Boundary layer wind tunnel tests of outdoor airflow field around urban buildings: A review of methods and status

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Abstract. Outdoor airflow fields have received increasing attention in the building aerodynamics community due to that the airflow distributions around outdoor buildings are closely related to issues such as thermal comfort, building ventilation, and pollutant dispersion. The focus of this paper is on the airflow distributions around buildings obtained through wind tunnel tests, and such studies are mostly conducted in boundary layer wind tunnel with long test section. This paper reviews current techniques for boundary layer wind tunnel tests of airflow distributions in urban outdoor environments. Then, the characteristics of airflow distributions around buildings in three typical configurations from previous studies (i.e. isolated building, street canyon, and building complexes) are reviewed. This review highlights that the proposed building models should be carefully assessed in combination with wind tunnel tests at the design stage. In addition, it is important to obtain wind tunnel test data for buildings with thermal effects, and the importance of arranging the underlying surfaces during the test is also emphasized.

1 Introduction

With the acceleration of urbanization, the form of buildings has changed from low-rise isolated building to multi-story buildings. However, the emergence of new buildings leads to changes in the urban microclimate environment and more significant climatic effects in urban areas. Especially when the background wind is weak, the temperature in urban areas is significantly higher than that in the surrounding suburbs. This urban microclimate difference is called urban heat island effect [1]. Climate models show that not only the mean temperature rises in summer, but also heat waves become more intense and frequent [2].

Wind tunnel tests provide a method to artificially change and control these influencing factors in simplified building configurations. The building configurations used in previous wind tunnel tests can be broadly categorized into isolated building, street canyon, and building complexes. Isolated building is the simplest form of construction used in wind tunnel research. Street Canyon is a typical urban basic unit with distinct microclimate characteristics, and it is also an important platform to understand the air flow pattern in the urban microenvironment. Whilst, the street canyon can be seen as a small building geometric unit, with many geometric units forming the building complexes.

The purpose of this review is twofold. First, it provides a description of the existing boundary layer wind tunnel technology from the perspective of theoretical basis, test setup and test techniques. Secondly, it distinguishes the airflow distributions around different configurations of building forms. The general understanding gained through these studies further supports the broader study. This review is expected to provide guidance for wind tunnel test, help to understand the airflow distributions around the proposed buildings, and put forward improvement measures for possible wind environment and thermal comfort issues.

2 Boundary layer wind tunnel test: facility, theory, measurement

Until now, wind tunnel tests on buildings have almost always been conducted in boundary layer wind tunnels. Boundary layer wind tunnels emerged in the mid-1960s. Thanks to the construction and use of boundary layer wind tunnel, studies related to building aerodynamics have gradually become abundant and have made it possible to accurately simulate the airflow around buildings.

2.1 Wind tunnel settings

In order to be able to reasonably simulate the atmospheric boundary layer wind field in the wind tunnel, the boundary layer wind tunnel usually has a long test section. The researchers arranged spires, air ejection and rough elements in the test section of the wind tunnel to simulate the gradient distribution and turbulence structure of natural wind along the height direction. Wind tunnel modelling is designed to simulate wind properties without using actual wind speeds, and measurements are usually made in the form of dimensionless ratios. Furthermore, the size of the scaled-down model should achieve the blocking ratio requirement. Generally, logarithmic

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function or power function is usually selected to represent the relationship of height above ground and wind speed, and simulate the flow surface wind. In light of different topographic features, the corresponding values of power-law exponent (α) are different (Fig.1).

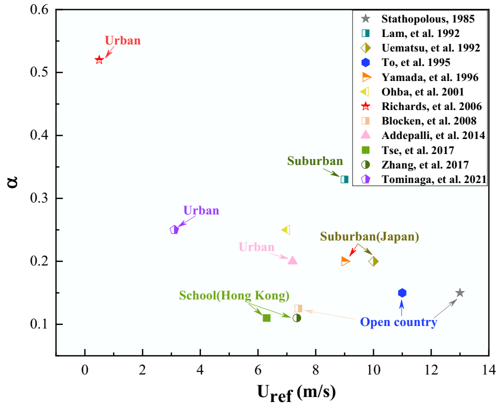

Fig. 1. Combination of reference wind speeds (U_{ref}) and power-law exponents (α) for different terrains.

2.2 Theory of wind tunnel modelling

In order to obtain the flow field similar to the actual situation in the wind tunnel, the similarity criterion must be satisfied between the model and the prototype, and its theoretical basis is the similarity principle of flow. However, due to the limitation of wind tunnel size and other factors, it is difficult to achieve similarity of all parameters at the same time in the wind tunnel. Usually, the most important similar parameters are selected for simulation according to the study. This paper only considers the relational equation between the inertial force and other forces, including buoyancy, viscous force and gravity. Reynolds numbers (*Re*) a very important similar number. When the *Re* is large though, the flows are also similar under the conditions of geometric similarity, that is, *Re*-independence is achieved. When considering the effect of thermal effects on the airflows around a building, the relative magnitudes of buoyancy and inertia forces are usually controlled using the bulk Richardson number or the Froude number.

2.3 Measurement techniques of airflow field

Airflow field testing techniques can be divided into two categories: one is "point measurement", that is, point-by-point measurement with instruments, such as hot-wire anemometry, hot-film anemometry, pulse wire anemometry, Irwin probe, etc. This method requires a sufficient number and density of measurement points to obtain a full picture of the airflow field. The other method is "area measurement", which gives continuous information about the whole airflow field, such as particle image velocimetry, infrared thermography and scour techniques. In addition, visualization techniques are also widely used for airflow field measurements, such as oil mist and smoke that can qualitatively indicate airflow.

3 Airflow patterns around an isolated building

Compared to buildings, isolated buildings generate simpler airflow, but all-important airflow characteristics can be generated in the surrounding wind. The airflows around a square bluff body have been well studied and the mean airflow pattern is shown in Fig.2 [3]. As for the airflows around a single bluff body, not only the airflow patterns around an ordinary cube building are investigated, but also the airflow patterns around an isolated building in combination with different roof shapes are investigated. Rahmatmand et al. [4] found that the maximum value of turbulence intensity appeared at the edge of the doom-roof shear layer. Furthermore, Ntinas et al. [5] found that the flow and velocity components of arched-roof buildings showed dramatic changes from the upstream corner of the roof, while pitched-roof buildings started from the roof.

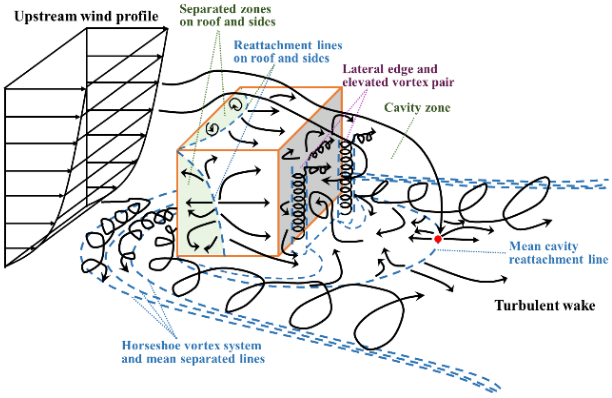

Fig. 2. Schematic diagram of mean airflow pattern around isolated building (Modified from Ref [3]).

4 Airflow patterns in and around a street canyon

Ideally, the street canyon refers to a relatively narrow street with a continuous line of buildings on both sides of the street. In wind tunnel studies, with certain level of simplification, the canyon can be regarded as an open cavity. The flow patterns in the cavity are determined by the geometric properties of the cavity and the shear layer flow. The most typical feature of street canyon airflows is the formation of a main vortex located in the center of the canyon. For different shape ratios, different vortex structures are generated in the street canyon.

4.1 Flat street canyon

It is well acknowledged that flat canyon is a symmetrical canyon. The geometry of the flat street canyon is expressed by the aspect ratio, defined as the height of the building divided by the width of the canyon (H/W). In terms of street canyon with different aspect ratios, Oke [6] proposed three prominent flow regimes, i.e. isolated roughness flow, wake interference flow and skimming flow. The airflows are driven by the wind above the roof level, and the angle between the incoming wind direction and the central axis of the street canyon is also very important for the street canyon airflow patterns (Fig. 3).

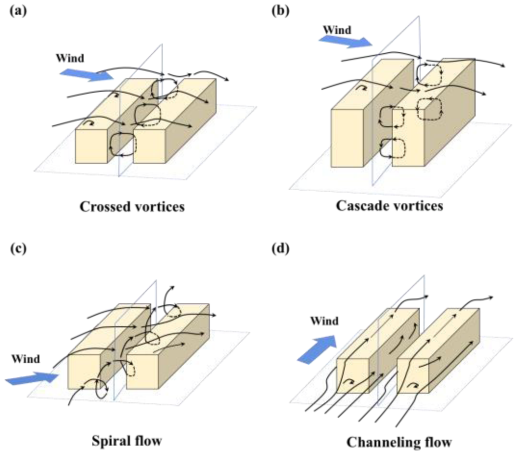

Fig. 3. Typical airflow patterns of a street canyon (Modified from [9]).

Local geometry of a street canyon has a significant impact on the airflows, and changing the shape of the roof is an effective way to improve ventilation in urban street canyons. Flat roofs generate less turbulence, while pitched roofs trigger intense disturbance flows that cause the vortex core to shift upward and secondary vortices are observed in both corners of the canyon. Furthermore, pitched roofs can suppress the generation of cross vortices, thereby reducing the wind speed in the street canyon.

Several studies have focused on the influence of the interaction between buoyancy and inertial forces on the airflow field in the street canyon with unit aspect ratio. When heating all surfaces of the street canyon, the downward airflows into the street canyon weakens due to the presence of buoyancy, a phenomenon that contributes to the formation of a highly stable airflow layer. For a street canyon with unit aspect ratio, Marucci et al. [7] heated the windward and leeward wall of the street canyon, respectively. When heating the windward wall, a counter-rotating vortex is created within the canyon, resulting in a decrease in velocity within the canopy. In contrast, when heating the leeward wall, the canyon airflow patterns are approximately the same as at isothermal, and only a vortex structure is observed in the canyon, accelerated by buoyancy. Further, Allegrini et al. [8] extended the study to the case where the ground, leeward walls or all surfaces are heated.

4.2 Step street canyon

Step street canyon is asymmetrical. According to the wind direction, the asymmetric canyon can be divided into step-up and step-down types, several investigations have employed the wind tunnel to investigated airflow patterns in and around the step street canyon. It is found that the vortices in the step canyon are obviously stronger than that in the flat canyon. Studies on step street canyon focus on the effects of different height ratios (H_u/H_d), width ratios (L_{sc}/W), and heating conditions on canyon flows (Fig. 4).

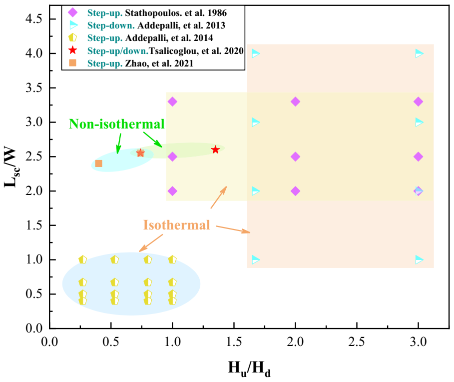

Fig. 4. Combination of height ratios ($\boldsymbol{H_u/H_d}$) and width ratios ($\boldsymbol{L_{sc}/W}$) under isothermal and non-isothermal conditions.

In step-up street canyons, the airflow separates above and around the upwind building, and makes a strong vertical movement in the cavity of the downwind building. In the step-down canyon formed by tall and slender buildings, the momentum transport of lateral flows into the canyon has a great influence on the airflow patterns in the canyon.

As for non-isothermal canyon, the vortex in the flat canyon is mainly controlled by the shear-layer airflow and buoyant airflow at the roof level. While in the step street canyon, the upward buoyant plumes are also suppressed by the downward airflows from the windward side of the high-rise building. When buoyancy is weak, a strong lateral airflow can be observed in the step-down street canyon.

5 Pedestrian-level wind (PLW) around building complexes

The PLW fields around the building complexes are mainly affected by the building morphology, which determines a more complicated airflow pattern. Wind tunnel studies applied to PLW mainly focus on wind discomfort caused by high wind speeds near buildings. In addition, some studies concern poor ventilation due to excessive shading of building.

5.1 Wind speed suppression

High-rise buildings in urban can significantly change the structure of the PLW fields. The airflows through the building complexes are squeezed, so that part of the high-speed airflows move down to ground, and the wind speed at certain special locations will be enhanced. The increase of wind speed at the pedestrian level is usually expressed by the wind speed amplification factor. The narrow passages between buildings are areas with high wind speed amplification factors and are more susceptible to adverse wind conditions near passages entrances. In windy environments, the mean wind speed at the passage is 70% higher than that in free sites. Under extreme wind conditions, local wind speeds in some areas may be up to three times higher than in free sites [10]. For buildings with side-by-side structures, when the wind is perpendicular to the building alignment direction, the channelling effect causes an increment in wind speed around the side walls of the buildings, resulting in instantaneous strong wind. For vertically aligned buildings, the wind speed amplification factor of the divergence passages is greater than that of the convergence passages.

In order to mitigate the hazards caused by excessive wind speed on the pedestrian level, Lam [11] proposed to use permeable floor in the middle level of the building. Adding vegetation to the ground surface is also an effective way to reduce PLW speeds. Alternatively, the adverse wind conditions at pedestrian level can be mitigated by changing the building characteristics, such as the corner shapes of the buildings.

5.2 Wind speed enhancement

While improving urban operation efficiency, closed-space tall buildings will also bring some negative effect, such as reducing wind permeability for pedestrian level. At the same time, the high surface roughness of the urban area is not conducive to urban air circulation. It is assumed that the greater the surface roughness, the greater the extent of the low wind speed zones and the worse the airflow circulation performance.

It is recommended to maintain proper building permeability to improve poor ventilation at the pedestrian level. From the perspective of urban planning, it is proposed to build the air paths to reduce the blocking effect of buildings to the prevailing wind and improve the wind permeability. Tse et al. [12] proposed to design buildings as “lift-up” shape, “lift-up” buildings have higher wind permeability and higher mean high wind speed ratios than those without.

6 Discussion

Generally, solar radiation is simulated in a wind tunnel by heating the model surface to a certain temperature level. In most cases the surface temperature is uniform. Although in reality the surface temperature is non-uniform, such a simplified approach allows for better control of the surface temperature of the model, ensuring better stability and repeatability of the experimental results. Initially, the boundary layer wind tunnels were chiefly used to carry out studies related to structures and wind loads. It is in the last decades or so that outdoor thermal comfort or urban microclimate studies including thermal comfort have moved into this field extensively. This is one of the reasons why most of the available work is limited to isothermal tests. Furthermore, the underlying surfaces is also an important urban element that cannot be ignored, such as vegetation and waterbody.

7 Conclusions

Wind tunnel tests of buildings with thermal effect could be performed using artificial heated surfaces, i.e., to set suitable wall heating temperatures by controlling the bulk *Ri*. It is worth noting that the temperature of the heated surfaces must be evenly distributed, which is one of the key factors to obtain accurate test data.

For buildings with potential wind and thermal environment problems, redesigning the building structure. Future work should give priority to establishing the general model and empirical relationship between wind-thermal conditions and buildings according to the literature and existing studies, and developing the assessment systems for the preliminary evaluation of urban environment under specific situations in combination with wind tunnel tests.

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