Investigation of air flow and pollutant dispersion in street canyon

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Abstract. With the rapid development of the city, more and more attention has been paid to the air quality of street canyon. We numerically investigate the air flow and pollutant dispersion in the street canyon with different window opening percentage, different wind speed and roof shapes. The results show that the window opening area leads to a significant improvement of removing pollutant out of street canyon, especially for pollutants distributed on upsides of leeward and windward walls. With increasing window opening percentage, the pollutant concentration K distributed on downsides of leeward and windward walls gradually decreases. With the growth in wind speed, the pollutant concentration K also drops. The slanted roof shape may be a better choice to improve the efficiency of pollutant removal.

1 Introduction

Motor vehicles promote economy and improve standard of living. But it brings about serious pollution to the environment especially in urban cities. To have a better understanding of the mechanisms about emission flow and pollutant transport in street canyons, many studies in street canyon have been widely carried out. Meroney et al. [1] investigated pollutant dispersion in street canyons through wind tunnel experiment. Rafailidis [2], Kastner-Klein and Plate [3] reveal the impacts of building roof shape on the emission flow and pollutant diffusion. Chan et al. [4] have pointed out that the geometry of street canyon has important effect on the pollutant dispersion. Huang et al. [5], Mohammed [6] and Takano et al. [7] investigated a series of simulations for air flow and pollutant dispersion in the street canyons with different height and shape of building roof. Ferrari et al. [8] reported the wind flow and pollutant dispersion in narrow urban street canyon.

Many investigations above mainly focused on the influences of building configurations, roof shapes and wind speed in street canyons. In this paper, the window opening percentage, roof shapes, wind speed are considered to investigate the pollutant concentration K in street canyon.

2 Methods and validation

2.1 CFD model

In this study, the computational domain is shown in Fig. 1 (a)-(d). It consists of a street canyon with different roof shapes (flat roof, slanted roof, downwind roof and upwind roof), different window opening percentages ($w=10\%$, 20% and 30%) and the line source S in the center. The investigated domain is $0.48 \times 0.72\text{m}$. The whole model is scaled at 1:500 in the experiment design, in which the inlet and outlet domain are $4H$ and $8H$ from the target building respectively. The height of building and width of street canyon are $H=0.06\text{m}$ and $W=0.06\text{m}$ (Chan et al. [4]).

At the inflow boundary, the profiles of wind velocity, zero-gradient conditions are imposed for the outflow condition. At the top of domain, a symmetry boundary condition is applied. In addition, to solid surfaces with no-slip in the street canyon, The pollutants (the mixture of air and ethane) are emitted from the line source S located at the central street canyon at a constant volume flow rate.

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Fig. 1 Computational domain

In this study, the Reynolds Averaged Navier-Stokes (RANS) equations for fluid flow and transport principles are employed to describe air flow and pollutant dispersion in street canyons for different window opening percentage (WOP), wind speeds and roof shapes in terms of continuity, momentum and transport equations. Equations for turbulent kinetic energy and turbulent dissipation rate are solved with standard $k-\varepsilon$ scheme. The wind flow in the street canyon is considered to be incompressible turbulent flow, and the densities of air and pollutant are assumed to be constant.

2.2 Model validation

Fig. 2 shows the dimensionless concentration K computed in this study and the experimental data obtained by Meroney et al. [1]. The experiment was conducted out in the atmospheric boundary layer wind tunnel at Meteorological Institute of Hamburg University. It can be found that the results of this paper show a good agreement with the experimental data when wind speed are equal to 3m/s and 5m/s respectively. Fig. 2 also shows that the pollutant concentration K of leeward wall is much higher than that windward wall. Meanwhile, the value of concentration K distributed on the leeward wall increases faster than windward wall from roof to ground. A slight difference occurs between CFD and experiment at the leeward wall when $Z/H < 0.02$ and at the windward wall when $Z/H < 0.06$.

Fig. 2 (a) Comparisons of non-dimensional concentration K $U_{ref} = 3\text{m/s}$.

Fig. 2(b) Comparisons of non-dimensional concentration K $U_{ref} = 5\text{m/s}$.

3 Results and Discussions

In this paper, the air flow and pollutant dispersion characteristics in street canyons containing a line source S located at the center are investigated numerically. The WOP ($w=10\%$, 20% , 30%) are attached to leeward and windward walls with different roof shapes in street canyon respectively. The building roof shapes including flat roof, slanted roof, downwind roof and upwind roof are taken into account. Meanwhile, the air inflow reference velocity are considered to be $U_{ref} = 3\text{m/s}$ and $U_{ref} = 5\text{m/s}$. A numerical study on the impacts of wind speed, roof shapes and WOP is carried out in this section.

3.1. The influences of wind speed

Fig. 3 depicts the dimensionless concentration K distributed on upside ($Z/H > 0.03$) and downside ($Z/H < 0.03$) of leeward and windward walls respectively with $U_{ref} = 3\text{m/s}$ to $U_{ref} = 5\text{m/s}$ for flat roof. It is clear that the concentration K distributed on upside of windward and leeward walls is in an extremely lower level than on another two sides and the value of it is almost equal to zero. The reason is mainly that the removal of pollutants near leeward upside and windward upside are significantly efficient when the wind is blown across the position of window opening.

In Fig. 4, the concentrations along the downside of leeward and windward walls decrease slightly when the

wind speed varies from $U_{ref} = 3\text{m/s}$ to $U_{ref} = 5\text{m/s}$. And when Z/H is close to zero, the K between downside of windward and leeward walls becomes larger. Meanwhile, it is interesting that the concentration K distributed on the downside of leeward wall is lower than on the downside of windward wall. This phenomenon is different from the urban street canyons without WOP. The reason is that near leeward downside, the counterclockwise vortex is formed and then it transports more pollutant (ethane) from the line source to windward downside.

3.2. The influences of roof shape

Above mentioned that the concentration K distributed on leeward and windward wall downsides is far greater than other sides (leeward and windward wall upsides). Therefore, in this section, the concentration K distributed on leeward and windward wall downsides is only described. It can be seen in Fig. 4 that for upwind roof, the value of concentration K distributed on leeward wall downside is the highest but distributed on windward wall downside the value is the lowest. Meanwhile, it can be easily observed that for downwind roof, the concentration K exactly shows an opposite phenomenon to upwind roof. In comparison with other three roof shapes, for downwind roof, the pollutant concentration K distributed on leeward wall downside is lowest but on windward wall downside is the largest. The reason is mainly that for downwind roof shape

Fig.3 Dimensionless concentration K distributed for flat roof shape

the wind has a stronger hitting on the windward wall which helps to remove more pollutant. But for leeward wall, the intensity of wind hitting declines and more pollutant could stay at this district. The same reason is also fit for upwind roof shape. In regard to slanted and flat roof shapes, the pollutant concentration K distributed on leeward and windward wall downside is very close and the slanted roof shape shows a more positive impact on transport pollutants effectively. The pollutant

concentrations distributed on leeward and windward walls downside are both lower than flat roof shape. As a result, it shows us that downwind and upwind roof shape may not be a better choice to remove pollutants out of street canyons and slanted roof shape may be a good recommendation to promote the reduction of pollutants.

3.3. The influences of WOP

Fig.5 exhibits the dimensionless pollutant concentration K distributed on leeward and windward wall downsides for three kinds of WOP with four kinds of building roof shapes including flat roof, downwind roof, slanted roof and upwind roof. It is visibly observed that for all kinds of building roof shapes, with the increase of the WOP from $w=10\%$ to $w=30\%$, the non-dimensional pollutant concentration K gradually decreases, whether it is at downside of leeward wall or windward wall. It can be stated that with increasing WOP, more pollutant escapes from the street canyon. It has pointed out above that the value of pollutant concentration K distributed on upsides of leeward and windward wall is almost equal to zero. So, it can be inferred that in real urban street canyon, the WOP has a very significantly positive impact on removing pollutants distributed on upsides of leeward and windward wall. And it also can contribute to removing more pollutant distributed on downsides of leeward and windward walls. At the same time, for all kinds of roof shapes, the WOP show a greater influence on pollutant concentration K distributed on downside of windward wall than leeward wall. With the enlargement of WOP, the pollutant concentration K distributed on downside of windward wall decreases more evidently than leeward wall. This is mainly due to flow intensity is enhanced at this district. As for pollutant concentration K distributed on downside of leeward wall, its amplitude of fluctuation is obviously weakened. A slight decrease occurs at pollutant concentration K distributed on downside of leeward wall.

Fig. 4 Dimensionless concentration K distributed for different roof shape.

Fig.5 The dimensionless concentration K distributed

4 Conclusions

In this study, the non-dimensional pollutant concentration K in urban street canyon is investigated numerically. Three kinds of WOP ($w=10\%$, 20% , 30%), wind speeds ($U_{ref} = 3\text{m/s}$, $U_{ref} = 5\text{m/s}$) and four kinds of roof shapes (flat roof shape, downwind roof shape, slanted roof shape and upwind roof shape) are taken into consideration. Based on the results above mentioned, the general conclusions are as follows:

1) For flat roof shape, the pollutant concentration K distributed on downside of leeward wall is much lower than windward wall under two kinds of wind speeds. With increasing the wind speed, for four kinds of roof shapes, the height and width of vortexes at the corner of leeward and windward walls show a different change.

2) The roof shape has a great effect on flow characteristics especially for the wind blow across street canyon and there is a difference in value of pollutant concentration K .

3) The existence of WOP has a significantly positive impact on removing pollutant out of street canyon. With the increasing of WOP, the pollutant concentration K distributed on windward wall shows a sharper drop than leeward wall. The downwind and upwind roof shape may be a bad choice to remove the pollutant out of street canyon and yet, the slanted roof shape may be a better choice.

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