Buoyancy Combined with Buildings Layout Effects on the Thermal Diffusion under Background Wind: Wind Tunnel PIV Measurement

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Abstract. The temperature in the urban areas are higher compared with rural areas because of the UHI effect. The wind-driven ventilation play a significant role on the heat removal. Moreover, the air velocity in the urban areas is influenced by the background wind speed, the exposure of heated surfaces and building layout. However, available experimental data for the thermal diffusion mechanism of different heat source conditions and building layout is limited. Aim at the problem above, the thermal diffusion mechanism of different surface heating conditions and building layout was analysed by conducting wind tunnel experiment with PIV system. To investigate the thermal diffusion mechanism, the building façade, impervious road surface, and traditional roof are heated up three different temperatures to induce buoyant. The effects of three different buildings layouts on flow and temperature also were investigated in this paper. The results showed that building layouts had a marked impact on the flow field near buildings. The terraced building layout is best for heat removal. This study improves understanding of how the buoyancy and wind speed influence the thermal diffusion in different buildings layouts, expands experimental database under different surface temperature conditions and buildings layouts in wind tunnel experiments with PIV.

1 Introduction

With the economic and social development and quickening the urbanization process, the deterioration of the global climate, especially in urban areas, the concentrated distribution of tall buildings, frequent windless weather, heat and pollutants accumulated serious and difficult to discharge, leading to air pollution growing intensified, heat island effect, the contradiction between the rapid evolution of urbanization and urban environment problems also increasingly highlight. It has greatly threatened economic development and people's health. Optimizing urban layout, strengthening urban ventilation, eliminating air pollution, improving the thermal and wind environment in urban areas, and enhancing the comfort level of living environment and residents' satisfaction have become one of the major issues in urban development and environmental protection.

In recent years, a lot of researches [1-6] have been done on how to improve the thermal-wind environment under no-wind conditions. And, previous scholars mainly studied outdoor thermal-wind environment and proposed optimization methods on the following five aspects: building height, urban ventilation corridor, urban green rate, urban form and urban road layout. Few studies have focused on building scale, especially to thermal plumes on building surfaces.

In this paper, based on the similarity theory, the model scale ratio of model experiment was determined, and the thermal diffusion characteristics of buildings were tested experimentally in the wind tunnel, and the outdoor wind speed field and temperature field of buildings were obtained, so as to study the thermal diffusion characteristics of buildings.

2 Experiment measurement

2.1 Experiment setup

The wind tunnel experiment was conducted on a single-zone cube building model with dimensions of 0.1×0.05×0.2m³(1:100 scale), as shown in Fig 1. The scale is based on the plugging ratio and dynamic similarity criteria in the wind tunnel.

Fig.1. Wind tunnel coordinates (x, y, z) of the studied urban matrix model.

Wind-thermal environment and particle diffusion PIV wind tunnel test is in Harbin university of technology in wind tunnel and the wave trough large laboratory in atmospheric boundary layer wind tunnel experimental section is completed, the experimental section of interior
space for the rectangle, the size of 25 m × 4 m × 3 m (length x width x height), test section can be generated within 3 m/s to the stability of 50 m/s wind field, empty wind tunnel steady running state, It can realize the precise control of wind field velocity inhomogeneity less than 1% and Angle deviation less than 0.5°. The bottom base of the test end can be rotated 360° with the rotation error less than 0.1°, which is convenient for testing the environment in the area under different wind directions. Fig.2 shows the PIV wind tunnel photographing of wind-thermal environment in the wind tunnel test section.

Fig.2. PIV wind tunnel photo of wind-thermal environment
This experiment adopts high resolution PIV system, which is composed of hardware and software, as shown in Fig 3. The hardware includes high speed CCD camera, synchronizer, laser generator (wavelength 532nm; 135MJ dual-cavity Nd: YAG laser), laser plate generator, tracer particle transport device and computer. The software mainly includes high speed camera control system, synchronizer control system and particle image analysis and calculation system.

Fig.3. PIV wind tunnel test schematic diagram in wind-thermal environment.

2.2 Parameterization and working conditions of the model
Building spacing refers to the distance between two buildings. Different building spacing affects the wind and thermal environment of outdoor buildings. According to the building spacing specification, the building spacing should not be less than 18 meters in layout. The ratio between building height and building spacing is 0.5, 0.75, 1.0 and 1.25, respectively.

3 Result and analysis

3.1 Air velocity variations

Fig.4. Wind speed curve with spacing of 20m.
Fig.5. Wind speed curve with spacing of 40m.
Fig 4 and Fig 5 show that the wind environment outside the building varies with the height from the building ground. In general, with the increase of the distance from the ground, the outdoor wind speed of the building complex continues to increase, and with the increase of the distance, the wind speed outside the building is different. In the lower part of the complex, we can see that the wind speed decreases as the distance from the two ends of the complex increases. At the position 2m above the ground, the wind speed inside the building complex is less than 0.1m/s, and the wind speed is slightly higher at both ends of the building complex. At the height 10m from the ground, the wind speed inside the building complex is less than 0.2m/s, but the wind speed is generally higher than that at 2m from the ground, and the wind speed at both ends is still large and the wind speed in the middle is small. But with the increase of the height distance, can be seen from the diagram, the location of the 20 m from the ground, buildings and outdoor wind velocity with the increase of distance from building on both ends of the distance, the wind speed increasing, the area above the complex whole presents a parabola going downwards trend, in the middle of the complex regional wind speed to achieve the most great in 0.80 m/s, The wind speed at both left and right ends is less than 0.4m/s. 30m away from the ground, the maximum wind speed in the outdoor middle area of the complex reached 0.95m/s, and the wind speed at both ends of the complex was less than 0.30m/s. With the increase of distance, the outdoor wind speed of the complex increased from nearly 0.8m/s to nearly 1m/s. This is because with the increase of building height, the thermal plume characteristics on the
surface of the building complex become stronger. When the equal distance increases to a certain extent, the thermal streams on the surface of the building begin to converge and form stronger thermal plumes.

As can be seen from Fig 6, with the increase of building spacing, the outdoor wind speed of architectural complex decreases continuously. When the spacing is 20m, the maximum energy wind speed can reach 0.23m/s, and the minimum wind speed is 36m away from the edge of architectural complex. When the distance between buildings is 30m, the maximum wind speed is no more than 0.2m/s. When the distance between buildings is 50m, the maximum wind speed is 0.15m/s. This is because with the increase of the distance between buildings, there is less mutual influence between the thermal plume between building surface. For example, when the distance is 40m, the intermediate wind speed varies between 0.025m/s and 0.05m/s. The maximum wind speed at both ends is 0.2m/s and the minimum is 0.75m/s. This is because at 5m away from the ground, due to the action of hot plumes at both ends, the wind speed in the middle of the complex is very small, but the wind speed at both ends is large.

3.2 Temperature variations

As shown in Fig 7, the temperature decreases with the increasing distance between buildings 40m from the ground. When the distance between buildings is 20m, the maximum temperature reaches 20.40℃; when the distance between buildings is 30m, the maximum temperature reaches 20.10℃; when the distance between buildings is 50m, the maximum temperature reaches 20.08℃. With the spacing of 40 m in basically the same, also differ with room temperature 20 ℃, with little, it shows that with the increase of distance, buildings under the effect of thermal plume, the outdoor temperature is continuously reduce, when the spacing increases to a certain extent, between the surface of the building thermal plume had little impact, outdoor temperature basically unchanged. Under the same spacing level height, building edge distance increases as the temperature continuously reduce, the spacing of 30 m, complex outdoor temperature is at 250 m building edges, temperature is 20 ℃ and room temperature, with the increase of distance, in the middle of the 280 m or building location, temperature is 20.25, the temperature increasing. This is similar to the conclusion of the indoor wind environment of the building complex. This is because the heat plume gathers in the middle of the building complex, and the heat exchange between the edge of the building and the surrounding space is relatively large, so the temperature in the middle is high and the temperature at both ends is low.

Fig. 8 shows that with the increase of distance, the thermal plume has greater influence on the outdoor thermal environment of the building complex, and the temperature at the top is greater than that at the bottom. In the position 2m from the ground, the wind speed is close to room temperature 20℃, and in the middle of the building complex, the wind speed is slightly higher, reaching 20.02℃. However, the overall temperature difference is relatively small, so the temperature can be considered unchanged basically. 10 m location off the ground, the temperature is higher, the biggest ends at 20.05 ℃ temperature is small, with room temperature level, this is because in the lower part of the buildings, the influence of thermal plume is small, and the thermal plume will heat exchange with the buildings on the ground, so the buildings under the temperature is not too big, basic and room temperature and ground temperature in balance. At a position 30m from the ground, the temperature increases first and then decreases in the range of 250m-275m in the horizontal direction, with the same trend as the wind speed, with the minimum temperature reaching 20.15℃. In the range of 275m-
320m, the temperature still presents a parabolic form. The maximum temperature is 20.40 ℃, the minimum is not more than 20.1℃, and the temperature difference exceeds 0.3℃.

4 Conclusion

Through PIV test and simulation study on the thermal plume characteristics of building facades under different wall heat flow densities, the following conclusions are drawn:

The smaller the distance is, the greater the wind speed is. When the distance is 20m, the maximum wind speed outside the building complex is 0.13m/s, but the wind speed distribution within the building complex is more uniform and there are more areas with high wind speed. When the distance is 30m, the maximum wind speed inside the building complex is 0.12m/s, although there is little difference between the maximum wind speed and the distance of 20m. However, at this time, the outdoor wind speed distribution of the complex is not very uniform.

When the distance is 40m and the distance is 50m, the maximum wind speed is 0.08m/s, and there are many areas with wind speed below 0.04m/s in the complex. As can be seen from the figure, the larger the distance, the larger the windless area inside the building complex. This is because with the increase of the distance, the more difficult it is for the thermal plume on the surface of the building complex to gather, and the less influence the thermal plume on the surface of the building wall has on each other.

Buildings of outdoor thermal environment and wind environment is essentially the same change trend, with the increase of building space, complex outdoor temperature increasing, and the height distance, horizontal, complex increased after decreased outdoor temperature line, presents a parabola form basically, but little change of temperature in the buildings, The maximum temperature difference in the same horizontal direction shall not exceed 0.5℃, and the maximum temperature difference in the vertical direction shall not exceed 0.5℃.

It can be concluded that with the increase of building spacing, the mutual influence between single building thermal plumes becomes smaller. In order to reduce the mutual influence between thermal plumes, we can appropriately increase building spacing during building group design.

Acknowledgments

The work described in this paper was supported by the Fundamental Research Funds for the Central Universities (Project No. 2572020BJ05).

References

1. J H Thysen, T V Hooff, B Blocken, CFD simulations of two opposing plane wall jets in a generic empty airplane cabin: Comparison of RANS and LES, Build. Environ, 174 (2021):10-8.
2. K, katarina, V hoof, T, V, C, Cross-ventilation in a generic isolated building equipped with louvers: Wind-tunnel experiments and CFD simulations, Build. Environ, 154 (2019):263-280.
3. S Kumar, PK Vijayan, U Kannan, M Sharma, DS Pilkhwal, Experimental and computational simulation of thermal stratification in large pools with immersed condenser, Appl. Therm. Eng, 117 (2017):353-382.
4. F, Y., L, Y., H, J., W, K., Y, X., Natural convection flows along a 16-storey high-rise building, Build. Environ, 107, (2016): 215-225.
5. H, Jian, X, Z., W, D., M, C.M., Wang, B., Fan, Y., The impacts of viaduct settings and street aspect ratios on personal intake fraction in three-dimensional urban-like geometries. Build. Environ, 143, (2018): 138-162.
6. Y Jing., H.Y Zhong, W W Wang, Y He, Quantitative city ventilation evaluation for urban canopy under heat island circulation without geostrophic winds: Multi-scale CFD model and parametric investigations. Build. Environ, 196, (2021):107793.