The impact of urban parameters on the ventilation in idealized urban model with fixed area

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Abstract. With population growing rapidly, the lack of land is becoming serious. In order to make full use of land, more and more buildings are built in a limited area and the building height is higher and higher. However, the change of the building height and building density has the significant impact on the efficiency of the urban ventilation. This papers investigates canyon ventilation under neutral atmosphere condition with same building area density (λp = 0.25) and fixe ground area (300mX300m) but various frontal building area density (λf = 0.075~0.425), plot ratio (λr = 2.52~4.00). The roof air change rate per hour (ACHroof) induced by turbulence and the horizontal air change rate per hour (ACHhorizontal) induced by mean flow, calculated by the CFD simulation by standard k-ε model, is adopt to quantify the vertical and horizontal air exchange, respectively. The results show that: 1) with the increase of the frontal building area density (λf), ACHroof increases logarithmically and ACHhorizontal decays exponentially. With the increase of λf, the resistance of buildings to airflow increases gradually, this is why the ACHhorizontal decreases exponentially, the remaining air flow is discharged through the roof, so ACHroof increases logarithmically, but the sum of ACHhorizontal and ACHroof is constant, equal to 10.2h⁻¹. 3) ACHhorizontal is negatively correlated with plot ratio, while ACHroof is positively correlated with plot ratio. This is because plot ratio represents the building density, drag force increases with building density. This study can be used to guide urban planning and improve urban ventilation environment.

Keywords: Urban canopy layer; urban ventilation; air change rate per hour; frontal building area density; plot ratio

1. Introduction

With the sustainable development of urbanization, a large number of people poured into the city, which caused city increasingly crowded. In order to solve the contradiction between people's living demand and the shortage of construction land, urban buildings are becoming denser and taller, which trigger some urban ventilation environmental problems, such as urban heat island and increasing air contamination [1].

Good urban ventilation is regarded as an effective measure to reduce urban temperature, dilute pollutants and lower energy consumption of building air conditioning [2]. Urban canopy layer (UCL) refers to the space area from the bottom of buildings to the roof of buildings, and canopy ventilation has a direct impact on outdoor thermal comfort in pedestrian zone (Height from ground (z) less than 2m).

In recent years, many study has been conducted to investigate the relationship between UCL ventilation and urban parameters. The street aspect ratio, frontal area density, building area density [3-4]
have significantly influence UCL ventilation. Some other parameters such as building height, urban size building height variation, wind direction, vegetation [6-9] as so on, also has been studied to explore the mechanism for UCL ventilation. At the same time, in order to evaluate urban ventilation, many rating indicators have been proposed including volumetric flow rate, air exchange rate per hour (ACH), pollutant exchange rate, purging flow rate, age of air exchange velocity [10-13], which is created to evaluate pollutant removal capacity, air cleanliness and outdoor thermal comfort.

However, with the swift growth of population and the shortage of construction land, it is necessary to build more buildings on limited land and the height of buildings is constantly increasing to improve the efficiency of land use and solve the contradiction between man and land. In this paper, the exchange rule of UCL ventilation is studied by frontal building area density (\( \lambda_f = 0.075 \sim 0.425 \)), plot ratio (\( \lambda_r = 2.52 \sim 4.00 \)) caused by increasing the number of buildings on fixed area (300m \( \times \) 300m) under neutral atmosphere condition with same building area density (\( \lambda_p = 0.25 \)), The evaluation index air exchange rate per hour (ACH) is selected to assess the ventilation condition. The roof air change rate per hour (ACH\text{roof}) induced by turbulence and the horizontal air change rate per hour (ACH\text{horizontal}) induced by mean flow is adopt to quantify the vertical and horizontal air exchange, respectively.

The remainder of this paper is structured as below: Section 2 describe the CFD methodologies including model arrangement and CFD setup (subsection 2.1), concept of frontal building area density (\( \lambda_f \)), plot ratio (\( \lambda_r \)) (subsection 2.2), the grid independence test (subsection 2.3). Section 3 presents results and discussion and conclusions are in Section 4.

2. Methodology
2.1 Model arrangement and CFD setup
As shown in figure 1, the model area is fixed (300\( \times \)300) with the square shape, all buildings with the same height (30m). The setup of boundary condition is presented in the figure 1(a), the velocity in inlet is 1.5m/s and the approaching wind is parallel the main street, the two lateral sides and the roof of the computational domain are set into Symmetric boundary conditions, the outlet is pressure outlet. The distance from UCL boundaries to domain roof, domain outlet and domain inlet are 9H, 8H, 5H respectively in figure 1(b) and 1(c). No slip boundary condition with standard wall function [13, 14] is used at all wall surfaces.

The width and length of all buildings are equal to the street width (B=L=W), and the value of B is related to the number of buildings with fixed area. All cases are shown in the table 1.

In spite of their limitations in predicting turbulence, steady Reynolds-Averaged Navier-Stockes (RANS) approaches have been widely adopted to predict the flow and pollutant dispersion in urban models [62-64], as one of the most widely-adopted RANS approaches, the standard k-\( \varepsilon \) has been successfully validated in predicting mean flows and pollutant dispersion in urban models [13-15], so the standard k-\( \varepsilon \) is selected in this paper to solve urban airflows and its quality in CFD prediction.

| Table 1. Case arrangement |
|--------------------------|
| Case | N | B | W | H | \( \lambda_p \) | \( \lambda_f \) | \( \lambda_r \) |
|------|---|---|---|---|-------------|-------------|-------------|
| 2    | 4 | 100.00 | 100.00 | 30 | 0.25 | 0.075 | 4.00 |
| 3    | 9 | 60.00 | 60.00 | 30 | 0.25 | 0.125 | 3.24 |
| 4    | 16 | 42.86 | 42.86 | 30 | 0.25 | 0.175 | 2.94 |
| 5    | 25 | 33.33 | 33.33 | 30 | 0.25 | 0.225 | 2.78 |
| 6    | 36 | 27.27 | 27.27 | 30 | 0.25 | 0.275 | 2.68 |
| 7    | 49 | 23.08 | 23.08 | 30 | 0.25 | 0.325 | 2.61 |
| 8    | 64 | 20.00 | 20.00 | 30 | 0.25 | 0.375 | 2.56 |
| 9    | 81 | 17.65 | 17.65 | 30 | 0.25 | 0.425 | 2.52 |
2.2 Concept of frontal building area density ($\lambda_f$), plot ratio ($\lambda_r$)

Frontal building area density ($\lambda_f$) is the ratio of the frontal area of building to the total floor area, which represents the degree of obstruction to horizontal airflow\cite{1,15}. As presented in Equation (1), $\lambda_f$ is determined by the H (building height), B (building width) and W (street width).

$$\lambda_f = \frac{H \cdot B}{(B + W) \cdot (B + W)}$$

Plot ratio ($\lambda_r$) is ratio of gross building area to land area, which directly relates to the comfort of living for households, but for developers, plot ratio determines the proportion of land price cost in housing. As presented in Equation (2), $\lambda_r$ is determined by the gross building area ($A_{\text{gross}}$) and land area ($A_{\text{land}}$). For the idealized urban model in figure 1, there are 9 floors in a building with the 30m height. The Equation (2) is transferred into Equation (3), n, k represents the street number and the floor number.

$$\lambda_r = \frac{A_{\text{gross}}}{A_{\text{land}}}$$

$$\lambda_r = \frac{(n + 1) \cdot (n + 1) \cdot B \cdot B \cdot k}{300 \cdot 300}$$

2.3 The grid independence test

In order to remove the influence of mesh size on simulation results and shorten the computing time, it is necessary to test the independence of mesh. As shown in figure 2 and table 2, medium grid, fine grid and coarse grid are selected for testing.

Because the quality of structured grid can satisfy the requirement of calculation well, but the aspect ratio
of grid is greatly affected by the size of grid and the setting of boundary layer, so aspect ratio of grid is selected as the criterion of grid quality.

| Size type | Total mesh | Building mesh size | domain mesh size | Aspect ratio |
|-----------|------------|--------------------|------------------|--------------|
| Fine      | 6874335    | 2.1                | 3                | 1.56         |
| Medium    | 2688186    | 2                  | 5                | 2.98         |
| Coarse    | 1886740    | 3                  | 5                | 4.55         |

Table 2. Grid size for independence test

Figure 3(a)-(c) compare the CFD results with different grid size including horizontal velocity $u(z)$, vertical velocity $w(z)$ and turbulence kinetic energy $k(z)$ at the central line shown in figure 1 (c). It shows the medium grid arrangement can successfully predict $u(z)$ with the same accuracy as the fine grid, the $w(z)$ and $k(z)$ of medium grid is little worse than that of fine grid. However, the coarse grid has worst prediction in $u(z)$, $w(z)$ and $k(z)$. To reduce time assumption and get relatively high accuracy, the medium grid is selected for the simulations.

Figure 3. The results of independence test: (a) $u(z)$, (b) $w(z)$, (c) $k(z)$

3. Results and discussion

The effects of the frontal building area density ($\lambda_f$), frontal building porosity ($\lambda_b$) and plot ratio ($\lambda_r$) on the air exchange in UCL is analyzed in this section. Based on the result analysis, the regional planning for improving the air exchange in UCL is further discussed.
3.1 The impact of frontal building area density ($\lambda_f$) on the ACH

The effects of $\lambda_f$ are plotted in figure 4 (a). When the number of buildings increases from 4 to 81 in the fixed area (300m $\times$ 300m), the $\lambda_f$ changes from 0.075 to 0.425, the $ACH_{\text{roof}}$ increases logarithmically, the $ACH_{\text{horizontal}}$ decays logarithmically, the $ACH_{\text{total}}$ remains almost unchanged, equal to 10.22 h$^{-1}$. Due to the increase of $\lambda_f$, the resistance of buildings to airflow increases gradually, the most of the air flow is discharged through the roof by turbulence, the air flow by the mean flow decreases.

3.2 The impact of plot ratio and ACH

In figure 4 (b), $ACH_{\text{roof}}$ and plot ratio ($\lambda_p$) is linearly positively correlated, $ACH_{\text{horizontal}}$ and plot ratio ($\lambda_r$) is linearly negative correlated. When the plot ratio is approximately equal to 3.25, $ACH_{\text{horizontal}}$ is equal to $ACH_{\text{roof}}$. Compared with frontal building area density ($\lambda_f$), plot ratio can better describe the relationship with ACH. Plot ratio ($\lambda_r$) only considers horizontal building density, but also vertical building density. It is a three-dimensional urban density parameter. It can better express the obstruction of horizontal and vertical density of buildings to air flow.

4. Conclusions

This paper investigates canyon ventilation under neutral atmosphere condition with same building area density ($\lambda_p$=0.25) and fixe ground area (300m $\times$ 300m) but various frontal building area density ($\lambda_f$=0.075–0.425), plot ratio ($\lambda_r$=2.52–4.00).

The roof air change rate per hour ($ACH_{\text{roof}}$) induced by turbulence and the horizontal air change rate per hour ($ACH_{\text{horizontal}}$) induced by mean flow, calculated by the CFD simulation by standard k-ε model, is adopt to quantify the vertical and horizontal air exchange, respectively.

With the increase of the frontal building area density ($\lambda_f$), $ACH_{\text{roof}}$ increases logarithmically and $ACH_{\text{horizontal}}$ decays exponentially. With the increase of $\lambda_f$, the resistance of buildings to airflow increases gradually, this is why the $ACH_{\text{horizontal}}$ decreases exponentially, the remaining air flow is discharged through the roof, so $ACH_{\text{roof}}$ increases logarithmically, but the sum of $ACH_{\text{horizontal}}$ and $ACH_{\text{roof}}$ is constant, equal to 10.2h$^{-1}$.

$ACH_{\text{horizontal}}$ is negatively correlated with plot ratio, while $ACH_{\text{roof}}$ is positively correlated with plot ratio. This is because plot ratio represents the building density, drag force increases with building density. This study can be used to guide urban planning and improve urban ventilation environment.
Acknowledgements
This work was supported by Natural Science Foundation project of China (Grant NSFC 51561135002) and National Key R&D program 'Solutions to Heating and Cooling of Building in the Yangtze River Region' (2016YFC0700301).

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