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Study on the Influence of Non-Uniform Surface Temperature on the Wind-Thermal Environment of the Building Complex#

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ABSTRACT

The non-uniform distribution of building surface temperatures caused by building shading significantly affects the airflow structure within the building complex. However, previous numerical studies have mostly ignored the non-uniform distribution of building surface temperatures, instead using uniformly heated surfaces as an equivalent substitution. This approach compromises the accuracy of wind-thermal environment predictions within the building complex. Therefore, this study focused on a 4x4 dot-formed building complex and employed numerical simulation methods to explore the impact of the uniform surface assumption on the airflow structure within the complex. The airflow structure and the recirculation ratio rate were used as quantitative indicators in this analysis. The results indicated that the assumption of uniform surface introduced errors in predicting the risk of thermal accumulation within the building complex, and the errors increased with the increase of temperature difference. When the temperature difference was 10K, assuming a non-uniform surface as a uniform surface caused a change in the vortex structure of the airflow, leading to an error in predicting the airflow direction and overestimating the recirculation ratio by 23.74%. The research results emphasized the significance of considering the non-uniform surface temperatures caused by building shading for accurately predicting the wind-thermal environment of the building complex and further reducing energy consumption.

Keywords: micro-climate, non-uniform surface temperature, the effect of building shading, wind-thermal coupling

1. INTRODUCTION

With the continuous expansion of urban construction, high-density building complexes have become the predominant trend in urbanization. This shift has led to a gradual deterioration of the local thermal environment in cities, exacerbating the energy and environmental crisis. The quality of the outdoor environment of a building complex directly impacts the load on the building envelope, which is crucial for the design of the complex [1], building energy demand [2], and the implementation of passive technologies [3].

In the outdoor environment of the building complex, solar radiation serves as the primary heat source for the building envelope structure, directly determining the surface temperature of the buildings and influencing the ventilation performance within the complex [4]. Effective ventilation can significantly reduce thermal accumulation in the building complex, encourage outdoor activities, and extend the duration of outdoor stays. This in turn reduces building load, energy consumption, and carbon emissions. However, previous studies have primarily concentrated on individual buildings, frequently neglecting the impact of surrounding buildings on the target building. In the high-density building complex, the dense arrangement of buildings causes shading effects, leading to a non-uniform distribution of surface irradiance and a decrease in the sky view factor [5]. As a result, this leads to a non-uniform distribution of surface temperatures within the building complex.

The ventilation driving forces within a building complex can be classified into three types: wind pressure domination, with thermal pressure being negligible; a combination of wind and thermal pressure dominance; and domination by thermal pressure. When thermal pressure dominates, the surface temperature of the building directly influences the airflow distribution within the building complex [6]. Furthermore, the non-uniform distribution of surface temperature significantly impacts the structure of the thermal plume and the magnitude of buoyancy [7]. As the intensity of solar

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radiation increases, the temperature difference between shaded and directly exposed surfaces also increases, exacerbating the impact of surface non-uniformity on the ventilation performance of the building complex. However, previous numerical studies have mostly ignored the non-uniform distribution of building surface temperature, and only used uniformly heated surfaces for equivalent substitution [7]. In recent years, researchers have begun to pay attention to the non-uniform distribution of building surface temperature caused by the shading effect of buildings, which affects the velocity and temperature distribution within the building complex [9]. Chen et al. [10] explored the differences in airflow characteristics caused by real solar radiation boundary conditions and uniform surface temperature boundary conditions in an ideal building complex. The findings revealed significant errors in predicting the airflow vortex structure within the complex when using uniform surface temperature at low wind speeds (Ri=1.21), while errors at higher wind speeds (Ri=0.19) were relatively minor. Therefore, under conditions dominated by buoyancy, it is worth conducting further research to investigate the effectiveness of using uniform wall temperature as an equivalent substitute for non-uniform surface temperature induced by solar radiation on the ventilation effect of building complexes.

Addressing the identified research gaps, this study examined the impact of assuming a uniform surface on the wind-thermal environment of a dot-formed building complex through numerical simulation methods. And utilized airflow structure and ventilation flow rate as quantitative indicators to assess differences between two boundary conditions. This study provides substantial support for improving the ventilation performance of the building complex, reducing building energy consumption, and constructing efficient "urban breathing" systems.

2. METHODS

2.1 Mathematical model

The RNG k-ε model, a prevalent two-equation turbulence model, is widely utilized and validated across various engineering applications [11]. Due to the turbulent characteristics within the building complex, the RNG k-ε model equation was selected. The governing equations primarily encompass the continuity equation, momentum equation, and energy equation, which can be represented in the following general form:

$$\frac{\partial(\rho\varphi)}{\partial t} + \mathrm{div}\,(\rho\vec{U}\varphi) = \mathrm{div}\left(\Gamma_\varphi \mathrm{grad}\ \varphi\right) + S \qquad (1)$$

Where φ represents velocity, turbulent kinetic energy, turbulent dissipation rate, and temperature.

2.2 Assessment indicators for ventilation performance

In a building complex, not all heat can be dissipated by incoming wind. The vortices formed within the building complex may suck up external air, causing high-temperature airflow to re-enter the complex and resulting in poor ventilation in localized areas. Therefore, this study used the recirculation ratio at the top openings to indicate the impact of the uniform surface assumption on the ventilation performance of the building complex. Fig. 1 illustrates the schematic diagram of the street opening flow rate calculation. The blue surface represents the top opening area, and the gray surface represents the model of the building complex. The flow rate through the street opening is defined as:

$$q = \int_A \vec{V}\cdot\vec{n}dA \qquad (2)$$

The total inlet flow q_{ref} is used to normalize the flow as follows:

$$q^* = \frac{q}{q_{ref}} = \frac{\int_A \vec{V}\cdot\vec{n}dA}{\int_A \vec{u}_{ref}\cdot\vec{n}dA} \qquad (3)$$

Where $\vec{V}$ is the velocity vector, $\vec{u}_{ref}$ is the upstream flow velocity, m/s; $\vec{n}$ is the normal direction of the street opening, and A is the area of openings in the building complex, m^2. For the top area of the building complex, when the calculated flow rate is "-", it represents outflow, and when the calculated flow rate is "+", it represents recirculation.

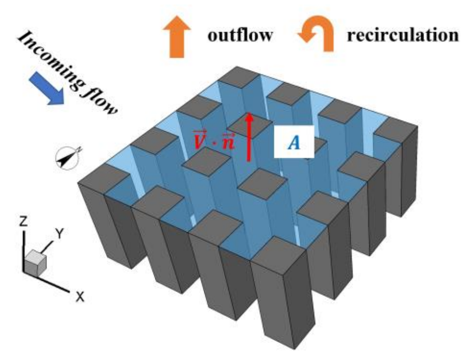

Fig. 1 The schematic diagram of the street opening flow rate calculation

3. CFD SIMULATION

3.1 Physical model and simulation settings

This study employed ANSYS Fluent to investigate the impact of the uniform temperature wall assumption on the wind-thermal environment of the building complex. As depicted in Fig. 2, a 4x4 dot-formed building complex located in Shanghai was selected as the study object. Each individual building measured 10 meters in length, 10 meters in width, and 30 meters in height, with a spacing of 10 meters between buildings. The numerical model was established using ANSYS ICEM, and structural grids were utilized for discretization. After validation through grid independence analysis, a total of 4.5 million grids were selected. The finite volume method was used to discretize differential equations. For pressure-velocity coupling, the semi-implicit pressure linked equations (SIMPLE) algorithm was employed. The process involved 5000 iterations, with a convergence criterion requiring the residual of each parameter to be less than 10^{-5}.

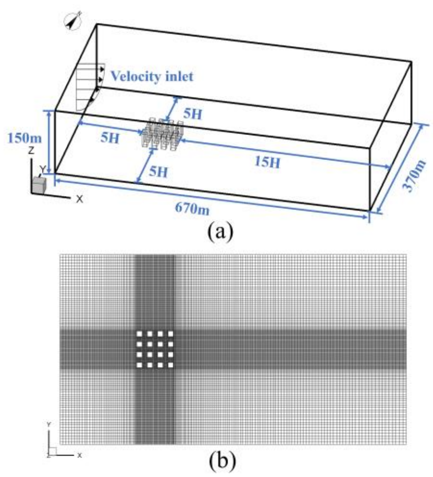

Fig. 2 Establishment of the building complex model

3.2 Simulation conditions and boundary conditions

At 16:00 during the summer, the upper part of the western side of the building complex is directly exposed to sunlight, while the lower part is shaded by surrounding buildings. Therefore, in the model, the western side surface was selected as the non-uniform surface to investigate the effect of building shading on ventilation performance. Fig. 3 illustrates the boundary condition settings for the building surfaces. In Fig. 3(a), the west surface and roof of the first column as direct sunlight surfaces. In Fig. 3(b), the southern, northern, and eastern surfaces are designated as shaded surfaces. In Fig. 3(c), the western surfaces of the second, third, and fourth columns are set as non-uniform surfaces, with a non-uniform ratio of 0.5. Fig. 3(d) represents the scenario where the non-uniform surface assumption is treated as a uniform surface, enabling comparison with the non-uniform surface.

According to the study by Chen et al. [12], in summer, the maximum temperatures on the east and west sides range from 40 to 50°C under varying solar radiation intensities. Therefore, the average surface temperature of the three groups of cases were set to 37/40/42.5 ℃, and sub cases with uniform and non-uniform treatment were set for each case. As shown in Table 1, under non-uniform surface conditions, the temperature of the shaded surface was assumed to be equal to the air temperature, and the temperature of the direct surface was set to 50/45/39 ℃. In uniform surface conditions, the surface temperature was the average of non-uniform surface temperatures. Studies have shown that when Ri >> 1, buoyancy-driven thermal forces dominate the airflow. When buoyancy forces play a dominant role, non-uniform surfaces have a greater impact on the ventilation effectiveness of building complexes. Therefore, in this study, the incoming airflow velocity was set to 0.5m/s and the temperature was set to 35 ℃.The Richardson numbers (Ri) for the three cases were 29.98, 19.99, and 7.99, respectively.

Table 1

Simulated conditions

Case	Ri	The direct sunlight surface (℃)	The shadow surfaces(℃)	Non-uniform surface - shaded area	Non-uniform surface - direct sunlight area
Non-uniform -15K	29.98	50	35	35	50
Uniform -15K	29.98	50	35	42.5	42.5
Non-uniform -10K	19.99	45	35	35	45
Uniform -10K	19.99	45	35	40	40
Non-uniform -4K	7.99	39	35	35	39
Uniform -4K	7.99	39	35	37	37

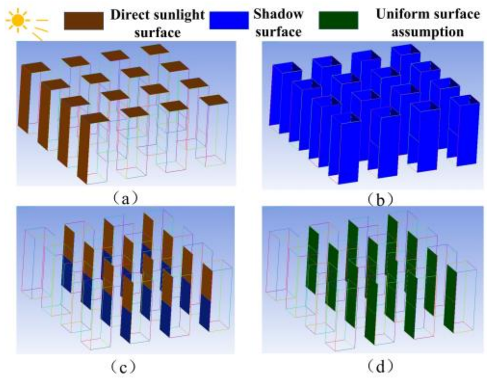

Fig. 3 Settings for direct sunlight and shadow surfaces

3.3 Validation of numerical simulations

This study utilized a wind tunnel experiment conducted by the Japanese National Institute for Environmental Studies to validate the CFD numerical model [13]. We chose the Richardson number of Rb=-0.21 for validation, as shown in Fig. 4. The Normalized Mean Square Errors (NMSE) for velocity and temperature were found to be 0.014 and 0.270, respectively, both within acceptable ranges. Overall, the current numerical model effectively predicts the overall distribution trends of U/U_{ref} and $(T-T_a)/(T_f-T_a)$, with good agreement between the CFD model results and the wind tunnel experiment results.

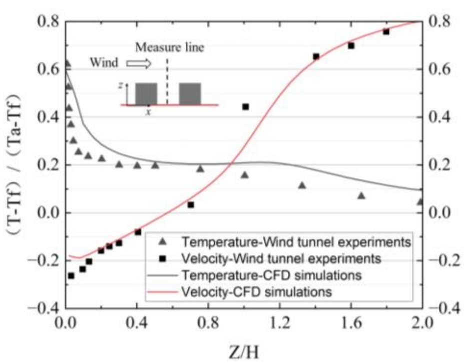

Fig. 4 Comparison between simulated and experimental results

4. RESULTS AND DISCUSSION

This study evaluated the impact of uniform surface assumptions on the wind-thermal environment from three aspects: the vortex structure of airflow within the building complex, temperature distribution, and the outflow and recirculation ratio. The velocity distribution and temperature distribution under various temperature differences are depicted in Fig. 8-9, while the vertical velocity results are illustrated in Fig. 5. From the perspective of temperature distribution, assuming a uniform distribution of surface temperature results in a relatively even temperature distribution within the building complex, leading to a certain degree of thermal accumulation. The lower part of the building surface is shaded, while only the upper part receives direct solar radiation. Consequently, assuming a uniform wall surface overestimates the thermal accumulation risk within the building complex. As solar radiation intensity increases, the temperature difference between shaded and unshaded areas also increases, resulting in a growing error in predicting the thermal accumulation risk in the building complex.

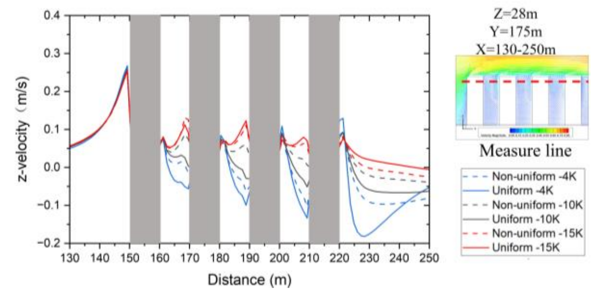

Fig. 5 z-velocity distribution curve

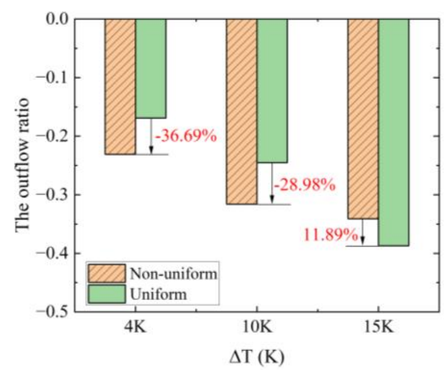

Fig. 6 The influence of surface boundary conditions on the outflow ratio

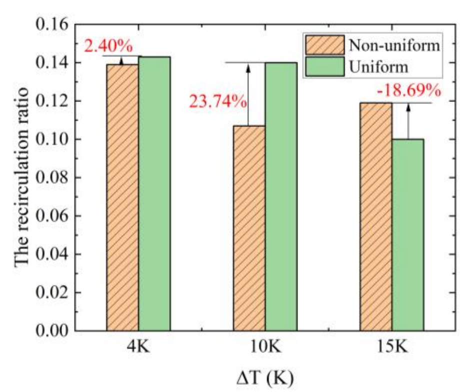

Fig. 7 The influence of surface boundary conditions on the recirculation ratio

From the perspective of airflow structure, when the temperature difference is 4K, assuming a uniform

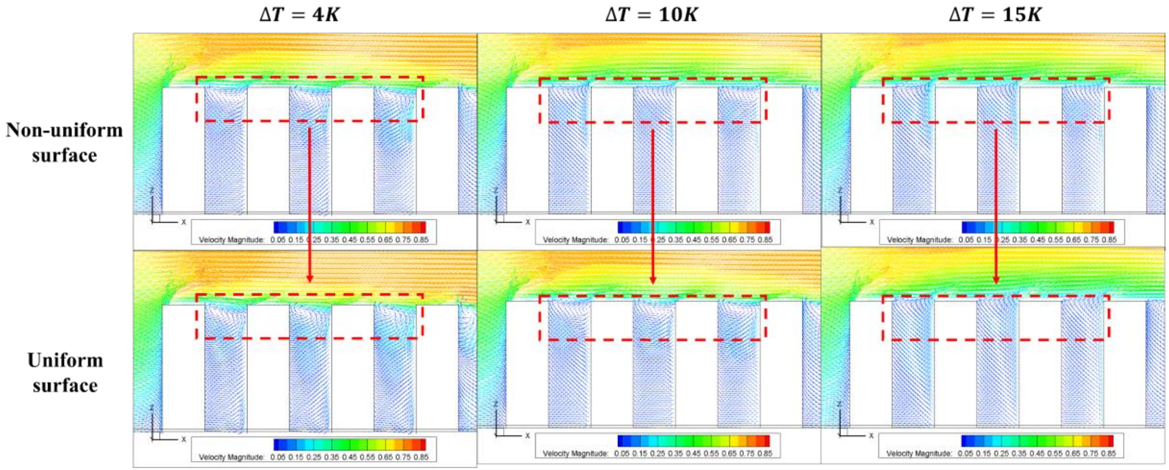

Fig. 8 The influence of surface boundary conditions on airflow structure (y=175m)

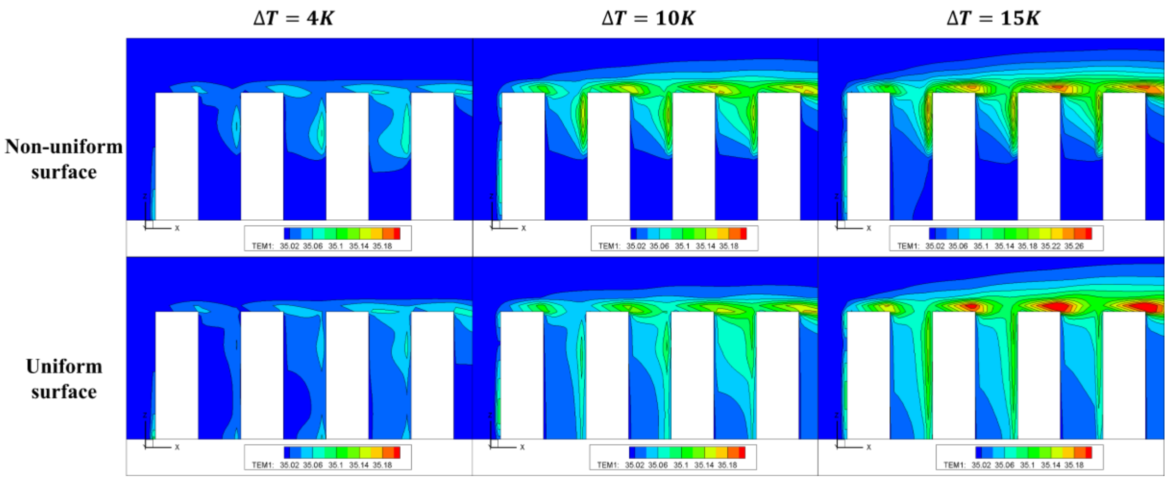

Fig. 9 The influence of surface boundary conditions on temperature distribution (y=175m)

distribution on the building surface will not lead to changes in the vortex structure of the airflow. As highlighted by the red dashed box in Fig. 8, vortex structures exist at the upper opening of the building complex under both boundary conditions. From the z-velocity distribution in Fig. 5, it can also be observed that at the same distance, the variation pattern of the z-velocity symbols for the two conditions is essentially the same. Due to the existence of vortices in the leeward direction, the z-velocity symbol changes from "+" to "-". This indicates that the airflow direction between uniform and non-uniform surfaces has not changed. When the temperature difference is 10K, the airflow on the non-uniform surface at the upper opening of the building moves vertically upward, with no vortex area present. The symbol for z-velocity is entirely "+". However, assuming a non-uniform surface to be uniform alters the vortex structure of the airflow, leading to the formation of vortex regions and negative z-velocity values in some areas, indicating a change in the flow direction. When the temperature difference increases to 15K, the airflow structure on both uniform and non-uniform surfaces flows upwards out of the building complex, and the vortex structure remains unchanged.

The changes in the vortex structure within the building complex cause variations in the flow rate entering or exiting the complex, directly affecting its ventilation performance. The assumption of a uniform surface impacts both the outflow and the recirculation ratio at the top of the building complex, as depicted in Fig. 6-7. When the temperature difference is 4K, the two boundary conditions do not alter the shape of the vortex structure within the building complex, resulting in a relatively small difference in the recirculation ratio between them, at 2.40%. The greatest impact on the recirculation ratio occurs when the temperature difference is around 10K, potentially differing by 23.74% between non-uniform and uniform surfaces. This is attributed to changes in the vortex structure at the top of the building complex under this condition. The non-uniform surface generates a substantial counter-flow during flow field prediction, resulting in an overestimation of the recirculation ratio at the top and an underestimation of the outflow ratio. As the temperature difference increases to 15K, the difference in the recirculation ratio between the two conditions decreases to 15.74%.

The airflow's vortex structure within the building complex is influenced not only by temperature differences but also by non-uniform proportions. The non-uniform proportion of building surfaces correlates closely with both geometric configuration and time of day [14]. This aspect warrants further research in the future.

5. CONCLUSIONS

This study focused on a 4x4 dot-formed building complex, using airflow structure and ventilation flow rate as quantitative indicators, and explored the impact of the uniform surface assumption on the wind-thermal environment of the building complex. The main conclusions are as follows:

Under conditions dominated by buoyancy (Ri=7.99-29.98), non-uniform surfaces had a decisive impact on the risk of thermal accumulation and the ventilation performance of the building complex. The assumption of uniform surfaces led to errors in predicting the risk of thermal accumulation within the building complex, and the errors increased with the increase of temperature difference. When the temperature difference was 10K, assuming a non-uniform surface as a uniform surface caused a change in the vortex structure of the airflow, leading to an error in predicting the airflow direction and overestimating the recirculation ratio by 23.74%.

Therefore, neglecting the shading effect of the building complex and assuming a constant temperature boundary condition makes it challenging to accurately reveal the distribution of building surface irradiance in the real environment. This leads to certain errors in predicting the airflow vortex structure within the building complex and further affects the ventilation performance of the building complex.

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