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Flow pattern and pollutant dispersion over three dimensional building arrays

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HIGHLIGHTS

- Accomplishment of LES investigation of flow and pollutant dispersion in building arrays.
- Discovery of five identifiable flow patterns which is closely related to building density.
- Exploration of the relationship between flow patterns and pollutant dispersion.

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ABSTRACT

The flow pattern and pollutant dispersion in urban canopies is investigated by large eddy simulation of flow over an array of cubes. It had been found that the pattern of flow over an isolated cubical obstacle can be characterized by an external wake of horseshoe vortex around the lower part of the windward face and an internal wake of recirculation cavity leeward. The width of the external wake W_{ex} and the size of the internal wake L_{in} in the isolated roughness flow are used as key parameters to determine the wake effects on the flow and dispersion in the canopy of the same roughness height h in the isolated roughness flow. Flow patterns are categorized into five types based on the packing density as a result. The five types of urban canopy flow are introduced as (1) Isolated roughness flow when the lateral building interval W_L is much greater than W_{ex} and the streamwise building interval W_S is much greater than L_{in}; (2) External wake interference flow when W_L is less than W_{ex} while W_S is greater than L_{in}; (3) Internal wake interference flow when W_S is in the same order of the size of L_{in}; (4) Skimming flow when W_L is less than W_{ex} and W_S is less than L_{in} (5) Street network flow when W_L and W_S are much less than the W_{ex} and L_{in} respectively. Results of time-averaging velocity field and pollutant concentration contours are demonstrated for each type of flow patterns. It is concluded that the behavior of flow pattern and pollutant dispersion is governed by the packing density from a very low packing density case, approximated as the flow around an isolated roughness element, to a high packing density case, resembled as the network flow.

1. Introduction

The pollutant dispersion in urban atmosphere is an important topic in urban environment and has been paid great attention since late last century. It is well known that the pollutant dispersion is governed by flow patterns that consist of complex turbulence in the urban canopy, of which the geometric configuration is complicated and different from case to case. For two dimensional (2D) urban canopies Oke (1988) proposed a street canyon model that the flow pattern over 2D street canyon is dependent on the ratio of the building interval of l to its height h. The flow pattern is denoted as isolated roughness if $l/h > 2$ (Fig. 1a), wake interference if $l/h \sim 1$ (Fig. 1b) and skimming when $l/h < 1/2$ (Fig. 1c).

The pollutant dispersion is closely related to the flow pattern in flow over two dimensional canyons. If the pollutant source is located in the isolated roughness canyon it is spreading far behind roughness element and high concentration exists in the recirculation zone behind the building. When the pollutant source is situated in the skimming canyon the pollutant concentration is great in the leeward surface of the canyon and the pollutant is transported to the next canyon with considerable concentration (Walton and Cheng, 2002). The classification of flow regimes for 2D street

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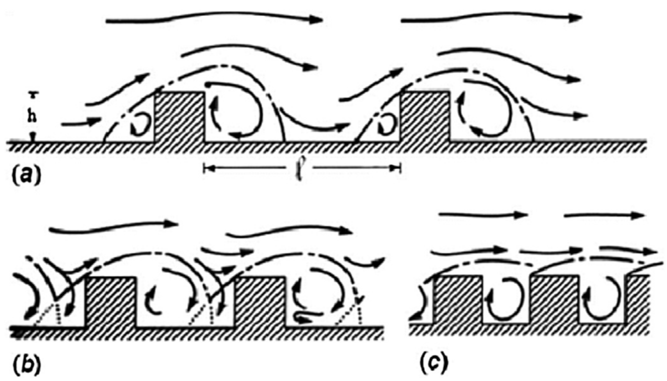

Fig. 1. The flow regimes in 2D street canopy (Oke, 1988).

canyon gives great help for understanding pollutant dispersion in building canopy and casting engineering models (Walton et al., 2002).

However in real urban canopies the geometrical configuration is three dimensional (3D) and flow patterns are different from those in 2D street canyon. For instance the flow pattern of 3D isolated roughness, shown in Fig. 2 (Hanna et al., 1982), is completely different from the flow pattern over 2D isolated roughness elements (Fig. 1a). Results of flow visualization (Martinuzzi and Tropea, 1993) indicate that there exist a horseshoe vortex around the roughness element and a pair of circulating vortex behind the roughness element. In this case the pollutant will be entrained into the horseshoe vortex with high concentration if there is a pollutant source at the front of the roughness element. Obviously the flow pattern around 3D roughness element is completely different from that in 2D street canyon for the pollutant dispersion is limited in the cavity in 2D isolated roughness flow without any lateral dispersion which is the dominant dispersion mechanism in 3D roughness case. Building wake effects on dispersion of pollutant and particles have been taken account of in urban and regional dispersion models. For instance, Holmes and Morawska (2006) and Schulman et al. (2000) developed a model considering plume captured by recirculation cavity in near wake and re-emitted to downstream far wake bounded by horseshoe vortex envelop. The 3D flow pattern and pollutant dispersion will be presented in detail in Section 3.

The purpose of this paper is to explore whether flow patterns can be classified into some identifiable regimes in 3D urban building canopy and the essential feature of pollutant dispersion in the classifications. In 2D street canyon the idea of the classification of flow regimes is based on the geometrical parameters of street canyon, i.e. the interval and height of the building (Oke, 1988). The geometrical parameters are also important criteria for identifying flow patterns in 3D building canopy but they are not the unique set of parameters. The characteristic length scales of average flow structures around each individual roughness elements are important as well. In concrete the spacing of horseshoe vortex tails and the streamwise and lateral size of the recirculation cavity behind roughness elements (see Fig. 2) are also key parameters in classification of 3D building canopy flow patterns. The criteria of the classification are established based on the comparison between geometrical parameters of urban building canopy and the characteristic length scales in isolated roughness flow. The flow pattern over 3D building canopies can be classified into five types and will be demonstrated in Section 3.

The tool of this investigation is modern computational fluid dynamics (CFD). The computational fluid dynamic method has been developed quickly for investigating complex turbulent flows, including atmospheric environmental flows, since late last century. It has been convinced that Large Eddy Simulation (LES) (one of modern CFD methods) is an appropriate method for investigating flow and pollutant dispersion in complex atmospheric environment flow (Britter and Hanna, 2003). In particular a number of authors applied LES to investigate the flow and dispersion in 2D

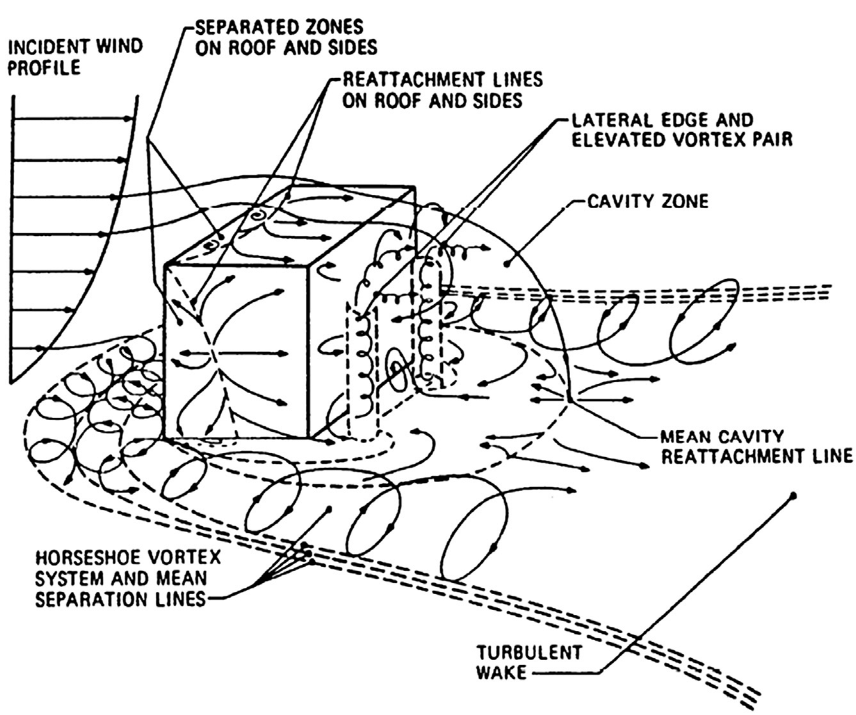

Fig. 2. Flow pattern around 3D isolated roughness element (Hanna et al., 1982).