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Flow and pollutant dispersion in urban street canyons: Semi-Lagrangian approach with zero equation turbulence model

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Abstract: *We propose a semi-Lagrangian approach equipped with zero equation turbulence model to investigate the effects of flow and pollutant dispersion in a two-dimensional urban street canyon. The results of online Weather Research and Forecasting (WRF) model are used to provide the initial and boundary conditions and the input data for the CFD model. The airflow pattern is simulated in a 2D urban street canyon to show the capability of the proposed method to predict the airflow in a fast manner. These simulations are conducted for different canyon aspect ratios. We assume that the wind blows at a left angle to the canyon axis. The heat emission of buildings envelop is specified as a line source with a constant emission at building surface. We validate our model by comparing the results with the previous research. The proposed method has acceptable accuracy to simulate urban canyon airflow problems.*

Keywords: *Urban street canyon, heat emission, Semi-Lagrangian approach, zero equation turbulence model*

INTRODUCTION

Urbanization causes many challenges such as urban heat-island phenomenon, air quality degradation and discomfort of city inhabitants (Fernando et al., 2001; Britter and Hanna 2003; Bottema 1993; Akbari et al., 2016; Taha 2008). The street canyon indicates a distinct climate where micro-scale meteorological processes affect the local air quality (Oke 1988). Physical parameters such as wind speed, direction, and building configurations affect the pollution dispersion process in a street canyon (Vardoulakis et al., 2003; Ahmad et al., 2005; Li et al., 2010; Wang et al., 2013). The flow in an urban street canyon depends on the local urban morphology such as the aspect ratio (AR)- the building-height-to-street-width ratio (AR = H/S, where H is the building height and S is the street width) and wind patterns. The flow inside street canyons can be classified into different flow regimes based on the aspect ratio such as isolated roughness flow, wake interference flow, and skimming flow regimes (Oke 1988). Another factor that affects the pollutant emission, transformation and dispersion is the temperature affected by solar radiation, anthropogenic heat emission and release of stored heat in urban envelop (Ca et al., 1995; Sini et al., 1996; Uehara et al., 2000; Kim and Baik 2001 and 2003; Xie et al., 2006). During summer, high temperature increases the rates of heat-related mortality and morbidity, the temperature-dependent rates of photochemical reactions (e.g. O_3 formation), the evaporation losses of organic compounds from mobile and stationary sources, and the cooling energy demands.

To address these issues at micro-scale, Computational Fluid Dynamics (CFD) models are applied because of their efficiency and relatively low cost (Li et al., 2006; Chen et al., 2010). These models are useful to gain insights into wind and temperature distributions in street canyons and reproduce more realistic behaviour with idealised boundary conditions (Buccolieri et al., 2010 and Li et al., 2010). The challenges of numerical modeling are the choice of time increments, turbulence model selection, or specification of boundary conditions.

One popular CFD model is the semi-Lagrangian method developed by Courant et al. (1959). It provides unconditional stability for large time steps by solving the advection terms based on the Lagrangian perspective, offering faster solution than other CFDs as so-called the Fast Fluid Dynamics (FFD). We used FFD approach with the zero-equation turbulence model developed by Chen et al. (1998) to capture the turbulence behavior of the flow in urban canyons. The FFD is configured for different aspect ratios of street canopy. Using this solver provides the ability to run many cases in much shorter time compared to other commercial CFD tools. To speed up the simulation, we also used the parallel computing of OpenMP. Here, the focus is to investigate the effects of buildings' heat generation on wind velocity and air temperature distribution, and thus pollutant dispersion in two-dimensional (2D) urban street canyons. We used the simulation results of the online coupled Weather Research

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and Forecasting model (WRF). WRF creates a realistic and reliable input to our FFD model and indicates the initial and boundary conditions in the CFD simulations, thus improving the prediction ability of these models (Tewari et al., 2010). Coupling CFD with other building simulation models has been done by other researches (Wang et al., 2010), but the current work is probably one of the first few studies coupling it with WRF for urban airflow problems. WRF is a non-hydrostatic mesoscale numerical weather prediction (NWP) system. The Advanced Research WRF is a dynamic solver that the equations are formulated using a terrain-following hydrostatic-pressure vertical coordinate. Reynolds-Averaged Navier-Stokes equations (RANS) are solved on a horizontal and vertical grid to represent the evolution of the state of the atmosphere. We coupled the WRF with the single-layer of the Urban Canopy Model (SL-UCM) to estimate the heat and moisture fluxes from surface of the urban canopy.

NUMERICAL APPROACH

MESOSCALE METEOROLOGICAL MODEL

We used the online WRFV3.6.1 to obtain the initial data and boundary conditions for the FFD simulation model. The WRF conducted for the Greater Montreal Area (GMA) for two days during the heat wave period from the 21st to 23rd of July, 2011. The horizontal domain of the simulation is composed of four two-way nested domains with the inner domain grid spacing of 333 m by 333 m. The simulation configuration is the same as Jandaghian et al., (2016a, b; 2017a, b and 2018).

The simulation is conducted with the initial and boundary conditions obtained from the North American Regional Reanalysis (NARR) (Mesinger et al., 2006). Land use was derived from the USGS 24-category data set. There are various physical parameterizations in the solver of WRF. We used Lin scheme (Lin et al., 1983), rapid radiative transfer model scheme (RRTMG), Mellor-Yamada-Janjic scheme (Janjic 2002), and Grell-Devenyi ensemble scheme (Grell and Devenyi 2002) for microphysics, shortwave and longwave radiations, planetary boundary layer, and cumulus parameterizations, respectively (WRF User 's Guide).

We also coupled the WRFV3.6.1 with the single-layer of the Urban Canopy Model (SL-UCM). The Single-layer UCM calculates the multi-reflection effects based on urban geometry. The model can consider the two-dimensional approximation for streets with a single orientation. It provides a more accurate estimation for sensible heat by simulating a wind distribution in the canopy. We also activated the positive-define advections of moisture, scalars and turbulent kinetic energy to maintain model stability. We disregarded the first 12-hrs of the simulation as the spin up time. The results were then evaluated by comparing to the observations obtained from two weather stations close to the city center. The performance of the model is generally consistent with the observations and the results are well suited for the FFD simulations and further investigations. The WRF results can be used in FFD models to provide boundary conditions and to estimate the flow fields for the sub-domain scale simulations.

NUMERICAL SIMULATION SETUP

We defined a street canyon with two buildings enclosing a street and urban environment. The wind is perpendicular to the direction of the street. The heat emission from buildings are assumed to be the same over the entire envelope. Figure 1 shows the front view of the computational street canyon configuration. The H, S, θ_a and θ_b refer to building height, street width, ambient temperature, heat emission from buildings' envelope, respectively. The grids are uniform ($\Delta x = \Delta y = 0.1$ [m]), and the number of grids in X and Y directions are 500 and 300, respectively.

The background atmospheric flow is simulated by prescribing a uniform pressure difference in the free shear layer. No-slip conditions are set at rigid walls. A shear-free boundary condition is assumed at the top of the domain and the air temperature is set to the ambient temperature (θ_a).

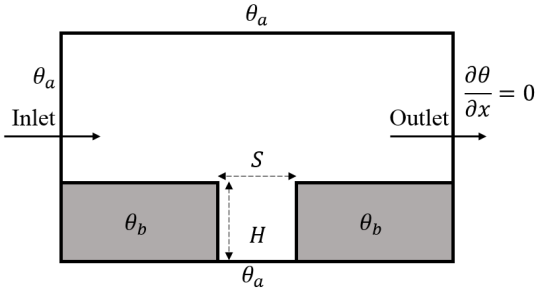

Figure 1: Schematic diagram of the computational domain in a street canyon.

We defined four scenarios for the FFD simulations. Table 1 represents these different setup simulations concerning the changes in width of street, height and length of buildings, and aspect ratios accordingly.

Table 1: simulation setup for the FFD simulations.

No	Width of Street (m)	Leeward Building Height (m)	Windward Building Height (m)	AR
1	10	10	10	1
2	20	10	10	0.5
3	10	20	10	2

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4	10	10	20	0.5

Here, we applied the semi-Lagrangian solver approach. The followings are the governing equations in the dimensional forms:

$$\nabla.\vec{U} = 0 \quad (1)$$

$$\frac{\partial \vec{U}}{\partial t} + (\vec{U}.\nabla)\vec{U} = -\frac{1}{\rho}\nabla p + (v + v_t)\nabla^2\vec{U} + g\beta\theta \quad (2)$$

$$\frac{\partial \theta}{\partial t} + (\vec{U}.\nabla)\theta = (\alpha + \alpha_t)\nabla^2\theta \quad (3)$$

where $\vec{U}$, θ, and p are the velocity, temperature, and pressure, respectively. g is the gravity acceleration and β is thermal expansion. Additionally, v, v_t, α, and α_t are the viscosity, turbulence viscosity, thermal diffusivity, and turbulent thermal diffusivity, respectively. Eq. (4) shows the relation between v_t and α_t:

$$Pr_t = \frac{v_t}{\alpha_t} \quad (4)$$

Pr_t is the turbulent Prandtl number. For semi-Lagrangian approach, the advection terms of equations 2 and 3 are written in the Lagrangian form:

$$\frac{\partial \vec{U}}{\partial t} + (\vec{U}.\nabla)\vec{U} = \frac{d\vec{U}}{dS} \quad (5)$$

$$\frac{\partial \theta}{\partial t} + (\vec{U}.\nabla)\theta = \frac{d\theta}{dS} \quad (6)$$

where S is the characteristic curve:

$$dS = \vec{U}dt \quad \rightarrow \quad S^n \approx S^{n+1} - \vec{U}\Delta t \quad (7)$$

Diffusion terms in equations 2 and 3 are calculated by using a 3-level V-shape multigrid method to speed up the convergence rate. This method is a fast solver to simulate matrix equations. To update the pressure domain, a Poisson equation is solved (Mortezazadeh et al., 2016 and 2017).

Here, a simple model, the zero-equation turbulence model, is used to capture the turbulence behavior of the flow. The zero-equation turbulence model is developed by Chen et al., (1998) and used by others to simulate airflow problems (Fernando et al., 2001; Vardoulakis et al., 2003; Wang et al., 2008). Accordingly, the turbulent viscosity is calculated as follows:

$$v_t = 0.03874.L.\sqrt{u^2 + v^2} \quad (8)$$

where u and v are the velocity components and L is the length of shortest distance to the wall inside the domain.

Model Performance Evaluation

The mesoscale simulation results from WRF are evaluated by comparing with the observations obtained from two weather stations close to the city center of Montreal. Figure 2 shows the daily distribution of air temperature and wind speed in one station (McTavish) in the downtown of Montreal.

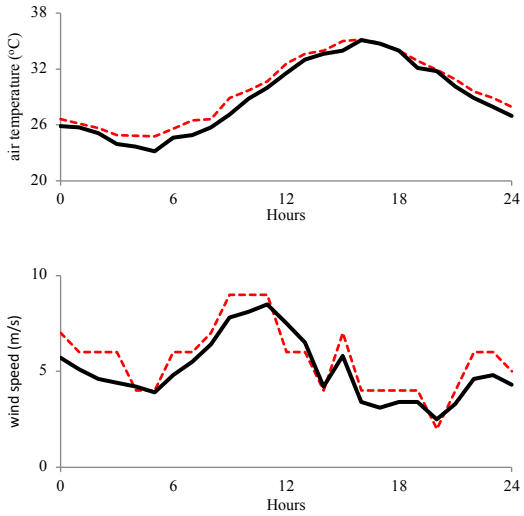

Figure 2. The diurnal cycle of air temperature (°C) and wind speed (m/s) of simulated (solid line) vs. observations (dashed line) in McTavish station on the 23rd of July 2011 heat wave period.

We also evaluated the FFD model performance by comparing our results with previous study to demonstrate the capability of the proposed solver to simulate the airflow around buildings. We simulated the airflow around seven buildings and compared the results with Lien et al., (2004) works. Figure 3 shows the comparison between Lien 's results based on RNG k-ε (3a) and non-linear k-ε models (3b) with our proposed method (3c). It represents the spatial distribution of the dimensionless stream function in the street canyon. The results show a good agreement between Lien et al., (2004) approach and ours. By applying this model, the recirculation area between two buildings and also the large recirculation area behind the last building is simulated very well (Figure 3c).

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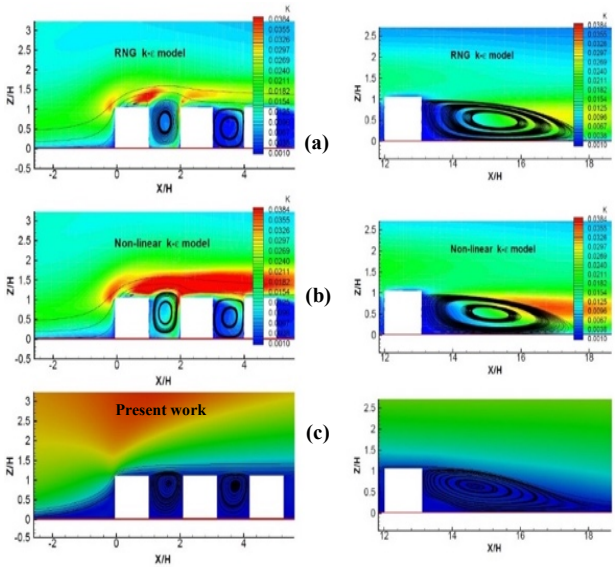

Figure 3: Spatial distribution of the dimensionless stream-function in the street canyon.

RESULTS AND DISCUSSION

The temperature differences are available between the ground and the ambient temperature, but since the differences are small, it has negligible effect on the heat distribution to the street canyon. The heat circulates inside the street canyon at the core region and there are local maxima at the leeward roof level and minimum at the windward ground corners. We disregarded the effects of anthropogenic heat emissions from vehicles and human metabolism in the street canyon. The temperature distribution depends not only on the aspect ratio of the street canopy, but also the rate of heat emission from various sources, solar radiation and sky view factors of the streets, that are disregarded in our analysis, but will be investigated in our future research.

Figure 4 and 5 show the flow pattern of temperature distributions and wind velocities in the street canyon with different aspect ratios. In the street canyon with the aspect ratio of 1 (AR=1, Figures 4a and 5a), the air is well mixed, the wind has normalized stream wise velocities (Figure 5a), thus the temperature distribution is uniformed. For the second scenario with the AR=0.5 (Figures 4b and 5b), where the height of leeward and windward buildings is the same and the width of the street is doubled (comparing to the AR=1), the air temperature reduces by crossing the width of the street and the temperature plum raises more toward the leeward side. The stream function plot for AR=1 exhibits a roughly symmetric pattern with corner vortices and an impinging streamline on the windward wall near the canyon roof (Figure 5b). Much the same of mixing heat and temperature is observed in the street canyon with AR=2 (Figure 4c and 5c). But, the temperature distribution is less in the windward side comparing to the leeward side, because the height of windward building is less than the leeward one, thus the temperature reduces faster toward the free stream (Figure 4c). The magnitude of the temperature distribution is smaller than that in the street canyons of aspect ratio of 1 and 0.5, presumably due to the lower momentum fluxes (Figure 5c). Considering the other AR=0.5 (Figures 4d and 5d), where the windward height is higher that leeward one, the temperature is trapped between street canyon and thus the temperature distribution in the windward side is as high as the leeward side (Figure 4d). There are two large counter-rotating vortices, one above the other with again an impinging streamline (Figure 5d). The negative impact of geometry will be even more obvious if considering pollutants emission and concentrations. Trapping the temperature in the street canyon shows that pollutants concentrations will increase and thus the rate of temperature-dependent photochemical reaction rates increase and will endanger the human health and comfort.

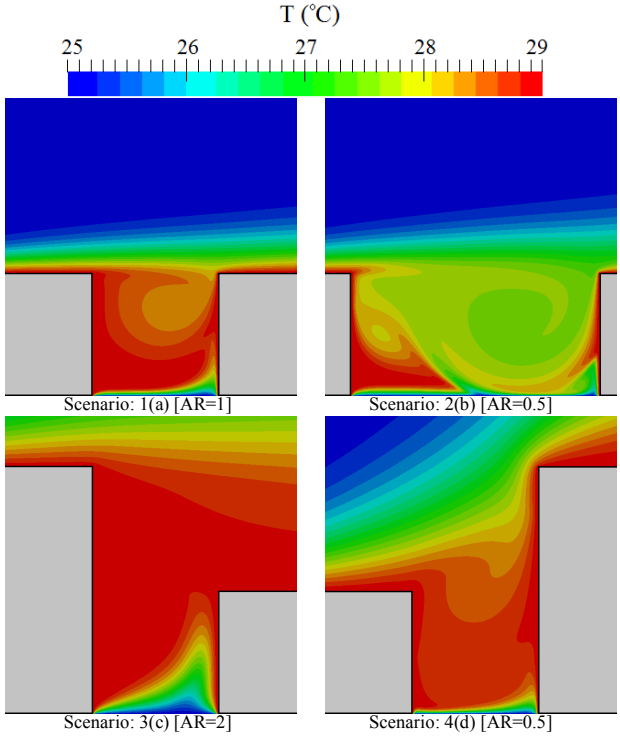

Figure 4: Flow pattern of air temperature distribution in the street canyon of AR=1 (a), AR=0.5, with the same leeward and windward buildings' heights, (b), AR=2 (c), AR=0.5, with differences between leeward and windward buildings' heights, (d)

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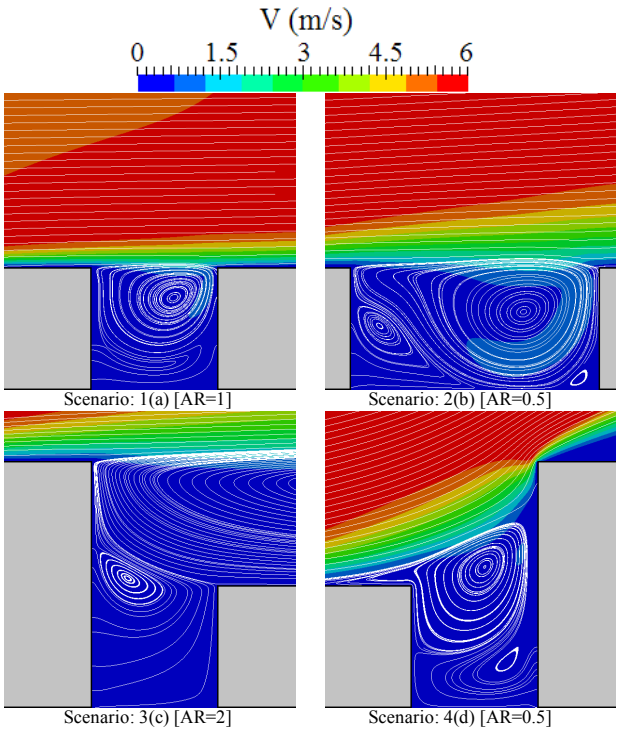

Figure 5: Flow patterns of wind velocities in the street canyon of AR=1 (a), AR=0.5 –with the same leeward and windward buildings' heights- (b), AR=2 (c), AR=0.5 – with differences between leeward and windward buildings' heights (d).

Here, we also considered the effects of air temperature and wind speed along a horizontal distribution in different scenarios (Figure 6). The horizontal height is assumed to be 175 cm based on the standard of pedestrian thermal and wind comfort for Greater Montreal Area. The wind velocity at this height shows a uniform distribution in the street canyon with the AR=1, but the wind velocity distribution is higher in the windward envelop when the AR is 0.5 and is higher in the leeward envelop when the AR is 2 (compared to AR=1). Thus, a better wind velocity distribution can be seen in the streets that the height of the buildings in both sides of the street are equal to the width of the street.

However, the air temperature distribution is different due to the heat emission from buildings envelop. The temperature is high in the leeward side of the buildings and reduces by reaching to the windward side of the buildings. In AR=1, the temperature dropped by nearly 1˚C at the windward side by crossing the street width, but as the aspect ratio increases to 2, this difference jumped to 3˚C and thus provides a better thermal condition for pedestrian at this side of the street. Although the wind velocity distribution is less or more the same in the AR of 0.5, but the air temperature behaves differently. When the width of the street is doubled, and the heights of leeward and windward buildings are the same, the temperature reduces by nearly 2˚C at two points, whereas in the street canopy with the higher windward buildings, the temperature reduces by just 0.75˚C at the windward corner, fewer than the other scenarios.

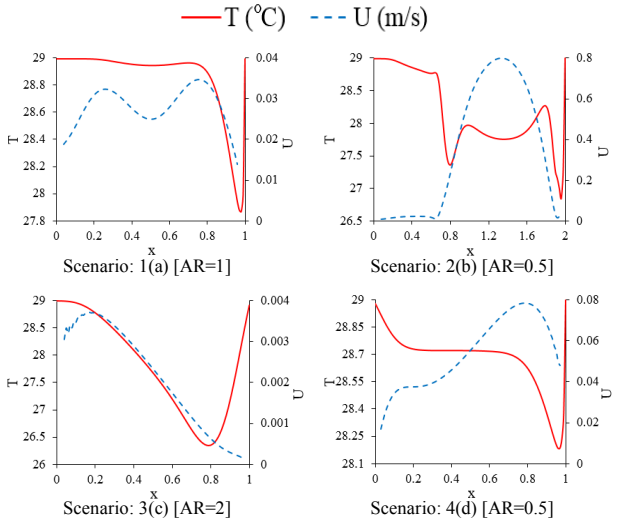

Figure 6: Temperature and velocity magnitude distribution along a horizontal line at $y = 1.75\ m$.

SUMMARY AND CONCLUSION

We employed a validated FFD approach with the zero-equation turbulence model to investigate the flow pattern and pollutant dispersion inside a 2-dimentional urban street canyon with different aspect rations (AR= 0.5, 1 and 2). We used the simulation results of the online Weather Research and Forecasting model (WRF) coupled with the single layer of the Urban Canopy Model (SL-UCM) to provide the initial and boundary conditions and input data for the FFD model.

The results indicated that by increasing the width of the street, we have a better wind and temperature distributions and thus pollutant dispersion. But, the temperature reduces more in the urban canopy by the AR of 2, thus provides a better circumstance and more pleasant conditions for pedestrians. Meanwhile, the air is well mixed in AR of 1, thus the temperature distributions and wind speed distributions are quite uniform. If the height of the windward buildings is higher than the leeward buildings, the temperature will be trapped, and the wind speed effects will be negligible and thus may causes higher pollution concentrations that will endanger human health and comfort. However, we suggest further investigations for future decisions and mitigation strategies implementation.

This study is only a beginning of an endless road to develop an innovative method in order to extend the concept of the field. There are other aspects ratio that needs be considered,

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especially for those who are interested in the urban planning and air quality studies. This study is based on a 2D street canyon and a 3D simulation setup is suggested. The results are also based on the FFD model simulations with a simple turbulence model, and we recommend other simulation and turbulence models for further investigations.

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