus is invoked to start the simulation experiment.

2.3.2 Energy simulation results

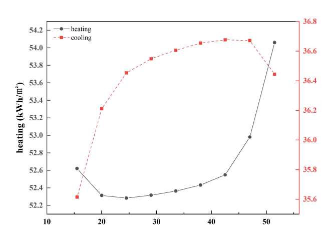
The contact area between the first floor and the top floor of the building and the outdoor environment is larger than that of the standard floor, and the energy consumption is also much higher than that of other floors. In addition, the enclosure structure of the podium building on the ground floor of the case building is different from that of the standard floor. Therefore, this experiment only focuses on the energy consumption of the standard floors 3-11, and divides the building into two parts: south and north for discussion.

For the rooms on the north side of the building, as the height increases, the heating energy consumption shows a trend of first decreasing and then increasing.At the height of 44m, the heating energy consumption increases suddenly due to the influence of edge effects. The cooling energy consumption shows a trend of first increasing and then decreasing, and at a height of 44m, the cooling energy consumption suddenly decreases due to the influence of edge effects.In winter, the north side is the main windward side, and the edge effects has a more significant impact on heating energy consumption (Fig. 3a).

For the rooms on the south side of the building, the trend of heating energy consumption with height is the same as that on the north side. At the height of 44m, the heating energy consumption increases suddenly due to the influence of edge effects. The cooling energy consumption shows a trend of first increasing and then decreasing, and at a height of 44m, the cooling energy consumption suddenly decreases due to the influence of edge effects. The influence of edge effects on heating and cooling energy consumption is about the same (Fig 3b).



a.South room



b.North room

Fig. 3 Case building energy consumption

It can be clearly observed from the energy consumption curve that the energy consumption near the top edge of the building changes more sharply than other locations. This is consistent with the distribution and trend of wind speed on the facade, proving that edge effects can have a significant impact on building energy consumption.

2.4 Modeling method based on space division of hi gh-rise buildings

This paper proposes a modeling method suitable for studying the distribution of energy consumption in vertical direction. Firstly, the space of high-rise buildings is simplified into two types: functional space and traffic space. Secondly, according to the different space types, a basic space unit is established respectively. The basic units of the same type have the same basic geometric size, thermal performance of the envelope structure and operational energy consumption technical indicators such as equipment and lighting. Finally, a series of basic space units are combined into a complete building. The method proposed in this paper can effectively avoid the interference caused by the difference of room area and function, and facilitate the observation of the influence of edge effects on the distribution of building energy consumption.

3. ENERGY SIMULATION EXPERIMENT OF TYPICAL HIGH-RISE BUILDING

3.1 Typical high-rise building model

The basic types of high-rise buildings are mainly divided into two types: tower and plate. Using the method proposed above, the basic space units are established according to different space types, and the building plan and function are simplified. In order to more clearly observe the influence of edge effects on energy consumption on the facade, the geometric size of the basic space unit is appropriately reduced, so that there are more units on the same facade, and the simulation results have higher accuracy.

The geometric size of the basic space unit of the plate high-rise and the tower high-rise is uniformly set to 4m ×6m ×4m, the window opening rate of each unit is 0.35, and the window size is 2.8m ×2m. In order to study the influence regulate of edge effects on high-rise buildings of different heights, the basic units are combined into 32m, 56m, 80m, 96m tower high-rise and plate high-rise, and ensure that the building area of each floor of plate and tower high-rise is the same.

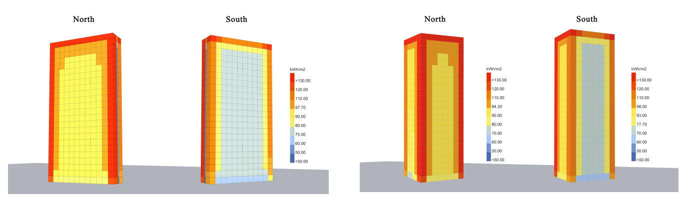
3.2 Parameter setting and energy simulation experi ment

The heat transfer coefficient of the wall of the basic unit is set to 0.3W/(m^2 • K), and the heat transfer coefficient of the glass is set to 2.2W/(m^2 • K). The lighting power density of the plate and tower basic units is set to 8W/m^2, the equipment power density is set to 10W/m, and the permeability is set to 0.0003m^3/s. The background meteorological conditions of the energy simulation experiment are selected in Shenyang, North China. The energy simulation experiment is carried out after parameter setting.

4. RESULTS AND ANALYSIS

4.1 Results

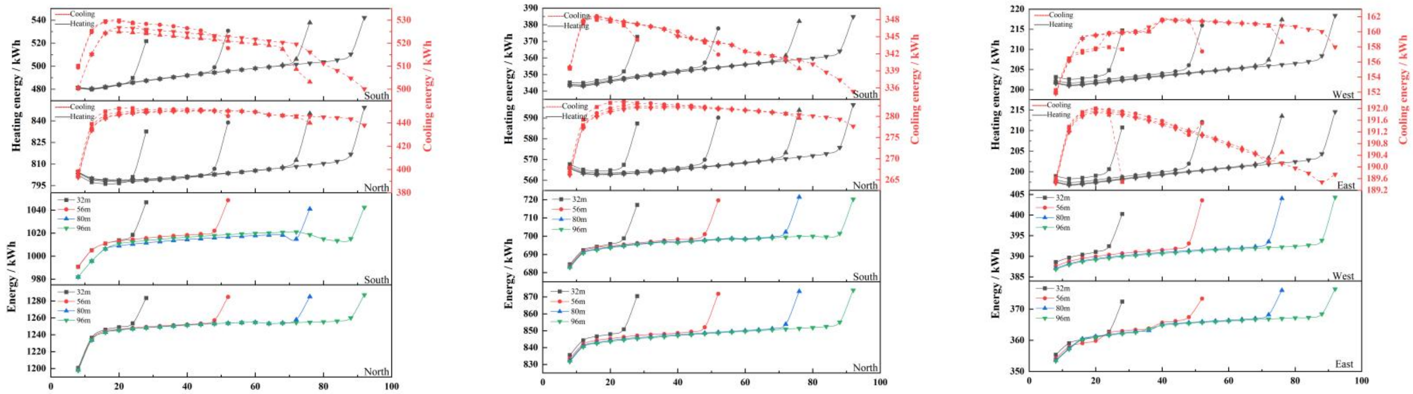
Visualizing energy consumption data using Ladybug Tools related components is shown in Fig 4 (taking 96m plate and tower high floors as examples). As can be seen from the figure, the energy consumption level of the rooms near the top and the side edge of the building is significantly higher than that of the rooms in other positions, and this regulate is shown in the plate and tower high-rise buildings of different heights, which is consistent with the experimental results based on actual cases mentioned above. The area affected by the edge effects is always in the top three floors and the two rows of rooms near the side.



*a.*plate high-rise *b.*tower high-rise

Fig. 4 Visualization of energy consumption information

Fig. 5 shows the energy consumption of plate and tower high-rise buildings of different heights.And the overall trend of all energy consumption curves is basically the same, showing an overall upward trend. Near the top of the building, each curve shows a significant increase in energy consumption. The change of energy consumption in the bottom area of the plate high-rise is more drastic than that in the tower high-rise. The curve of the east and west side of the tower is relatively gentle, and the energy consumption increases significant only near the top.



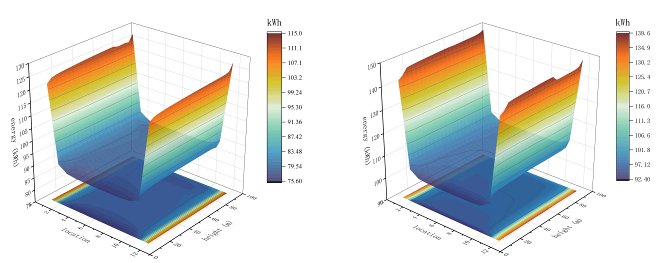
*a.*plate high-rise *b.*tower high-rise north and south side *c.*tower high-rise east-west side

Fig. 5 Floor by floor energy consumption results

4.2 Analysis of the influence area of edge effects

Affected by the edge effects, the energy consumption curves of the plate and tower high-rise buildings in different orientations in Fig. 5 show an inflection point at 12m from the top edge,and there is no significant change in the area affected by the edge effects as the height increases.

In order to explore the influence area of the edge effects on the building, a 96m plate high-rise is taken as an example, and the distribution of building energy consumption is expressed by using three-dimensional curved graph. As shown in Fig. 6, the energy consumption not only increases gradually with the change of height, but also changes more significant with the change of position, showing a trend of gradual increase from the central region to the edges of both sides, and begins to increase sharply near the edges of both sides. The overall energy consumption shows a gradient rising trend, but in the inverted U-shaped area enclosed by 8m of the side edge 12m away from the top edge, the energy consumption increases sharply under the influence of the edge effects, and the closer to the edge, the more significant the change in energy consumption. There is no significant change in the area affected by the edge effects for buildings of different heights.



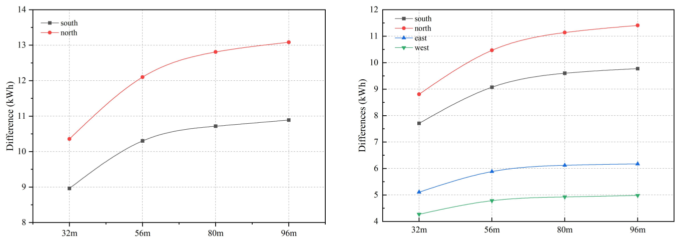
a.South room *b.North room*

Fig. 6 Plate high-rise building energy consumption per room on the façade

4.3 Edge effects intensity analysis

This paper proposes the concept of edge effects intensity, which is used to characterize the impact of edge effects on building energy consumption. The calculation method is the difference between the average energy consumption of the room affected by edge effects and the overall average energy consumption. The edge effects intensity of plate and tower high-rise shows an overall rising trend, and the increasing trend is gradual with the increase of height. In the 100m range, the average energy consumption of the room affected by the edge effects is 7.516kWh higher than the overall average energy consumption, and the average energy consumption of the room affected by the edge effects is 11.1526kWh higher than the overall average energy consumption in the tower high-rise.

As shown in Fig.7, with regard to plate high rise building, the edge effects intensity of the room on the north side is larger than that of the room on the south side on the whole, and the trend of the room on the south and north side is the same. The change trend is more significant in the height range of 0-56m, and the growth tends to be gentle after 80m. For the tower high-rise , the intensity of the edge effects on the south and north side is significantly greater than that on the east and west side, and the intensity is ordered from the top to the bottom as North side > South side > East side > West side, and the intensity change trend on the south and north side is significantly larger than that on the east and west side. In the height range of 0-56m, the strength growth trend of the four facades of the tower high-rise is relatively sharp. After 68m, the strength growth of the east and west side rooms begins to flatten out, while the strength growth of the south and north side rooms tends to flatten out after 80m.



*a.*plate high-rise *b.*tower high-rise

Fig. 7 Edge effects intensity

From the perspective of a single facade, the plate high-rise is greatly affected by the edge effects, and from the perspective of the whole building, the tower high-rise is more significantly affected by the edge effects.

5. DISCUSSION

5.1 Discussion

Through energy simulation, we have summarized the regulate of the influence of edge effects on energy consumption, and it is necessary to further explore the influence mechanism of edge effects and energy consumption. In summer, the edge effects increases the wind speed, takes away more heat in the room, reduces cooling energy consumption,and has a positive impact on building energy efficiency. In winter, the edge effects increases wind speed, increases heating energy consumption, and has a negative impact on building energy efficiency. The background meteorological conditions of the experiment in this paper are located in Shenyang, a severely cold area. The influence of edge effects on heating energy consumption is much greater than that of cooling energy consumption, so the edge effects will significantly increase the total energy consumption. The influence of edge effects in different climate zones reflects certain differences in the performance of total energy consumption. For cold and cold regions, the influence of winter edge effects on heating energy consumption should be mainly considered and reduced. Other climate zones can use edge effects to cool buildings and reduce energy consumption.

5.2 Edge effects optimization strategy

Based on the above quantitative analysis, this paper proposes an optimization strategy to reduce the influence of edge effects on building energy consumption: in the influence range of edge effects, the thermal performance of the envelope should be improved, especially the thermal performance of the window. And strictly control the window to wall ratio to improve the overall air tightness of the room, thereby reducing the impact of edge effects on building energy consumption.Appropriately increase the height of the top floor room and the height of the parapet, or set structures on the top and side edges of the building to reduce the area of the building facade affected by the edge effects, reduce the impact of edge effects on the building itself.

The optimization strategy for the edge effects can significantly reduce the overall energy consumption level of the building with relatively low cost, and balance the energy consumption level of each part of the high-rise building, which has certain significance for the energy-saving research of the high-rise building.

5.3 Limitations and development

The limitation of this paper is that the discussion of the influence regulate of edge effects on energy consumption is an ideal model based on the basic form of typical high-rise buildings, and the building function and plane are simplified, which may be different from the actual situation. This simplified method has no effect on the discussion of the influence regulate of edge effects on energy consumption. The results of this paper can be used as a quantitative application reference in engineering applications, but it needs to be comprehensively considered in the context of the actual situation in engineering. In future research, more detailed modeling and simulation experiments can further improve the experimental results, and the combined application with image recognition, deep learning and other fields has a very broad development prospect.

6. CONCLUSIONS

Taking a high-rise building in northern China as an example, this paper uses CFD simulation and energy simulation to verify the influence of edge effects on energy consumption. This paper proposes a modeling method suitable for studying the energy consumption distribution regulate of high-rise buildings, establishes an energy consumption prediction model for the edge effects, and discusses the influence regulate of edge effects on energy consumption based on typical high-rise buildings of different heights. The experimental results show that the average building area affected by edge effects accounts for about 54%, but its energy consumption accounts for 59.3%, which has a more significant impact on building energy consumption.

Secondly, through the analysis of the experimental results, the influence area of edge effects on high-rise buildings is basically fixed within 100m height. Within 12m from the top edge and 8m from the side edge, buildings are affected by edge effects, and energy consumption increases significantly, and the intensity of edge effects increases with the increase of building height.

Finally, this paper proposes the corresponding optimization strategy for the edge effects, which can provide a certain reference for the low-carbon and energy-saving design and renovation of high-rise buildings.

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DECLARATION OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

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