Wind tunnel study on the pedestrian-level wind comfort in residential areas of Harbin

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Abstract. Pedestrian-level wind conditions in residential areas are closely related to the quality of urban residents’ daily life. In this paper, seven representative building layouts of urban residential areas were summarized from actual residential areas of Harbin, and wind tunnel experiments were carried out to study the pedestrian-level wind comfort in these residential areas. The assessments of pedestrian wind comfort are performed by combining the wind tunnel results and long-term local wind statistics. The results show that the hybrid-type and the enclosed-type layouts can provide better pedestrian wind comfort than parallel-type layouts, and the building heights of residential areas need to be controlled in cities of severe cold regions.

1 Introduction

Wind conditions at the pedestrian-level in residential areas play an important role in the dispersion of pollutants around buildings, efficiency of natural ventilation, and wind and thermal comfort of pedestrians. In the past, a great amount of research has been carried out to assess the wind conditions at the pedestrian-level around buildings [1-3]. These studies show that the pedestrian-level wind flow pattern around buildings is complicated and closely related to various factors, such as the dimensions, shape and configuration of buildings, the building coverage ratio, the upstream terrain conditions, and the wind directions. The layouts in these studies are mainly simplified models. Studies on the simplified models can provide a fundamental understanding of the wind flow pattern around the cubic models with a regular configuration, such as symmetrical or staggered layout. However, the actual urban morphology is considerably complicated, which implies that the research results of the simplified models with regular configurations cannot reflect the actual urban wind environment.

The main purpose of this study is to assess the pedestrian-level wind conditions in residential areas of Harbin. In this study, seven representative building layouts of urban residential areas were summarized from actual residential areas in Harbin, one of the major cities in severe cold regions of China. Wind tunnel experiments were carried out to investigate the pedestrian-level wind conditions in these residential areas. Firstly, the results of wind tunnel experiments on the mean wind velocity and the gust wind velocity were presented and analysed. Secondly, the pedestrian-level wind comfort of these residential areas was evaluated and compared based on the wind tunnel results and long-term local wind statistics. The results will help to better understand the types of building layout that are suitable for residential wind environment in severe cold regions of China.

2 Experimental setup for wind tunnel experiments

The wind tunnel experiments were conducted in the Laboratory of Wind Tunnel and Water Flume at Harbin Institute of Technology (WTWF-HIT). The experiments were performed in the smaller test section of the wind tunnel with a cross-section of 3 m (H) × 4 m (W) × 25 m (L). Seven representative building layouts were summarized from actual urban residential areas in Harbin to reflect the common and actual urban residential areas, as shown in Table 1. Three different building heights, which correspond to multi-story buildings (6-storey) and high-rise buildings (12- and 18-storey), are considered. Besides, for cases with high-rise buildings, the ground-floor shops are also taken into account. The floor height of residential buildings is 3 m and the height of ground-floor shop is 4 m. In order to fulfil the requirement of the blockage ratio of wind tunnel, the building models were scaled to 1/200. The building models were made of acrylic plastic sheet or acrylonitrile-butadiene-styrene (ABS) materials. For each case, approximately 50–90 simplified Irwin probes were installed at 7.5 mm (model scale) above ground to measure the wind velocity at the pedestrian-level.

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Table 1. Brief description of the seven layouts of residential areas that were studied.

| Case | Layout | Schematic diagram | Scaled models | Case | Layout | Schematic diagram | Scaled models |
|------|--------|-------------------|--------------|------|--------|-------------------|--------------|
| 1    | Parallel | ![Schematic Diagram](image1) | ![Scaled Model](image2) | 2    | Parallel | ![Schematic Diagram](image3) | ![Scaled Model](image4) |
| 3    | Parallel | ![Schematic Diagram](image5) | ![Scaled Model](image6) | 4    | Enclosed | ![Schematic Diagram](image7) | ![Scaled Model](image8) |
| 5    | Enclosed | ![Schematic Diagram](image9) | ![Scaled Model](image10) | 6    | Hybrid | ![Schematic Diagram](image11) | ![Scaled Model](image12) |
| 7    | Hybrid | ![Schematic Diagram](image13) | ![Scaled Model](image14) |

Based on the Lode Code for the Design of Building Structures in China (GB50009-2001), terrain roughness D (TR-D) with a power law of 0.3, which represents an intensive urban area with high-rise buildings, was reproduced in the wind tunnel by using wedges, fences, and roughness elements, as shown in Fig. 1.

![Fig. 1. Wind tunnel setup for TR-D](image15)

The approaching vertical profile of the mean wind velocity was measured by a DENTEC 55P11 hotwire anemometer. The results of the mean wind velocity and the turbulence intensity are shown in Fig. 2, and it is observed in the figure that the mean wind velocity is normalized by the reference wind velocity, \( U_{\text{ref}} \), at the reference height of 1 m (model scale).

![Fig. 2. Vertical profile of approaching flow](image16)

3 Results of wind tunnel experiments

High-speed steady winds and instantaneous gusts are both important parameters for pedestrian wind comfort. In this study, both the mean wind velocity and the gust velocity were obtained by the Irwin probes for each case under 16 wind directions. The wind velocity ratio, presented below, are normalized by the approaching wind velocity at the height of 10 m in the prototype scale (0.05 m in the model scale). It should be noted that we use the wind velocity at 10 m above the ground to calculate the wind velocity ratio because the meteorological data is normally available.
at 10 m height and for the convenience of the following study on wind comfort.

In order to evaluate both the mean and gust wind, the gust equivalent mean (GEM) method [4, 5] is employed in this study. The GEM wind velocity is defined as the maximum value between the mean and gust wind velocities divided by a factor of 1.85:

\[
U_{\text{GEM}} = \max \left\{ \bar{U}, \frac{\tilde{U}}{1.85} \right\}
\]  

(1)

where \( U_{\text{GEM}} \) is the GEM wind velocity (m/s), \( \bar{U} \) is the mean wind velocity (m/s) and \( \tilde{U} \) is the gust wind velocity (m/s). In this study, the gust wind velocity was determined using the ‘multiple extremes method’ proposed by Tsang et al. [6].

The spatial average of the mean and GEM wind velocity ratios in each wind direction are summarized in Fig. 3. From the figure, it can be found that the wind velocity ratio of the hybrid-type and the enclosed-type layout cases is lower than that of parallel-type layout cases. The wind velocity ratio in case 4 is the lowest, while case 3 shows the highest wind velocity ratio. The average wind velocity ratio of parallel-type layout cases is about 1.2 to 1.5 times greater than that of hybrid-type and the enclosed-type layout cases with similar building heights, while the average wind velocity ratio increased about 10% to 30% when high-rise buildings exist for the same building layout.

For parallel-type layout, as all the buildings have the same orientation, the spatial average of the wind velocity ratio has a notable decrease when the approaching flow is perpendicular to the buildings. The wind velocity ratio has a significant increase for northeastern wind directions as observed in case 5 due to its converging arrangements under those wind conditions. For other cases, the spatial average of the wind velocity ratio does not show significant differences for different wind directions.

4 Pedestrian wind comfort assessment

4.1. Analysis of long-term meteorological data

In this study, twenty years (January 1994 – December 2013) of hourly observed meteorological wind data at Harbin is acquired from the National Oceanic and Atmospheric Administration’s Integrated Surface Data database. The annual and seasonal variations of wind velocity and directions are illustrated in Fig. 4. It can be seen from the figure that most prevailing winds are from the southwest and the southwesterly winds (S, SSW, SW, WSW, and W) all have high occurrence probability and high wind velocity. The most prevailing winds are from the southwest with an occurrence probability of 12.28 % and the maximum annual mean wind velocity of 3.18 m/s.
### Table 2. Wind comfort and safety criteria proposed by Soligo

| Category   | Mean wind velocity | Frequency |
|------------|--------------------|-----------|
| Sitting    | 0~2.5 m/s          | ≥80%      |
| Standing   | 0~3.9 m/s          | ≥80%      |
| Walking    | 0~5.0 m/s          | ≥80%      |
| Uncomfortable | >5.0 m/s   | ≥20%      |
| Danger     | ≥14.4 m/s          | ≥0.10%    |

#### 4.3. Assessment results of pedestrian wind comfort

The assessment results of the annual pedestrian wind comfort in the studied residential areas are illustrated in Fig. 5. The results are depicted in different colors to represent the wind comfort levels judged by the Soligo criterion at each of the measurement points. It can be seen that the points be suitable for walking in cases 2 and 3 are mainly located in the passages or ventilation routes between high-rise buildings, which correspond to the areas of high wind velocity ratio. For the other five cases with no points been classified as walking, most of the measured locations have a good wind comfort for sitting in cases 4-7, while fairly large areas that are moderate for standing with only a small region comfortable for sitting in case1. Comparison between case 1 (4/6) and case 3 (5/7) reveals that, for the cases with the same building layouts, the proportion of locations be suitable for sitting reduced by nearly half due to the presence of high-rise buildings. Besides, due to the prevailing southwest wind direction, the eastern parts of these residential areas generally have a better wind comfort. Based on the evaluated results, the hybrid-type and the enclosed-type layout is recommended, while the parallel-type layout is not suggested. In addition, the presence of high-rise buildings causes a deterioration of wind comfort, and a strict control of building height is important to improve the pedestrian-level wind conditions in residential areas.

![Fig. 5. The assessment results of the pedestrian wind comfort for the seven case](image)

#### 5 Conclusions

In this study, seven representative building layouts of urban residential areas were summarized from actual residential areas in Harbin, China, and wind tunnel experiments were conducted, combined with the long-term meteorological data and the wind comfort criterion, to study the pedestrian wind comfort in the residential areas. Several conclusions can be drawn as follows:

1) The average wind velocity ratio of parallel-type layout cases is about 1.2 to 1.5 times greater than that of enclosed-type and hybrid-type layout cases with similar building heights, while the average wind velocity ratio increased about 10% to 30% when high-rise buildings exists for the same building layout.

2) No area in the seven cases is classified as unacceptable or severe. Most part of the residential areas from parallel-type layout cases is moderate for strolling, while fairly large areas are suitable for sitting for enclosed-type and hybrid-type layout cases.

According to the assessment results, the hybrid-type and the enclosed-type layout is recommended, and the parallel-type layout is acceptable but not suggested for cities in severe cold regions. It should be noted that the comparisons and assessments in this study are conducted for the pedestrian wind comfort and not for the quality of daylight or land-use efficiency. Thus, the advice are mainly proposed from the perspective of wind prevention and the pedestrian wind comfort in winter.

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