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Modelling of Flow Structure and Pollutant Dispersion in Symmetric Street Canyon

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Abstract – *The quality of air condition is one of the major factors affecting the health of people living in urban areas. Different geometry of street canyon coupled with different wind direction will result in various concentration of pollutant accumulated in the canyon. The purpose of this research is to study the flow structure and also pollutant dispersion in a 3-D symmetric street canyon using computational fluid dynamics. Different k-Ɛ turbulent models were used to simulate the flow structure, and the result was compared to experimental. The effects of aspect ratio and Reynolds number to the flow structure and pollutant dispersion in a street canyon were investigated. The studied canyons were avenue, regular and deep canyon with the aspect ratio of 0.4, 1 and 2 respectively, and Reynolds number of 9000 and 30700.*

Keywords: Symmetric street canyon, k-Ɛ model, Flow structure, Pollutant dispersion, FLUENT

1.0 INTRODUCTION

Flow structure and particle dispersion inside urban street canyon has always been a significant scope to study due to its diverse aspects and practical purposes. Nicholson [1] describes that as a relatively narrow street in between buildings that line up continuously along both sides. Hunter *et al*. [2] stated that the canyon structure has been the center of attention for researchers as different variables such as geometry, wind profile and city climate will produce distinct environment inside the canyon itself. One of the significant properties of street canyon is the flow pattern inside the canyon created by the movement of wind on rooftop level.

Tall buildings that surround an urban street canyon limit the ventilation of air inside and when coupled with heavy traffics that emit pollutants, it will create a poor air quality condition, which has become a major concern in urban areas. The dispersion of pollutants mostly depends on the flow profile or air inside the canyon. Over the past two decades, numerous researches have been done to investigate the flow profile inside a street canyon through various methods such as field observation, fluid experiments using wind tunnels, and computational fluid dynamics simulation. Based on the researches done, it is found out that flow regime, mean flow and turbulence statistics, dispersion mechanism, thermal effect on flow and dispersion, and bulk effects of buildings on mean flow and turbulent kinetic energy are the important aspects in understanding the flow structure and pollutant dispersion in an urban street canyon.

Flow inside a street canyon has been investigated numerically and experimentally for decades. Over the year, vast improvements are made in this area with the advancement of technology

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such as CFD software. It has made the process of simulating a flow faster and easier. Previous studies on wind flow field and pollutant dispersion inside street canyons are mostly done in two-dimensional approach. There are few three-dimensional cases, but they did not compare the result of different k-Ɛ to experimental results.

This study used three-dimensional street canyon model and the results from simulation were validated against a wind tunnel experiment. Three different turbulent models namely Standard, Renormalization Group (RNG) and Realizable k-Ɛ were used for simulation and the results were compared to determine the best k-Ɛ model for simulating flow structure and pollutant dispersion in a three-dimensional symmetric street canyon. Building aspect ratio and Reynolds number were the manipulating variables in the simulations. The pollutant was assumed as massless and non-reactive, and the source only came from vehicular emission in the middle of street canyon. The results from this research will show the effect of different aspect ratio and wind velocity to the flow pattern and pollutant concentration on the building inside the canyon. It will also compare the difference between 2-D and 3-D modelling on street canyon features.

2.0 GEOMETRY MODELLING

The three-dimensional model of street canyon used in this simulation is shown in Figure 1 (View along the canyon; front view), which was created by using Design Modeler in ANSYS FLUENT. The model is based on previous wind tunnel measurement done by Allegrini *et al.* [3]. Some modifications were made to reduce the computational time without influencing the result.

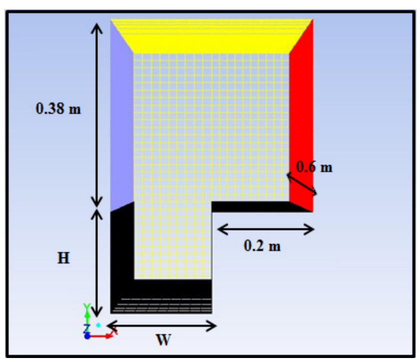

Figure 1: Dimensions of the model

For the variation of aspect ratio, the height was maintained but the width was adjusted. In the case of AR=1, H=W=2m, AR=0.4, W=0.5m and for AR=2, W=0.1m, the dimensions for pollutant were 0.1 x 0.2 x 0.6 m.

3.0 EXPERIMENTAL SETUP

ANSYS FLUENT software was used to solve the numerical calculation. The geometry was meshed using hexahedral and equidistant mesh. The number of cells was increased for mesh independent study purpose only in x and y directions. The mesh size in z direction was maintained for all cases.

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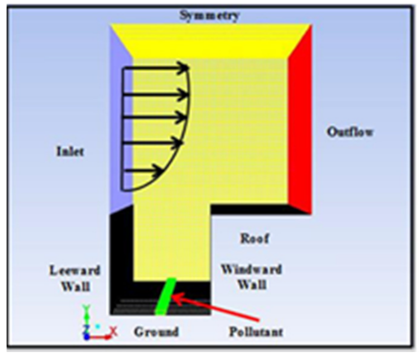

Figure 2: Geometry modelling

Boundary conditions were set accordingly. The wall type was set to be stationary and had no slip shear condition. The roughness constant was fixed to a constant of 0.5. The flow rate rating for outflow was fixed at 1. On the other hand, for inlet type, external data was required. The data of boundary layer velocities, kinetic energy and turbulent dissipation for different Reynolds number were extracted from wind tunnel measurement by Allegrini *et al*. [3]. These data were then saved as profile type and extracted to FLUENT. Boundary condition for outlet was set as the outflow.

In order to include the pollutants, the species transport was switched on to define the air-carbon monoxide mixture properties. In the cell zone condition, the part for carbon monoxide was set for a source term of 8.3333 kg/m^3s. This value was obtained using 1 g/s as calculated from the formula by Tsai and Chen [4]:

$$q_{ik}(t) = \frac{EF_{ik}(t) \times N_k(t)}{A_k \times 1000} \tag{1}$$

where EF_{ik} is the emission factor of pollutant i and N_k is the average traffic flow rate, with subscript $_k$ refers to the k^{th} lane. N_k was determined from the measurements, hence q_{ik} could be evaluated once EF_{ik} was known. The emission factor of CO given by Taneeb [5] was used in this calculation. The situation was assumed to be slow moving car (30 m/s) moving along a 60 m canyon. In an hour average time, 4,500 cars were assumed to have passed through the canyon.

4.0 RESULTS AND DISCUSSION

4.1 Validation

The simulation was validated against wind tunnel measurement by Allegrini *et al*. [3]. In order to find the most suitable turbulence model, the simulation was conducted using different k-Ɛ models namely Standard, RNG and Realizable. The results were then plotted against the result from the wind tunnel measurement. Figure 3 shows the result of Y (Situated in the middle of the canyon) against x-velocity for different turbulent models (AR=1, AR=9000).

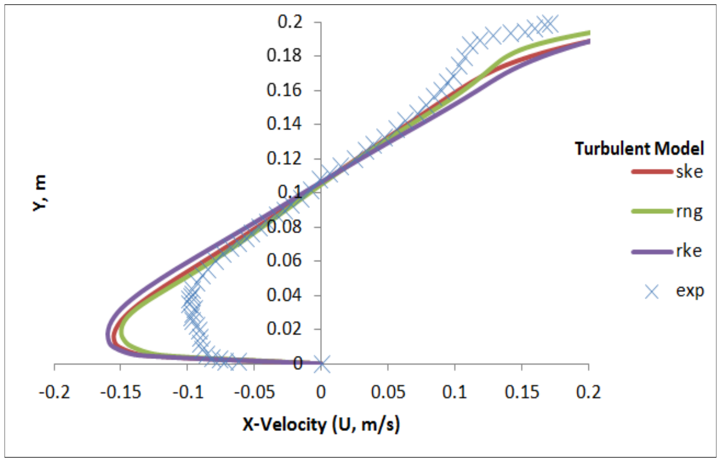

Figure 3: Variation of X-velocity along the height of canyon

From the graph, it is clear that RNG k-epsilon model is the best for modelling fluid flow over a cavity such as wind flow over wind canyon. This is in line with the result obtained from a numerical study by Baik and Kim [6,7], where RNG k-Ɛ turbulence model was shown to improve upon the standard k-Ɛ model in simulating turbulent kinetic energy field near the upwind edge of the building. RNG k-Ɛ also has been proven by Chan *et al*. [8] as the best model for simulating 2-D street canyon.

4.2 Flow Structure

The flow structure depends on the velocity of air flowing at roof level and also the geometry of the canyon. Figure 4 shows velocity contour of different Reynolds number and aspect ratio inside the street canyon.

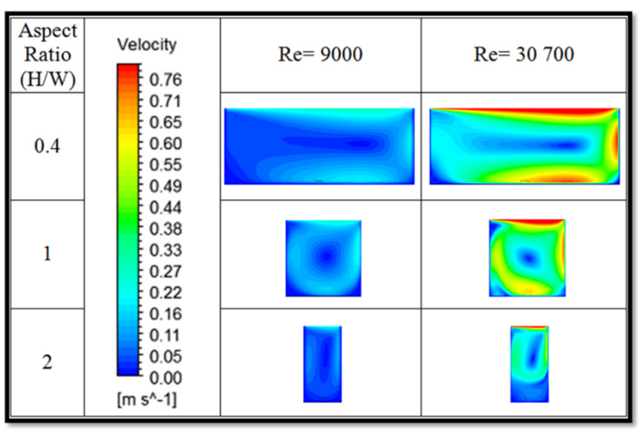

Figure 4: Velocity contour

Generally, a vortex, which is a spiral motion of fluid within a limited area, will appear in street canyon as a result of wind flow at the roof level. The number and shape of vortex depend on the wind velocity, as well as the containment area.

For low wind speed and AR=1, one circular shaped vortex was formed at the middle of the canyon. As the aspect ratio decreased to 0.4, the vortex stretched horizontally and its center shifted to the right. However, for deep canyon (AR=2), two vortices were spotted to align vertically. The primary vortex situated near the roof level with the center at the middle is much stronger compared to the secondary vortex situated near the backwind building. All of the said vortices moved in clock-wise direction except for the secondary small vortex, which flowed in the opposite.

As the wind speed increased, the flow structure inside the street canyon for the aspect ratio 1 and 0.4 maintained the same. However, for AR=2, the secondary vortex merged with the primary vortex to form only one vertically stretched vortex, which flowed in clock-wise direction. Stretched vortex is caused by the increasing vorticity in the stretched direction, but it is also limited by the control volume. The fact that vorticity increases with component velocity explains the formation of the flow structures as stated above.

When the roof level velocity flow across a canyon increases, the velocity variation across the canyon will also increase, thus creating vortex with high strength. From the velocity contour, it shows that higher building aspect ratio will result in lower air velocity at the pedestrian level, but higher Reynolds number will have the opposite effect. This is due to the distance between the roofs, where the free-stream velocity is to the ground.

Viewing from the building aspect, the ratio of wind velocity at the backwind building to upwind building decreased with the reduction of aspect ratio and Reynolds number. This can be explained by the fact that when air flows into a street canyon, it will first strike the backwind building than the ground and upwind building, therefore losing momentum along the way due to friction or any obstructions on the pedestrian level. The results obtained for AR=1 and AR=0.4 shows that the flow structures are almost the same along the street canyon, which means that the effect of z-axis is nearly non-existent, and this is similar for the two-dimensional simulation done by Baik and Kim [6,7] and three-dimensional analysis by Christian and Banerjee [9]. For the deep canyon case, the z-direction does have a significant effect to the flow field as the flow structure along the canyon keeps changing. The length of street canyon should be taken into consideration when modelling in three dimension.

The analysis of flow structure is important as it will affect the dispersion of pollutants inside a street canyon. Turbulent intensity, vortex shape and strength are major factors that dictate the behavior of pollutant transportation.

4.3 Pollutant Dispersion

Pollutants emitted from vehicles such as carbon monoxide are very harmful to human being. It is necessary for urban area developers to build street canyon with proper air ventilation to increase the health of people inside the area. Figure 5 shows the contour of carbon monoxide mass fraction inside a street canyon with different aspect ratios and Reynolds number. For the variation shown in Figure 6 and Figure 7, the measurement was taken at leeward and windward side of buildings.

From the carbon monoxide contour and the molar concentration variation, leeward wall generally has higher pollutant concentration as compared to windward wall for all aspect ratios and both Reynolds number, except for the case of AR=2 coupled with Re=9000. In this case, high concentration of pollutants resided at the bottom of windward side as opposed to leeward side. The concentration at the windward wall decreased gradually with the height of the

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building and the concentration was equal for both sides at y=0.085 m. The concentration continued to decline until half of the building height, and it became almost constant after that.

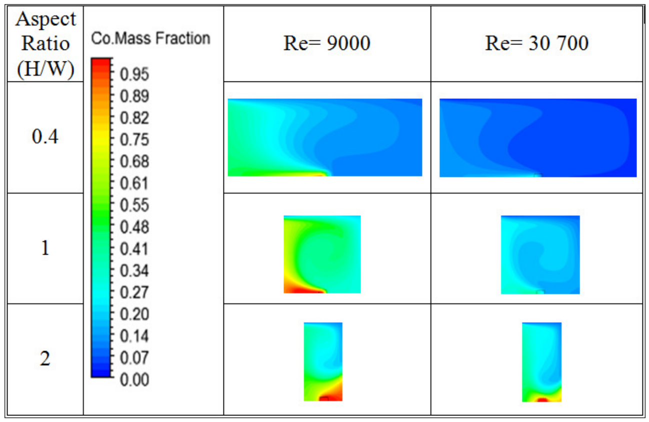

Figure 5: Contour of carbon monoxide mass fraction

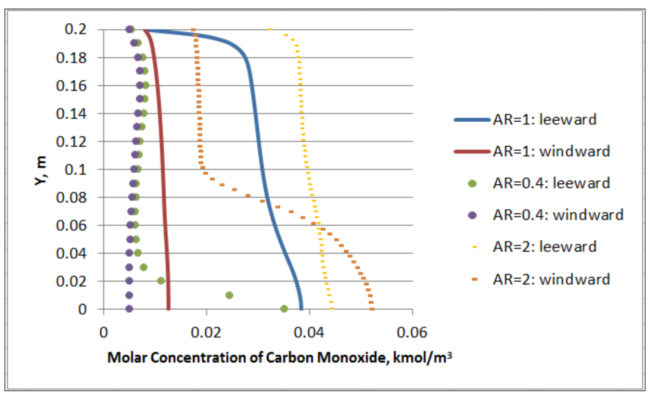

Figure 6: Variation of molar concentration along the height of street canyon (Re=9000)

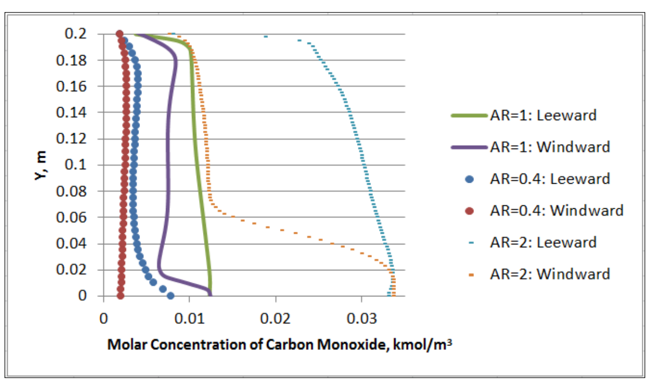

Figure 7: Variation of molar concentration along the height of street canyon (Re=30 700)

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The distinctive dispersion pattern for this case is affected by the formation of vertically-aligned double vortex in the street canyon. The primary vortex does not allow vehicular emissions to be carried by the secondary vortex from the ground level to rise beyond the mid canyon height.

High concentration at the leeward wall is the result of formation of wind flow vortex characterized by the downdraft near the windward building and updraft at the leeward building. The average concentration level in street canyon increases as the building aspect ratio increases. As discussed before, higher aspect ratio will result in the formation of two vortices, but the vortex nearer to the pollutant source is much weaker than that at the roof level. This weak vortex is caused by the dominance of molecular diffusion over advection and turbulent diffusion, therefore resulting in high accumulation of pollutant at the bottom of the street.

Figure 6 and Figure 7 also show that the pollutant concentration decreases along the height of the leeward side of backwind building, which is consistent with the findings from the 2-D simulation by Huang *et al.* [10] and street measurement by Xie *et al.* [11]. However, the declination is tremendous as the speed increases. This phenomenon is contributed by the increase of vortex strength with the increase of free-stream velocity. This vortex facilitates the ventilation of vehicular emission through roof level. However, for the windward side of the upwind building, the pollutant concentration shows little to no change along the height of building.

From the carbon monoxide mass fraction contour, it can be observed that higher Reynolds number enhanced the removal of pollutant from inside the canyon. Referring to Figure 8, the pattern shows that the pollutant concentration is almost halved when the Reynolds number increases. This trend can be explained in terms of turbulent intensity, where the wind speed affecting the vortex strength causing the increment in the vertical mean velocity, which subsequently improves the transportation of pollutants to the roof level.

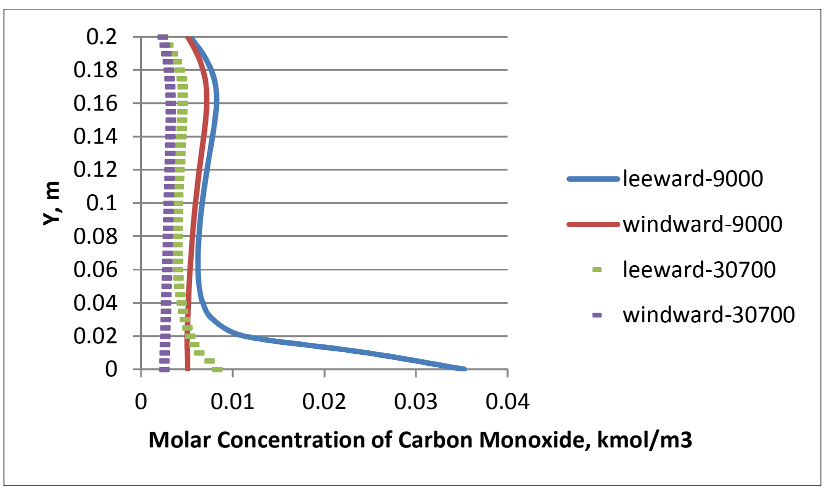

Figure 8: Variation of molar concentration along the height of street canyon (AR=0.4)

Similar to the flow structure in the street canyon, the results obtained for pollutant dispersion shows good agreement on the effect of z-axis. This effect is not tangible in AR=1 and AR=0.4, but significant in the case of AR=2 for both Reynolds number. Pollutants accumulated at the middle of the street canyon at high Reynolds number but dispersed quite evenly at certain

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length along the canyon for low Reynolds number. Street canyon's length may be one of the factors that influence the study of street canyon in 3-D modelling.

5.0 CONCLUSION

Based on the comparison against wind tunnel experiment, RNG k-Ɛ turbulent model shows the best result for simulating 3D symmetric street canyon, which is also in line with the finding by Chan *et al.* [8], where RNG k-Ɛ is the best turbulence model for simulating 2D street canyon.

For the effect of building aspect ratio to the flow structure, it was found out that only one vortex was formed inside the street canyon of AR=1 and AR=2, but there were two vortices formed in AR=2 for low aspect ratio. However, as the Reynolds number increased, the pattern and number of vortex remained the same for the case of AR=1 and AR=0.4, but for AR=2, the two vortices merged to form one vertically-stretched vortex. It was also found out that higher velocity increased the turbulent intensity inside a canyon, thus increased the vortex strength.

Different aspect ratios and Reynolds number also affect the dispersion pattern of pollutants inside the canyon. Leeward wall generally has higher pollutant concentration as compared to windward wall except for the case of AR=2, where the concentration was higher at the windward wall up until a certain height of the building. This result discrepancy is caused by the formation of secondary weak vortex near the ground. Higher aspect ratio results in higher pollutant entrainment in the canyon due to the increase in distance between the pollutant source and free-stream velocity. For the effect of Reynolds number, higher Reynolds number provides better ventilation for the street. This is due to the result of increasing vorticity, which acts as the transport medium for pollutants.

Considering the length of street canyon, the dispersion of pollutant is even along the street canyon for AR=1 and AR=0.4, but AR=0.2 shows the highest pollutant concentration at the middle of street for both Reynolds number. The same pattern is encountered with the flow structure, where the effect of z-axis is nearly non-existent for AR=1 and AR=0.4, but significant in AR=2.

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