A CFD MODELING ON THE EFFECT OF BUILDING DENSITY ON URBAN FLOW

Young-Su Lee and Jae-Jin Kim*
Pukyong National University, Busan, South Korea

Abstract

The effects of a building's density on urban flows are investigated using a CFD model with the RNG *k*-□ turbulence closure scheme. Twenty-seven cases with different building's density parameters (e.g., building and street-canyon aspect ratios) are numerically simulated. As the building's density parameters vary, different flow regimes appear. When the street canyon is relatively narrow and high, two counter-rotating vortices in the vertical direction are generated. The wind speed along streets is mainly affected by the building's length. However, it is very difficult to find or generalize the characteristics of the street-canyon flows in terms of a single building's density parameter. This is because the complicated flow patterns appear due to the variation of the vortex structure and vortex number. Volume-averaged vorticity magnitude is a very good indicator to reflect the flow characteristics despite the strong dependency of flows on the variation of the building's density parameters. Multi-linear regression shows that the volume-averaged vorticity magnitude is a strong function of the building's length and the street-canyon width. The increase in the building's length decreases the vorticity of the street-canyon flow, while, the increase in the street-canyon width increases the vorticity.

Keywords: Urban flow characteristics, Building's density parameter, Volume-averaged vorticity, CFD model

1. INTRODUCTION

Serious air quality problems in urban areas as well as fluid dynamical interests have motivated studies on the urban flow and dispersion for the last three decades. Most of the studies have investigated the effects of a single building or obstacle and street canyon on the flow and dispersion. Most of all, some of the previous studies mainly focused on finding factors affecting the urban flow and dispersion in the street canyons. The important factors can be categorized into three. The first is the geometric factors that include the street aspect ratio generally defined as the ratio of the street height to the width. As the aspect ratio varies, different types of flow regime appear (Oke, 1988). The second is the meteorological factors including the ambient wind speed, wind direction, and turbulence intensity (DePaul and Sheih, 1986; Kim and Baik, 2004). The last is related to the thermal properties of the building and street surfaces (e.g., radiative heating or cooling, albedo, etc.) (Uehara et al., 2000).
Due to persistent urbanization, the population and traffic volume in urban areas increase year after year. Accordingly, urban areas become manhanttanized and compact through new construction and/or reconstruction. Resultantly, flow and pollutant dispersion in urban areas become much more complicated and quite dependent on the surrounding building environments (Kim and Baik, 2005). Recently, computational fluid dynamics models tried to be coupled with regional scale meteorological models for a more realistic simulation of the urban flow (Park, 2007). To take account of buildings in detail in simulating the urban flow and dispersion, a high-resolution grid system and a state-of-the-art computing system are required. At present, it is difficult to predict urban flow and dispersion using the coupled models in real time. Instead, studies on the urban flow and dispersion can be applied to the assessments against atmospheric impacts owing to the large-scale construction of apartment complexes and against the environmental impacts owing to ordinarily emitted pollutants from vehicles and/or poisonous gases from unexpected conflagration or intentional terror. Moreover, these studies have the potential to provide a good set of guidelines in establishing policies on city planning and development. For this, flow and dispersion characteristics should be generalized or parameterized by the main building's parameters (e.g., building length, width, height, and street width) in order to build in congested areas. However, it is very difficult to generalize the flow and dispersion characteristics due to very complicated urban and building morphology. This study focuses on the investigation of the effects of the arrays of buildings with different scales on the flow in an urban area.

2. EXPERIMENTAL SETUP

Fig. 1 shows the model's domain configuration. The computational domain sizes (cell numbers) are 300 m × 180 m × 163 m (150 × 90 × 60) in the x-, y-, and z-directions, respectively. The grid intervals in the x- and y- directions are 2 m. In the z-direction, the grid interval is 2 m for $0 \le z \le 40$ m and increases with the expansion ratio of 1.05 until it becomes about 3.3 m ($z \approx 65$ m). From the height to the top of the model, the grid interval is 3.3 m. For the systematic variation of the building density parameter in a definite computational domain, building width (L_x = 20, 32, 44 m), length (L_y = 20, 32, 44 m), and height (H = 20, 30, 40 m) vary and their combinations give 27 numerical experiments with different building densities. The smallest building sizes are 20 m in width, 20 m in length, and 20 m in height. In this case, the width between the buildings is widest (40 m). The largest building sizes are 44 m in width, 44 m in length, and 40 m in height and the width between the buildings is 16 m.

*corresponding author: Prof. Jae-Jin Kim. Tel.: +82-51-629-6645, jjkim@pknu.ac.kr

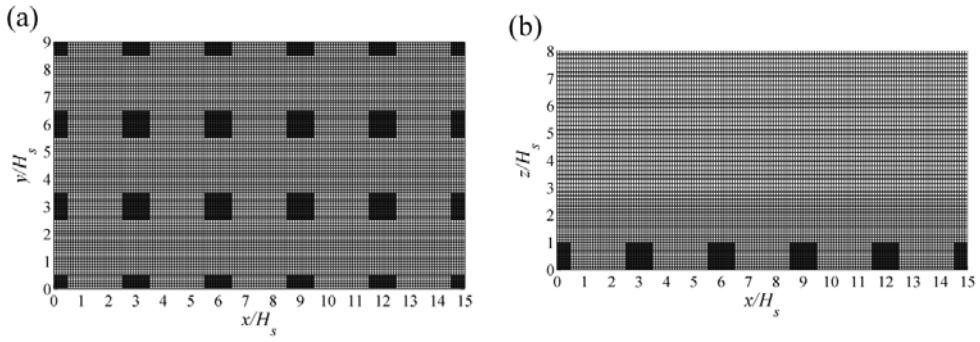


Fig. 1. (a) Top view and (b) side view of the computational domain and grid system. The rectangles in black indicate the buildings.

3. RESULTS AND DISCUSSION

Fig. 2a is shows that the double-eddy circulations are generated in the street canyons. Wake interference flow (WIF) occurs with the street-canyon aspect ratio (W_x/H, here, W_x is the street width and H is the building's height) of 2 and the building aspect ratio (L_y/H, here, L_y is the building's length) of 1 (Fig. 2a). In this study, the isolated roughness flow (IRF) does not appear because the street-canyon aspect ratios considered are relatively small (W_x/H_{max} = 2). When the building's width (L_x) and length (L_y) are smallest, WIF appears irrespective of the building's height (Fig. 2). The largest building width (L_x) and length (L_y), airflow outside the street canyons is nearly parallel to the street (Fig. 3). In the case with the relatively short buildings, one clockwise rotating vortex is generated in the vertical direction and the reverse flow appears near the bottom (Figs. 3a and 3b). In the cases with the relatively tall buildings, two counter-rotating vortices are generated. The lower vortex is rotating counterclockwise. It is seen that different flow patterns appear near the street bottom as the building's density varies. The flow patterns near the street bottom depend on the vortex intensity, the rotating direction of the vortex in the vertical cross section, and the intensity of the airflow beside the street canyons. To investigate the effects of the building's density on the wind environment, the vertical profiles of the horizontal wind, averaged in the streets and street canyons, are analyzed. Fig. 4 shows the averaged vertical profiles at the streets. As the building's length (L_y) increases (the street length, W_y decreases), the wind speed decreases. However, it is seen that the building's width (L_x) has little effects on the along-street airflow. The wind speed at the roof of the street canyon shows no dependency on the building's length but it decreases as the building's width increases (Fig. 5). In the street canyon, the wind speed is largely affected by the building's length when the building's width is smallest (Figs. 5a, 4d, and 5g). This effect of the building's length in the street canyon decreases as the building's width increases, and there is little difference in the wind speed when the building's width is largest (Figs. 5c, 5f, and 5i). In the lower layer, it is difficult to generalize the flow characteristics in terms of the building's density parameters because of the complicated flow patterns (e.g. different flow regimes and vortices numbers in the vertical cross sections).

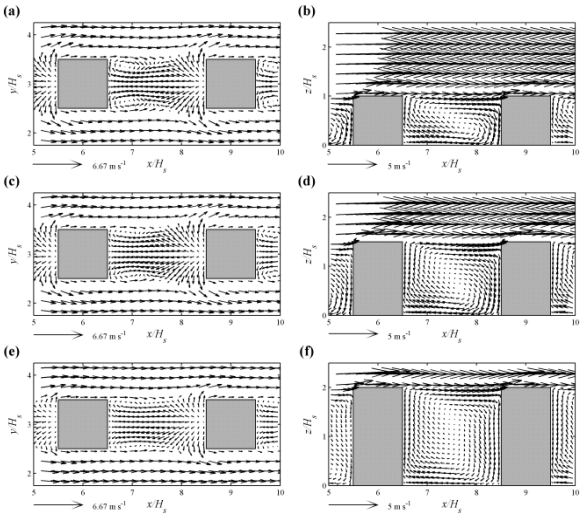


Fig. 2. The field of wind vectors at z/H_s = 0.05 and y/H_s = 2.75 for the wake interference flows.

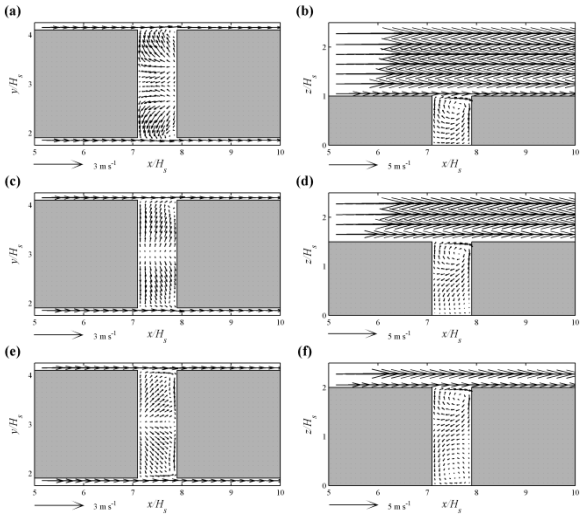


Fig. 3. The field of wind vectors at z/H_s = 0.05 and y/H_s = 2.75 for the skimming flows.

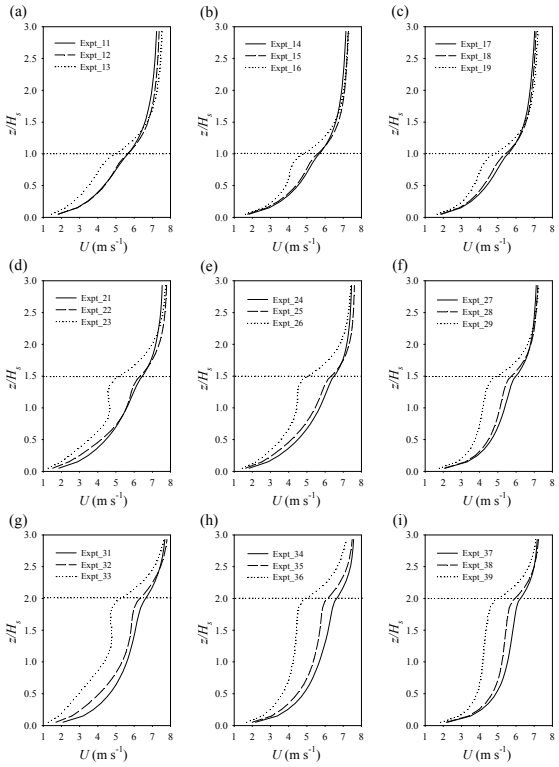


Fig. 4. The vertical profiles of the horizontal velocity (U) (U) averaged in the streets.

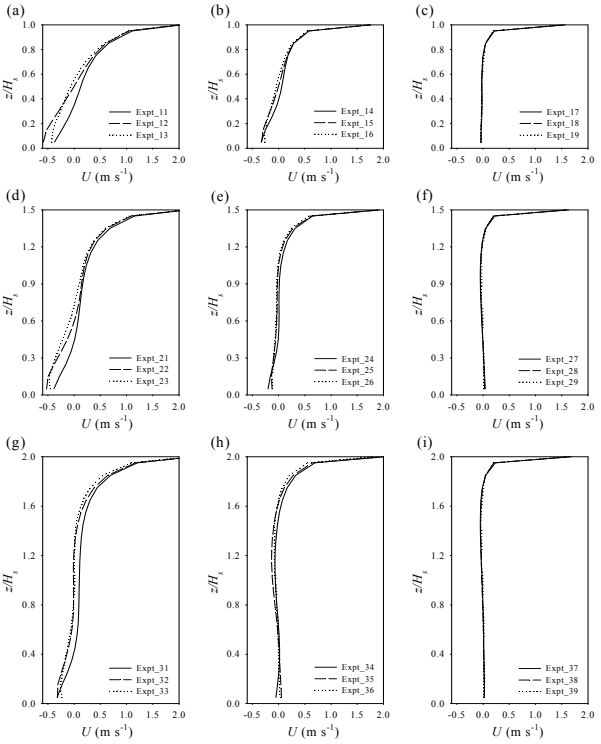


Fig. 5. The vertical profiles of the horizontal velocity averaged in the street canyons.

Airflow in the street canyons is composed of very complicated vortices rotating in the horizontal and vertical directions, so called, portal vortices noted in Kim and Baik (2004). Moreover, the position of the portal vortices is not fixed, which makes the comparison of the point-based wind profiles and generalization of the flow characteristics, in terms of a single building density parameter, not easy. The vortex circulations in the street-canyons are the main features of the street-canyon flows and can be characterized by vorticity, a measure of rotation in a fluid. For generalizing and representing the characteristics of complicated flows in terms of a single parameter, the vorticity is calculated at each grid point and the volume-averaged vorticity magnitude (hereafter VM) is defined as

$$\mathrm{VM} = \frac{1}{N}\sum_{n=1}^{n_{SC}}\sum_{k=1}^{k_{SC}}\sum_{j=1}^{j_{SC}}\sum_{i=1}^{i_{SC}}\left|\vec{\varpi}\right|_{i,j,k,n} \quad (N = i_{SC} \times j_{SC} \times k_{SC} \times n_{SC}), \tag{1}$$

$$\left|\vec{\varpi}\right| = \left(\varpi_x^2 + \varpi_y^2 + \varpi_z^2\right)^{0.5}, \tag{2}$$

$$\vec{\varpi} = \nabla \times \vec{u} = \varpi_x \hat{i} + \varpi_y \hat{j} + \varpi_z \hat{k}. \tag{3}$$

Here, i_{SC}, j_{SC}, and k_{SC} are the number of grid points in a single street canyon in the x-, y-, and z-directions, respectively and n_{SC} is the number of street canyons in a computational domain. Fig. 6a shows the VM in the street canyons. It is seen that the VM decreases as the building's length increases and other parameters are fixed. Nevertheless, it is still difficult to find regularities between the VM and the building's parameters. For finding the relationship between the VM and the building's parameters, a multi-linear regression is performed. The VM analyzed by the multi-linear regression (χ) is represented in terms of the building parameters as follows:

$$\chi = c_0 + c_1\left(\frac{L_y}{H}\right) + c_2\left(\frac{W_x}{H}\right) + c_3\left(\frac{L_x L_y}{H^2}\right) + c_4\left(\frac{L_y W_x}{H^2}\right) + c_5\left(\frac{L_y}{H}\right)^2 + c_6\left(\frac{W_x}{H}\right)^2 + c_7\left(\frac{L_x L_y}{H^2}\right)^2 + c_8\left(\frac{L_y W_x}{H^2}\right)^2. \tag{4}$$

Here, L_y/H is the building's length normalized by the building's height, W_x/H is the normalized width of the street canyon, L_xL_y/H^2 is the normalized horizontal building's area, and L_yW_x/H^2 is the normalized horizontal street-canyon area. The scatter diagram between χ and the calculated VM is shown in Fig. 6b The coefficient of determination (R^2) is 0.93 and the standard error of estimate is 0.014. This means that the VM estimated by the multi-linear regression model (χ) explains the

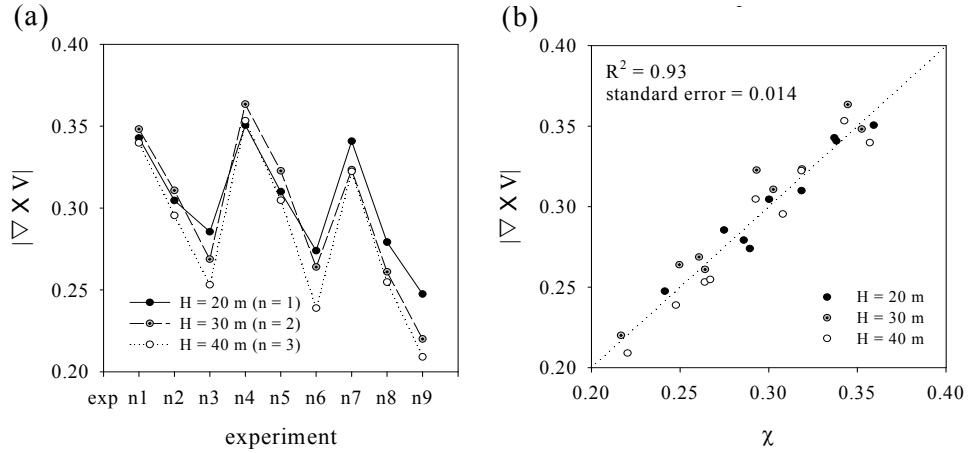


Fig. 6. (a) The volume-averaged vorticity magnitude in the street canyons and (b) the scatter diagram between the volume-averaged vorticity magnitudes simulated by the CFD model and estimated by the multi-linear regression model.

VM calculated in the street canyons very well. From the results, it is known that the building's density parameters that are important in determining the VM in the street canyons are the ratios of the building's length to the height (L_y/H) and the street-canyon width to the height (W_x/H).

4. CONCLUSIONS

The effects of the building's density on the flow characteristics are investigated. For the constant gross area, the building's density is systematically varied by increasing or decreasing the building's size. As the building's density varies, complicated flows are generated in the street canyons. There occurs the a double-eddy circulation in the street canyons in all the cases. In the five cases, wake interference flow occurs. In the other cases, skimming flow appears. This result is in relatively good agreement with that in the previous study based on the field and physical experiments. The wind speed in the street, parallel to the inflow, is mainly affected by the building's length. In urban areas, channeling flow is often observed where the street width becomes narrow. However, the channeling flow does not appear in this study because buildings with the same size are assumed to be regularly aligned. Because the complicated flow patterns appear, due to the variation of the vortex structure and vortex number, it is difficult to generalize the characteristics of flow in the street canyons in terms of the building's density parameters. The volume-averaged vorticity magnitude is a very good indicator to reflect the flow characteristics despite the strong dependency of flows on the variation of the building's density parameters. From a multi-linear regression, it is concluded that the volume-averaged vorticity magnitude is a strong function of the building's length and the street-canyon width normalized by the height. The increase in the building's length decreases the vorticity while the increase in the street-canyon width increases the vorticity.

Acknowledgements

This work was funded by the Korea Meteorological Administration Research and Development Program under Grant CATER 2007-3307.

References

DePaul, F. T., and C. M. Sheih, 1986: Measurements of wind velocities in a street canyon. Atmos. Environ., 20, 455-459.

Kim, J.-J., and J.-J. Baik, 2004: A numerical study of the effects of ambient wind direction on flow and dispersion in urban street canyons. Atmos. Environ., 38, 3039-3048.

Kim, J.-J., and J.-J. Baik, 2005: An investigation of flow and scalar dispersion in an urban area using a CFD model. Journal of the Korean Meteorological Society, 41, 821-837.

Oke, T. R., 1988: Street design and urban canopy layer climate. Energy and Building, 11, 103-113.

Park, S.-B., 2007: Urban flow and pollutant dispersion simulation using a coupled CFD-MM5 model. M.S. thesis, School of Earth and Environmental Sciences, Seoul National University, 74pp.

Uehara, K., S. Murakami, S. Oikawa, and S. Wakamatsu, 2000: Wind tunnel experiments on how thermal stratification affects flow in and above urban street canyons. Atmos. Environ., 34, 1553-1562.