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Journal of Advanced Research Design
ISSN (online): 2289-7984 | Vol. 1, No.1. Pages 1-17, 2014

Preliminary Study on the Wind Flow and Pollutant Dispersion in an Idealized Street Canyon

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Abstract – *This article describes the approach towards a sensitivity study of wind flow and pollutant dispersion in an idealized street canyon with tree plantings under thermal atmospheric conditions using computational fluid dynamics (CFD). First, validation studies were performed to determine the best turbulence model for the simulation of wind flow under thermal atmospheric conditions against the previous experimental wind tunnel data. The results of the numerical simulation indicate that large eddy simulation (LES) can accurately predict the wind flow structure at different thermal intensities and different locations of heated wall. Finally, detailed descriptions of future research are presented at the end of this article.*

Keywords: Street canyon, Thermal atmospheric conditions, Tree plantings, Turbulence models

1.0 INTRODUCTION

Deterioration of outdoor air quality in cities is one of the most serious environmental problems. The air pollutants from ground vehicles (i.e. cars, trucks, motorcycles) are one of a significant contributors to air pollution in cities and among the major amount of pollutants are sulfur dioxide (SO_2), nitrogen oxide (NO), carbon monoxide (CO), volatile organic compound (VOC), as well as carbonaceous and non-carbonaceous particles. Studies have shown that short-term or long-term exposure to traffic-generated pollutants results in various adverse health problems [1,2,3]. The concentration level of pollutants in cities is worsened by the increasing number of vehicles and affected by several factors such as urban surface geometry, atmospheric conditions and small obstruction [4,5].

The thermal stability of atmosphere can be categorized as stable, neutral (isothermal), and unstable, and several parameters are required such as ground temperature and wind speed to distinguish different thermal stability regimes. Wind tunnel studies by Uehara et al., 2000 [6] and LES simulation by Cheng and Liu, 2011 [7] showed that the primary vortex formed in between buildings became weaker under stable atmosphere. In contrast, the intensity of the vortex became stronger under unstable atmosphere as a result of enhancement of turbulence. Hence, the pollutant concentration for stable case was much higher compared to neutral and unstable cases near the bottom of a street canyon. The specific location of the accumulation of pollutant also varied. For the stable case, the pollutant was seen to accumulate at the windward wall, whilst for neutral and an unstable case, the accumulation of pollutant was higher near the leeward wall, with the latter had less concentration. The sun's position in the

Journal of Advanced Research Design
ISSN (online): 2289-7984 | Vol. 1, No.1. Pages 1-17, 2014

sky have major influences towards the area of the building's wall or ground surface receiving direct solar heating with the temperature difference between buildings surface and/or ground surface and the surrounding air temperature can exceed 10 ˚C [8,9,10]. When the windward wall is involved in more than one wall/surface heating, the vortex intensity is slightly weakened while leeward and/or ground heated wall will intensify the vortex [11]. The location of the heated wall also varies the resultant wind flow structure in the street canyon [12,13].

It has long known that trees have numerous benefits towards urban dwellers as trees provide thermal comfort against direct solar heating, air quality improvements through pollutant entrapment and aesthetic value [14,15]. However, they can also be unfavourable in a way that they reduce the air ventilation in a built-up environment. A few reduced-scale experiments [16,17] and through numerous numerical simulation studies [18,19] found that tree plantings are shown to exhibit a static obstruction that reduces the air ventilation, hence resulting in poor air quality. Recent studies focus on the strategies to efficiently utilize appropriate tree planting configurations and geometries for the improvement of local air quality [20,21].

Computational fluid dynamics (CFD) is one of the methods of studying the nature of turbulent flow especially in the aspect of wind engineering besides the experiment at full scale [8,15] or reduced scale (wind tunnel experiment) [22,23]. Two-equation Reynolds-Averaged Navier-Stokes (RANS) turbulence models have been widely adopted in computational wind engineering research due to its fast convergence and the ability to provide reasonable accuracy [24]. However, the performance of these turbulence models albeit at steady state or unsteady state is not accurate compared to physical experiments [25,26]. Large eddy simulation (LES) is a promising method for the computation of turbulent flows in wind engineering compared to RANS or to a more prohibitively high computational cost of direct numerical simulation (DNS) due to the fact that it performs relatively well compared to RANS against physical experiments [27] and acceptably close to DNS [28], with the computational cost lies between the cost of RANS and DNS. Previous experimental studies of wind flow under thermal atmospheric conditions in street canyon are limited to very few numbers of thermal atmospheric conditions, for example windward wall heated only [29] or ground heated only [6]. In addition, previous numerical validation studies [11,25,30] are limited to very few number of turbulence models and for very few thermal atmospheric conditions.

It may however be noted that most of the studies are aimed at the individual physical factors such as thermal atmospheric conditions or tree plantings, and a rigorous study for the combination of both has not been attempted. As observed from prior studies, there is a high uncertainty whether the chosen turbulence model could predict the airflow under various thermal atmospheric conditions correctly. Recent experimental work by Allegrini et al. [13] on thermal flow in street canyon has provided more reliable data on the airflow structure in street canyon under different thermal conditions. Therefore, another motivation for this study is to validate two turbulence models that are mostly used. In this paper, the comparison between RANS turbulence model of standard k-ε and LES against available wind tunnel data on wind flow structure was made to identify the most accurate turbulence model for simulation of turbulent flow under thermal atmospheric condition. This was followed by literature survey on design model of a full scale wind flow and pollutant dispersion simulation in an idealized street canyon with combined tree plantings and thermal atmospheric conditions.

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2.0 METHODOLOGY

The numerical models were validated against wind tunnel (WT) experiment of Allegrini et al. [13]. The experiment was conducted in a nominal 2D wind tunnel in the closed loop ETHZ/Empa atmospheric boundary layer wind tunnel in Dübendorf (Switzerland). The model of the street canyon have the dimensions of 0.2 (*H*) x 0.2 (*W*) x 1.8 (*L*) m. The flow direction was normal to the axis of the cavity and maintained at 23˚C. The aspect ratio H/W was 1 and the spanwise aspect ratio L/W was 9. Four cases of thermal effect associated with differential heated wall were measured and analyzed, namely leeward wall (located along the upwind building wall), ground floor, windward wall (located along the backwind building wall) and all heated surface wall. The isothermal flow was characterized by the Reynolds number as in (1), where U_{FS} is the free-stream reference velocity of wind tunnel (m/s) and H is the height of cavity (m). The importance of the buoyancy effect inside street canyons can be characterized by the Froude number as in (2), where g is the acceleration due to gravity (m/s^2), T_w is the heated wall temperature (K), and T_{ref} is the ambient reference temperature (K). The flow is dominantly induced by buoyant flow if $\mathrm{Fr} \approx 0$, while the flow is dominantly forced convective flow if $\mathrm{Fr} >> 1$. The airflow pattern inside the street canyon was measured using 2D Particle Image Velocimetry (PIV) for five Reynolds number (Re = 9000 - 30700) combined with four temperature values of heated wall that correspond to 20 different Froude numbers (Fr = 0.65 - 17.29). The critical Reynolds number of the turbulent flow to achieve Reynolds independent flow is about 13000, whilst the thermal conditions that lead to the similar conditions of real scale is at 1:100.

$$\mathrm{Re} = \frac{\rho U_{FS} H}{\mu} \tag{1}$$

$$\mathrm{Fr} = \frac{U_{FS}^2}{gH \dfrac{T_w - T_{ref}}{T_{ref}}} \tag{2}$$

A finite volume method of ANSYS FLUENT v14 was used by assuming incompressible flow with 3D spatial domain. The first study was conducted using standard *k-ε* (SKE) of two-equation RANS equations to solve the turbulence flow. Enhanced wall treatment was adopted in the study due to its ability to accurately simulate buoyancy flow. Second-order upwind for all the advection terms and PRESTO for pressure interpolation, as well as SIMPLE algorithm for the pressure-velocity coupling were used as the discretization schemes for SKE. The convergence was monitored at 1.0×10^{-6} for the isothermal case and 1.0×10^{-4} for the thermal case. The second turbulence model used was dynamic Smagorinsky-Lilly SGS model of LES technique. Bounded central difference for momentum, second-order upwind for energy transport equations, PRESTO for pressure interpolation and SIMPLEC algorithm for pressure-velocity coupling were used as the discretization schemes for LES by considering the recommendations for numerical quality, stability and computing time [31, 32]. The convergence was monitored at 1.0×10^{-3}. Boussinesq approximation was used in both studies to simulate the buoyancy flow, and the wall was homogeneously heated up at constant temperature.

Journal of Advanced Research Design
ISSN (online): 2289-7984 | Vol. 1, No.1. Pages 1-17, 2014

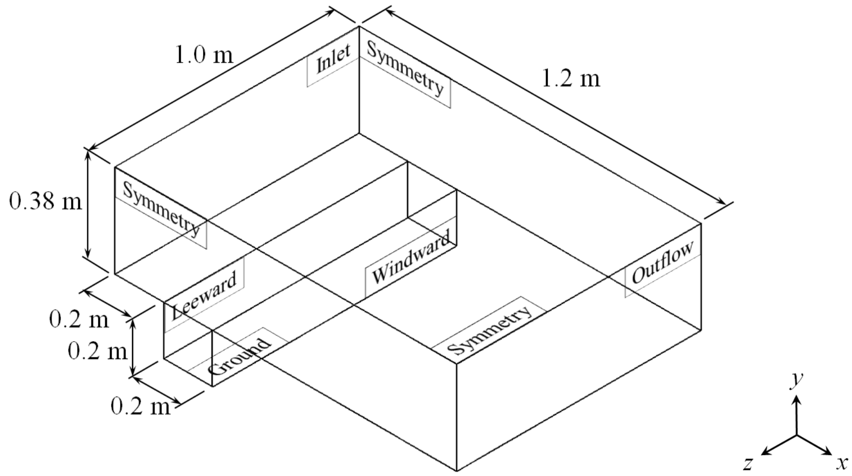


Figure 1: Schematic diagram of the computational domain and boundary conditions.

Table 1: Mesh resolution used in the current computational fluid dynamics study.

Mesh	Number of cells in street canyon ($x \times y \times z$)	Total number of cells
Mesh 1	30 × 30 × 150	340k
Mesh 2	40 × 40 × 150	533k
Mesh 3	75 × 75 × 150	1M

The numerical domain of the street canyon model has the aspect ratio of 1 (height to width ratio) with cavity dimensions of 0.2 (*H*) x 0.2 (*W*) x 1.0 (*L*) m. The computational domain and boundary conditions used for the current study are shown in Figure 1. The whole domain was discretized using hexahedral elements, whereas the overlying cavity was stretched away from the cavity with 1.2 ratio, and the corresponding spatial resolutions are listed in Table 1. Similar inlet profiles of velocity and turbulent kinetic energy from the experiment were adopted. The flow conditions being studied are at Re = 30700 with thermal conditions of isothermal flow, leeward heated wall at two Froude numbers (Fr = 17.29 and 7.59) and windward heated wall (Fr = 7.59).

The time resolution used in the current study was based on the requirement of Courant-Friedrichs-Levy (CFL) number of CFL = $U\Delta t/\Delta x < 1$, where U is approximately 0.7 m/s at roof level and Δx is the smallest element size. Hence, Δt = 0.000143 s was used, which is sufficient for the CFL requirement. Firstly, a steady state simulation using SKE was obtained, and the statistics for the steady state was used as the initial conditions for the LES simulation. The LES simulation was continued for 30 s of simulation time in order to establish the turbulent wind fields throughout the domain, and all the statistics were averaged at least for 15 s.

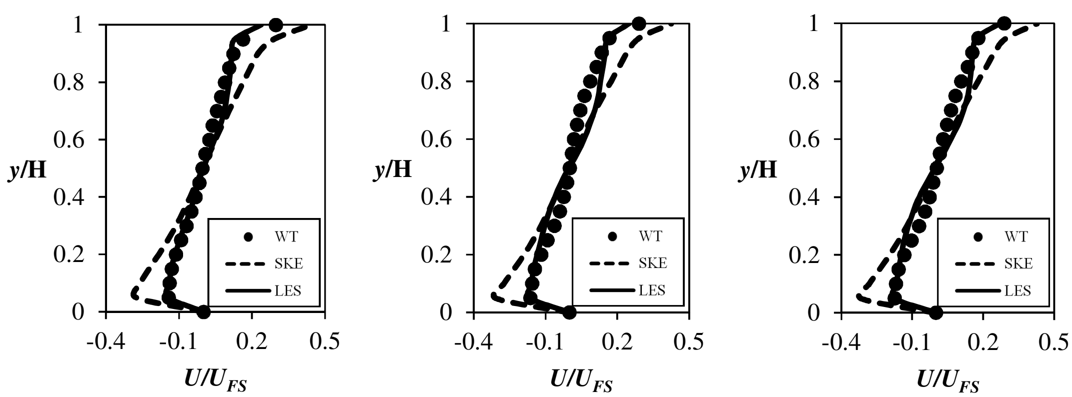
3.0 RESULTS AND DISCUSSION

A series of model sensitivity tests were first conducted to determine an optimum spatial resolution and the required period of time to achieve a statistically steady state for LES simulation while for SKE, the model sensitivity has been conducted in previous study [21]. For mesh independent study, the data of streamwise velocity along the vertical middle of street canyon were compared against different mesh resolutions. Table 2 shows that the deviation of streamwise velocity compared to WT with respect to the increase of spatial resolutions (between Mesh 2 and Mesh 3) was small, which differed about 7% to each other. However, the transition from Mesh 1 to Mesh 2 shows a large deviation of approximately 28% difference. An averaged value of 15 s simulation at 2 different time (after 30 s and 45 s) at 4 locations taken along the vertical middle of the street, which are 0.04, 0.08, 0.12 and 0.16 m from the ground were compared to determine the statistically steady state. The root mean square of streamwise velocity was about 0.013 m/s, which is relatively small compared to 0.1 m/s as suggested by Beare et al. [33].

Table 2: Average error of streamwise velocity along the vertical middle of street canyon for mesh independent study

Mesh	1	2	3
Average error (%)	61.9	33.5	26.6

The results of validation study of isothermal and leeward wall heated conditions at two Fr numbers are shown in Figure 2. The streamwise velocity data was normalized by the freestream velocity, U_{FS} = 2.32 m/s. In all cases, the LES results show a good approximation with the experiment, while the SKE had failed in all cases. Further calculation of the deviation between SKE and LES against WT (Table 3) shows increased of velocity for both SKE and LES, but it was more significant when using the former turbulence model.



a) Isothermal   b) Leeward (Fr = 17.29)   c) Leeward (Fr = 7.59)

Figure 2: Normalized streamwise velocity along the vertical middle of street canyon under different thermal flow conditions

Figure 3 shows the contour of velocity magnitude and vector plot for WT, SKE and LES. It is clear that the LES can well reproduce the flow field, while the SKE results show significantly

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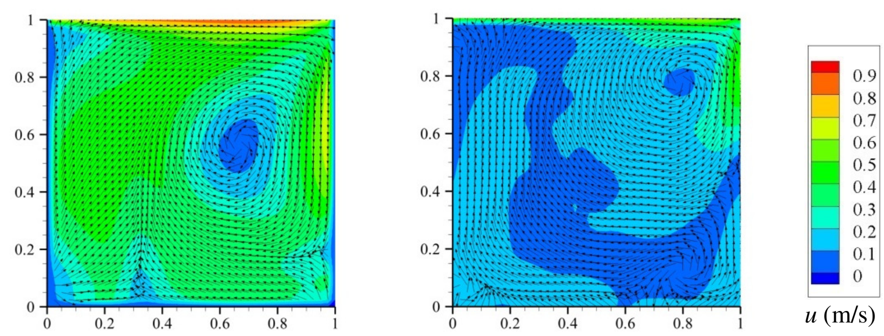
ISSN (online): 2289-7984 | Vol. 1, No.1. Pages 1-17, 2014

higher velocity magnitude. Further inspection on the vortex centroid for each vortex (Table 4) shows that SKE has failed to reproduce both the secondary and tertiary vortices as in WT. On the other hand, LES does not only able to reproduce all the vortices, but the location of the vortex centroid is also close to WT results.

The wind flow fields under windward heated wall conditions show more complex wind flow structure. At Fr = 7.59 and Re = 30700, 3 vortices were produced within the street canyon (refer to Figure 3). The primary cortex was circulating in the clockwise motion driven by the shear layer and located at the right top corner of the canyon. The secondary vortex was located at the right bottom corner of the canyon with anti-clockwise motion, driven by the primary vortex. A relatively small tertiary vortex was in anti-clockwise motion driven by both the primary and secondary vortices.

Table 3: Average error of streamwise velocity along the vertical middle of street canyon for the validation study

Simulation Case	Isothermal		Leeward (Fr = 17.59)		Leeward (Fr = 7.59)	
Turbulence model	SKE	LES	SKE	LES	SKE	LES
Average error (%)	78.3	33.5	118.1	86.2	80.7	64.5



a) SKE   b) LES

Figure 3: Contour and vector plot of velocity magnitude of the windward wall heated at Fr = 7.59

Table 4: Vortex centroid of windward heated wall at Fr = 7.59

Type of vortex	Vortex centroid (*x*, *y*)		
	WT	SKE	LES
Primary vortex	0.736, 0.736	0.673, 0.564	0.751, 0.766
Secondary vortex	0.850, 0.189	-	0.771, 0.122
Tertiary vortex	0.076, 0.057	-	0.034, 0.063

Journal of Advanced Research Design
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4.0 CONCLUSIONS AND FUTURE STUDY

The validation study between SKE and LES against WT on the airflow structure within street canyon with aspect ratio =1 was performed to determine the best turbulence model for the prediction of wind flow structure under thermal atmospheric conditions in street canyon. The results obtained show that LES can well calculate a complex simulation involving isothermal flow and thermal flow with different thermal intensities and different heat locations by producing lower deviation and predicting a good wind flow structure against WT. Therefore, LES is highly recommended to be used as a turbulent technique to perform simulation of thermal and turbulent flow in street canyon settings.

Future works would be to perform LES simulation on wind flow and pollutant dispersion in urban street canyon with tree plantings under different thermal atmospheric conditions at full scale. Small scale experiment such as in wind tunnel experiment provides benefits to researchers due to the ability to control the environment conditions and feasibility of measurements. However, at some conditions, it is unrealistic for the representation of the real flow condition at full scale, and similarity theory based on certain dimensionless number must be fulfilled to justify the representation of results in small scale to full scale [34]. At reduced scale, Reynolds number is less than that of full scale due to reduced geometry or length scale. Reynolds number independence in which the wind flow structure is no longer changes at higher Re number is often used. Froude number or Richardson number is the dimensionless number to characterize thermal conditions, and the value must similar in both of that full scale and reduced scale. As a result, it requires higher temperature compared to full scale. Porosity of tree crown is the property to characterize the effect of tree, where porosity number is scaled down when it is modelled at reduced scale [35]. When combining all of these similarity theories at small scale, the resultant flow field and pollutant dispersion may not agree with those at full scale. Hence, a full-scale simulation must be considered. The following section will explain the literature survey and numerical model relevant for the modeling of wind flow and pollutant dispersion in an idealized street canyon at full scale for future study.

4.1 Literature Survey

The following subsection will describe all the parameters required in modelling the wind flow and pollutant dispersion. These parameters include street canyon geometry, wind flow condition, thermal atmospheric condition, tree plantings configuration and pollutant source.

4.1.1 Configuration of Street Canyon

The configurations of street canyon vary depending on the heights of adjacent buildings, the proximity of nearby buildings and the variation of height of nearby buildings. For example, a street canyon ratio of one with 11 to 20 m height in homogeneous urban areas is categorized as the “tall and high density” category of urban surface form [36]. This category represents an urban surface form of closely spaced block or row of buildings with less than six-storeys high. The length of canyon is called infinitely long when the eddy circulation at the middle plane of the canyon is primarily driven by the roof top shear layer. The simplification is made by imposing a periodic boundary condition at both canyons lateral sides.

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4.1.2 Wind Flow Conditions

The direction, vertical profile, and speed of incoming wind have a significant effect on the resultant wind flow structure as the approaching wind provides the momentum towards air ventilation. Past studies have shown that the lowest pollutant accumulation in street canyons can be found with oblique wind, whilst perpendicular or parallel wind accumulate the pollutant near the leeward wall or end of canyons length respectively [37,38]. Hence, perpendicular wind direction will be considered as it causes high pollutant accumulation. There are two types of wind vertical profiles exist in the literature, which are power law profile and logarithmic law profile. The power law profile is the simplest equation of vertical wind profile because the exponential value describes the type of terrain via the surface roughness length, z_0 and the atmospheric stability as well. There exist relationships between power law exponent against atmospheric stability and surface roughness through semi-empirical formulation of the Monin-Obukhov similarity theory and micrometeorological experimental data [39,40]. However, there is no dependency of the power exponent against a more viable measurement of atmospheric conditions, namely the bulk Richardson number, R_b in built-up landscape. Therefore, neutral atmospheric condition will be assumed. The estimation of exponential value is $1/\ln(z/z_0) \approx 0.3$ by taking the mean geometric mean height as 20 m, and z_0 as 1.0, which falls under the "skimming" of Davenport terrain roughness classification representing an almost homogeneous building height variation [41]. The estimation of wind speed is based on the mechanism of pollutant dispersion as a result of wind speed and the observation of annual mean wind speed globally. Field measurement by Xie et al. 2003 [42] of wind speed at 2 m above 20 m buildings height alongside the pollutant concentration in a long urban street canyon found that wind speed of more than 1.5 m/s at roof level has shown to have caused the formation of eddy circulation, which also results in the accumulation of pollutant along the leeward wall compared to the windward wall. There was no vortex formation observed when the wind speed was lower than the threshold value and as a result, the pollutant would be stagnant and remain near the ground floor [43]. Mesoscale computer simulations datasets predicted the wind speed of 3 to 9 m/s in a 5 km resolution wind map at 80 m above the terrain height [44]. Extrapolating value of 3 and 9 m/s at 80 m down to 20 m height with power law of exponential 0.3 indicated that the wind speed was between 2 and 6 m/s respectively. Hence, a wind speed at roof level of 2 m/s is not only the minimum wind speed observed globally, but also the speed that will cause the formation of a vortex in a street canyon.

4.1.3 Thermal Atmospheric Conditions

The sun's position in the sky, as well as cloud cover influence greatly the location and surface area of buildings' walls and/or ground surface receiving direct solar heating. Past studies have shown that substantial amount of surface to air temperature difference occurs during midday, typically between 10 a.m. to 2 p.m. [8,9] at which the minimum sun's elevation angle is estimated at 40˚. For the purpose of simplification, clear cloud cover and minimum of 45˚ sun elevation angle will be used with the street axis and sun orientation that results in the morning and afternoon sunlight reaching leeward or windward wall. Bulk Richardson number, R_b will be used to characterize the thermal conditions in urban street canyon. Surface temperature and wind speed at certain height is needed to calculate the bulk Richardson number. Comprehensive wind speed and surface temperature measured in field experiment by Nakamura and Oke, 1988 [8] provide the parameters needed for the estimation of bulk Richardson number. The range of bulk Richardson number recorded in their study was between -0.96 and -2.06 for roof top wind speed more than 1.5 m/s and surface-to-air

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ISSN (online): 2289-7984 | Vol. 1, No.1. Pages 1-17, 2014

temperature difference of 8 ˚C. The data has been used by previous researchers to estimate the bulk Richardson number of a full-scale street canyon [45,46].

4.1.4 Tree Plantings Configurations

All trees are different in terms of its crown shape, sizes and crown properties, which are influenced by species, age, environment and others. The size of tree is characterized by its height, trunk size and crown diameter. Urban tree is generally shorter than 10 m, while park tree is higher than 10 m based on the average measured trees in a few field surveys in urban area [47, 48]. For an urban tree height of less than 10 m, the diameter at breast height is less than 0.25 m, and the crown diameter is less than 8 m. Therefore, a 5 m diameter of tree crown with the maximum height up to 10 m and the diameter at breast height of 0.25 m will be assumed. The presence of a tree crown exerts a drag force on the wind field, causing a net loss of momentum (momentum sink) or pressure drop. By assuming the tree crown as a simple homogeneous porous media, the porous media model incorporated in commercial ANSYS FLUENT software is composed of two parts, a viscous loss term (the first term on the left-hand side) and an inertial loss term (the second term on the right-hand side) as in (3):

$$S_i = -\left(\frac{\mu}{K}u_i + C\frac{1}{2}\rho|u_i|u_i\right) \tag{3}$$

where K is the permeability of the tree crown (m^2) and C is the inertial resistance coefficient of the tree crown (m^{-1}). Previous study shows that the viscous forces are not important to the forest porous medium modelling [49]. In addition, the drag force per unit volume of the tree crown can be expressed as in (4) [50].

$$S_i = -\rho L_{AD} C_D u_i^2 \tag{4}$$

where L_{AD} is the leaf area density of the tree crown (m^2/m^3) and C_D is the drag coefficient of the tree. Using the relationships in (3) and (4) by neglecting the viscous force term, the inertial resistance coefficient of the tree crown can be described as in (5).

$$C = 2L_{AD}C_D \tag{5}$$

The value of the dimensionless drag coefficient C_D depends on the type of forest or trees and can change with the wind speed as shown by previous physical experiments [51,52]. For wind speed less than 2 m/s, the typical values of drag coefficient for coniferous forest with mean canopy heights of more than 10 m range are from 0.1 to 0.4 [53,54]. Actual-sized tree of broadleaf deciduous trees (i.e. maple and poplar of 5 to 15 m height respectively) show higher drag coefficient of more than 0.5 with wind speed less than 5 m/s [52]. Small trees (i.e. shrubby specimens) of different species with height less than 1 m and wind speed less than 5 m/s tend to have higher drag coefficient of more than 0.8 [55]. A constant drag coefficient of 0.4 will be used in the future study. It is interesting to note that previous values of drag coefficient used in numerical studies of forest canopies or individual tree range from 0.075 to 0.5 [56, 57, 58]. The leaf area density of trees also varies between species. The tree survey carried out in the urban area of New York City found that the values of leaf area index, L_{AI} for deciduous trees reaching the height of 8 to 12 m range are from 2.54 to 4.84 [59]. Hence, the leaf area density values for deciduous trees range from 0.21 to 0.45 are deduced from the relationship between L_{AD} and L_{AI}, where L_{AD} = L_{AI} / tree height [60].

Conifer trees (i.e. blue and Norway spruce) on the other hand have higher L_{AI} of around 5.67 to 9.8 [59]. The leaf area density in the future study will use a constant value of 0.4 m^{-1}. With regards to the thermal conditions, the temperature of the crown tree is maintained at ambient temperature even under direct solar heating [61].

4.1.5 Pollutant Source

Two-way traffic generates the same flow pattern with no traffic case [62,63]. Therefore, two line sources will be placed near the center ground of the street and aligned parallel to the street canyon, representing a road with two lanes. Carbon monoxide (CO) will be used as the pollutant species because of two reasons. First, it is considered as a practically inert species because the reaction time is longer than the retention time of pollutant species in street canyon [64]. The second reason is CO removal by the canopy was neglected since previous study has shown that CO removal by urban trees in several US cities is estimated to be in the range between 0.001 and 0.002 % of the CO concentration in ambient air [15]. Due to these reasons, the numerical setup can be simplified by neglecting the effect of pollutant deposition and chemical reactions. Pollutant discharge rate of line source is calculated as [65]:

$$Q = \frac{EF \times N}{A \times 1000} \qquad (6)$$

where EF is the emission factor (g/km.veh), N is the traffic rate (veh/hr) and A is the cross-sectional area of vehicle (m^2). CO emitted by passenger car with three-way catalyst and 1.4-2.0 cc engine will be assumed. Typical specification of this type of car will have EF at a typical urban road speed limit of 50 km/h.veh [66] for CO at 1.944 g/km [67]. The traffic rate is assumed to be 1,700 vehicle/hr at 50 km/hr speed in a single lane traffic [68]. A typical cross sectional area of passenger car is 2.28 m^2 having the height of 1.2 m and 1.9 m width. Hence, $Q = 4.0 \text{ x } 10^{-7}$ kg/m^3.sec for each line source.

4.2 Numerical Model

The numerical domain of street canyon model has the aspect ratio of 1 (height to width ratio) with dimensions of 20 (H) × 20 (W) × 40 (L) m. The computational domain and boundary conditions that will be used are shown in Figure 4. A boundary layer flow with power law profile of $\alpha = 0.3$ and streamwise velocity of 2 m/s at 22 m height (2 m above the roof of upwind building) at the inlet and is normal to the axis of the cavity representing a neutral atmospheric boundary layer over built-up areas. Two pollutant source lines are aligned on the ground parallel to the street canyon axis representing a continuous two-way traffic, and CO is selected as the pollutant species. Pollutant sources are located along the center of the street and injected into the street canyon with a rate of 0.08 g/s (4.0×10^{-7} kg/m^3-s) per line source. The line sources have a dimension that is similar to the cross sectional area of a typical passenger car (2 m width and 1.25 m height each) and is separated 2 m from each other. The tree crown shape is round and is continuously aligned along the street axis. The tree crown is 5 m in diameter and stretched from 5 m to 10 m from the ground surface. There is a 5 m gap between the two trees. The porosity of this tree crown shape will be considered as having an ellipse-like form, where a maximum porosity near the middle of the tree crown, and least porosity near the top and bottom of the tree crown in vertical direction due to the leaf area distribution as shown in Figure 5. This form is also imposed for both sides of the tree crown in streamwise axis, which is constant for tree crown parallel to the street axis representing a rectangular-like form (Figure 5).

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ISSN (online): 2289-7984 | Vol. 1, No.1. Pages 1-17, 2014

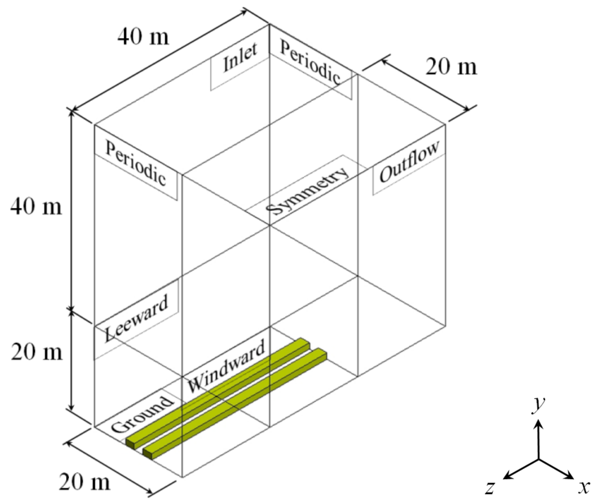

Figure 4: Schematic diagram of the computational domain and boundary conditions for the future study

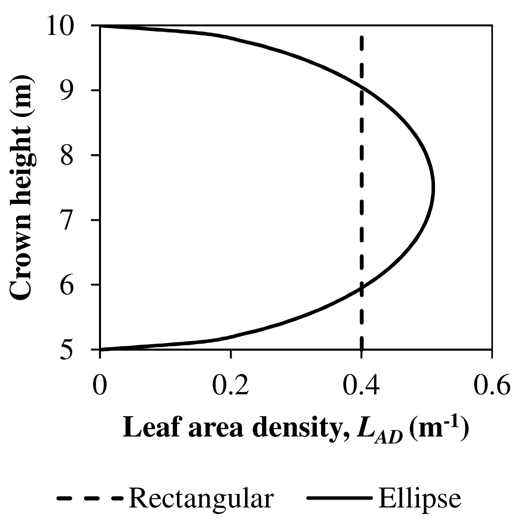

Figure 5: The leaf area density, L_{AD} for the two types of tree crown shapes used for the future study

The goal of the sensitivity analysis is to investigate how different parameters influence the wind flow structure and pollutant dispersion in an idealized street canyon. The variations of parameters involved are the location of heated wall due to the elevation angle of the sun (without sun, 45° and 90°) and the tree plantings (without tree, one tree and two trees), which can be seen in Figure 6. The bulk Richardson number for the flow under thermal atmospheric conditions is at -2.0, which is the maximum R_b for wind speed at roof level of more than 1.5 m/s [8]. In all, about 12 cases will be carried out using LES technique. A series of model sensitivity test will also be performed to ensure the reliability of LES. This includes determining the optimum spatial resolution, the period of flow to achieve statistically steady state and the sampling period.

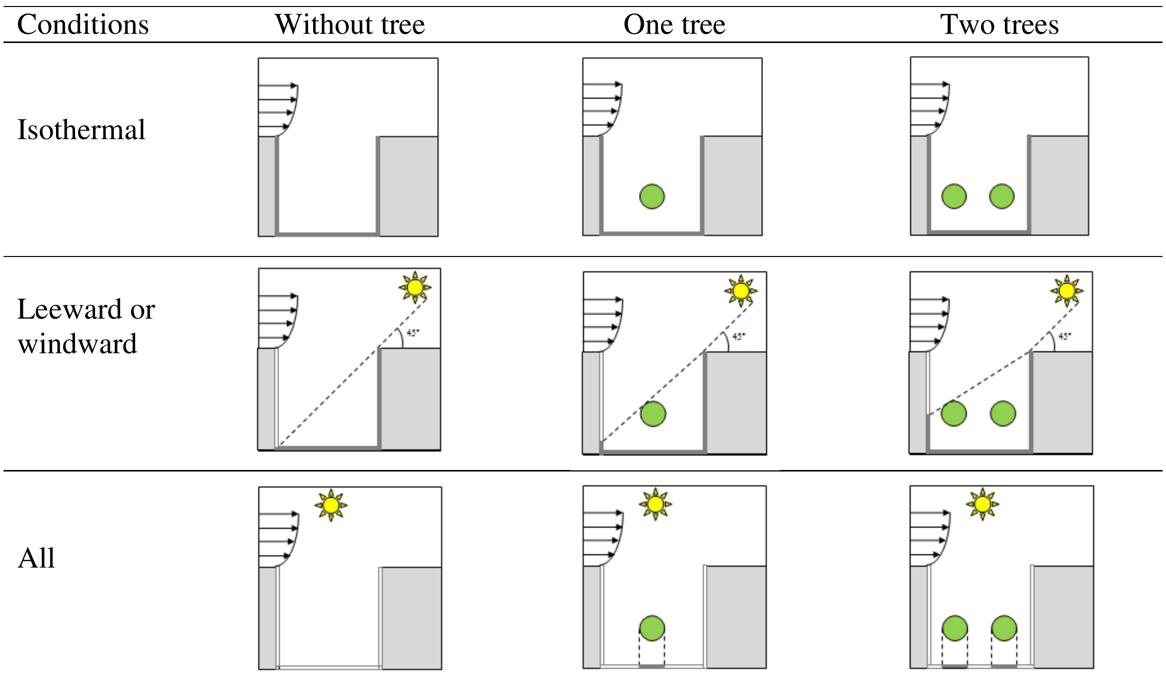

Figure 6: Schematic diagram of parametric setup for the future study

ACKNOWLEDGEMENT

The first author acknowledges the Zamalah UTM scholarship that he received for the duration of his PhD. We would like to thank the Center for Information and Communication Technology (CICT) in Universiti Teknologi Malaysia for supporting and providing facilities and services of high performance computing.

REFERENCES

[1] M. Krzyzanowski, Health effects of transport-related air pollution: summary for policy-makers. World Health Organization Regional Office for Europe, Copenhagen, 2005.

[2] S.D. Adar, J.D. Kaufman, Cardiovascular disease and air pollutants: evaluating and improving epidemiological data implicating traffic exposure. Inhalation Toxicology 19 (suppl. 1) (2007) 135–149.

[3] M.T. Salam, T. Islam, F.D. Gilliland, Recent evidence for adverse effects of residential proximity to traffic sources on asthma. Current Opinion in Pulmonary Medicine 14 (1) (2008) 3–8.

Journal of Advanced Research Design
ISSN (online): 2289-7984 | Vol. 1, No.1. Pages 1-17, 2014

[4] W.M.Y. Afiq, C.S.N. Azwadi, K.M. Saqr, Effects of building aspect ratio, wind speed and wind direction on flow structure and pollutant dispersion in symmetric street canyons: a review. International Journal of Mechanical and Materials Engineering 7 (2) (2012) 158–165.

[5] A.W.M. Yazid, N.A.C. Sidik, S.M. Salim, K.M. Saqr A review on the flow structure and pollutant dispersion in urban street canyons for urban planning strategies. Simulation: Transactions of the Society for Modeling and Simulation International 40 (8) (2014) 892–916.

[6] K. Uehara, S. Murakami, S. Oikawa, Wind tunnel experiments on how thermal stratification affects flow in and above urban street canyons, Atmospheric Environment 34 (10) (2000) 1553–1562.

[7] W.C. Cheng, C.-H. Liu, Large-eddy simulation of turbulent transports in urban street canyons in different thermal stabilities, Journal of Wind Engineering and Industrial Aerodynamics 99 (4) (2011) 434–442.

[8] Y. Nakamura, T.R. Oke, Wind, Temperature and stability conditions in an east–west oriented urban canyon, Atmospheric Environment 22 (12) (1988) 2691–2700.

[9] P. Louka, G. Vachon, J.-F. Sini, P.G. Mestayer, J.-M. Rosant, Thermal Effects on the Airflow in a Street Canyon – Nantes '99 Experimental Results and Model Simulation, The 3rd international conference on Urban Air Quality, Loutraki, 2001.

[10] B. Offerle, I. Eliasson, C.S.B. Grimmond, Surface heating in relation to air temperature, wind and turbulence in an urban street canyon, Boundary-Layer Meteorology 122 (2) (2007) 273–292.

[11] X. Xie, C.-H. Liu, D.Y.C. Leung, Impact of building facades and ground heating on wind flow and pollutant transport in street canyons, Atmospheric Environment 41 (39) (2007) 9030–9049.

[12] J.J. Kim, J.J. Baik, A numerical study of thermal effects on flow and pollutant dispersion in urban street canyons, Journal of Applied Meteorology 38 (9) (1999) 1249–1261.

[13] J. Allegrini, V. Dorer, J. Carmeliet, Wind tunnel measurements of buoyant flows in street canyons, Building and Environment 59 (2013) 315–326.

[14] I. Said, Z. Omar, L.F. Chang, Plant material booklet 2: wayside trees of Malaysia, Penerbit UTM, 2004.

[15] D.J. Nowak, D.E. Crane, J.C. Stevens, Air pollution removal by urban trees and shrubs in the United States, Urban Forestry and Urban Greening 4 (3-4) (2006) 115-123.

[16] Concentration Data of Street Canyons (CODASC). www.ifh.uni-karlsruhe.de/science/aerodyn/CODASC.htm (last accessed 10 December 2013).

[17] M. Park, A. Hagashima, J. Tanimoto, Effect of urban vegetation on outdoor thermal environment: field measurement at a scale model site, Building and Environment 56 (2012) 38–46.

Journal of Advanced Research Design
ISSN (online): 2289-7984 | Vol. 1, No.1. Pages 1-17, 2014

[18] S.M. Salim, S.C. Cheah, A. Chan, Numerical simulation of dispersion in urban street canyons with avenue-like tree plantings: comparison between RANS and LES, Building and Environment 46 (9) (2011) 1735–1746.

[19] R. Buccoleri, S.M. Salim, L.S. Leo, S. Di Sabatino, A. Chan, P. Lelpo, G. De Gennaro, C. Gromke, Analysis of local scale tree atmosphere interaction on pollutant concentration in idealized street canyons and application to a real urban junction, Atmospheric Environment 45 (9) (2011) 1702–1713.

[20] P.E.J. Vos, B. Maiheu, J. Vankerkom, S. Janssen, Improving local air quality in cities: to tree or not to tree?, Environmental Pollution 183 (2013) 113-122.

[21] A. Wania, M. Bruse, N. Blond, C. Weber, Analysing the influence of different street vegetation on traffic-induced particle dispersion using microscale simulations, Journal of Environmental Management 94 (1) (2012) 91-101.

[22] S.A. Zaki, A. Hagishima, J. Tanimoto, Experimental study of wind-induced ventilation in urban building of cube arrays with various layout, Journal of Wind Engineering and Industrial Aerodynamics 103 (2012) 31-40.

[23] S.A. Zaki, A. Hagishima, J. Tanimoto, A.F. Mohammad, A.A. Razak, Estimation of aerodynamic parameters of urban building arrays using wind tunnel measurements, Journal of Engineering Science and Technology, 9 (2) (2014) 176-190.

[24] S. Vardoulakis, R. Dimitrova, K. Richards, D. Hamlyn, G. Camilleri, M. Weeks, J.-F. Sini, R. Britter, C. Borrego, M. Schatzmann, N. Moussiopoulos, Numerical model inter-comparison for wind flow and turbulence around single-block buildings. Environmental Modeling and Assessment 16 (2) (2011) 169–181.

[25] A.W.M. Yazid, N.A.C. Sidik, S.M. Salim. Numerical simulation of wind flow structures and pollutant dispersion within street canyon under thermally unstable atmospheric conditions, Applied Mechanics and Materials, 554 (2014) 655–659.

[26] S.M. Salim, K.C. Ong, Performance of RANS, URANS and LES in the prediction of airflow and pollutant dispersion, in: H.K. Kim, S.-L. Ao, B. Rieger (Eds.), IAENG Transactions on Engineering Technologies: Special Edition of the World Congress on Engineering and Computer Science 2011, Springer, 2011, pp. 263-274.

[27] S.M. Salim, R. Buccolieri, A. Chan, S. Di Sabatino, Numerical simulation of atmospheric pollutant dispersion in an urban street canyon: comparison between RANS and LES, Journal of Wind Engineering and Industrial Aerodynamics 99 (2-3) (2011) 103–113.

[28] A.F. Mohammad, S.A. Zaki, M.S.M. Ali, A. Hagishima, A.A. Razak, A validation study for CFD simulation of a simplified urban model, Applied Mechanics and Materials, 548-549 (2014) 1795-1799.

[29] A. Kovar-Panskus, L. Moulinneuf, E. Savory, A. Abdelqari, J.-F. Sini, J.-M. Rosant, A. Robins, N. Toy, A wind tunnel investigation of the influence of solar-induced wall heating on the flow regime within a simulated urban street canyon, Water, Air and Soil Pollution: Focus 2 (5-6) (2002) 555–571.

[30] X.-M. Cai. Effects of differential wall heating in street canyons on dispersion and ventilation characteristics of a passive scalar, Atmospheric Environment 51 (2012) 268-277.

[31] Ansys Inc., A. ANSYS FLUENT User's Guide (2011).

[32] J. Franke, A. Hellsten, H. Schlünzen, B. Carissimo, Best practice guideline for the CFD simulation of flows in the urban environment, COST 732: Quality Assurance and Improvement of Microscale Meteorological Models, 2007

[33] R.J. Beare, M.K. Macvean, A.A.M. Holtslag, J. Cuxart, I. Esau, J.-C. Golaz, M. A. Jimenez, M. Khairoutdinov, B. Kosovic, D. Lewellen, T.S. Lund, J. K. Lundquist, A. Mccabe, A.F. Moene, Y. Noh, S. Raasch, P. Sullivan, An intercomparison of large-eddy simulations of the stable boundary layer, Boundary-Layer Meteorology 118 (2) (2006) 247-272.

[34] W.H. Snyder, Similarity criteria for the application of fluid models to the study of air pollution meteorology, Boundary-Layer Meteorology 3 (1) (1972) 113-134.

[35] C. Gromke, B. Ruck, Implications of tree planting on pollutant dispersion in street canyons. 45-50. Proceedings of the 2nd International Conference Wind Effects on Trees. Albert-Ludwigs-University of Freiburg, Germany. 13-16 October 2009

[36] C.S.B. Grimmond, T.R. Oke, Aerodynamic Properties of Urban Areas Derived from Analysis of Surface Form. Journal of Applied Meteorology 38 (9) (1999) 1262-1292.

[37] W.F. Dabberdt, W.G. Hoydysh, Street canyon dispersion: sensitivity to block shape and entrainment. Atmospheric Environment 25 (7) (1991) 1143–1153.

[38] P. Kastner-Klein, E.J. Plate, Wind-tunnel study of concentration fields in street canyons, Atmospheric Environment 33 (24-25) (1999) 3973–3979.

[39] J.S. Irwin, A theoretical variation of the wind profile power-law exponent as a function of surface roughness and stability, Atmospheric Environment 13 (1) (1979) 191-194.

[40] S.P. Arya, Introduction to Micrometeorology, second edition. San Diego. Academic Press (2001).

[41] J. Wieringa, A.G. Davenport, C.S.B. Grimmond, T.R. Oke, New Revision of Davenport Roughness Classification. Proceedings of the 3rd European & African Conference on Wind Engineering, Eindhoven, Netherlands, 2001, pp 285-292.

[42] S. Xie, Y. Zhang, L. Qi, X. Tang, Spatial distribution of traffic related pollutant concentrations in street canyons, Atmospheric Environment 37 (23) (2003) 3213–3224.

[43] F.T. DePaul, C.M. Sheih, Measurements of wind velocities in a street canyon, Atmospheric Environment 20 (3) (1986) 455–459.

[44] 3TIER Inc, 3TIER Global Wind Dataset Annual Mean Validation 2009, http://www.3tier.com/en/support/wind-prospecting-tools/what-were-3tiers-data-validation-procedures-prospecting/ , (last accessed 26 August 2014).

[45] L. Yang, Y. Li, Thermal conditions and ventilation in an ideal city model of Hong Kong, Energy and Buildings 43 (5) (2011) 1139–1148.

[46] R.A. Memon, D.Y.C. Leung, C.-H. Liu, Effects of building aspect ratio and wind speed on air temperatures in urban-like street canyons, Building and Environment 45 (1) (2010) 176–188.

[47] J. Karps, J. Darling, M. Allen, N. Hill, A. Montegna, C. Seyb, Portland's urban forest canopy – assessment and public tree evaluation, Portland Parks and Recreation, City Nature Urban Forestry, Portland, OR, October 2007.

[48] B. Troxel, M. Piana, M.S. Ashton, C. Murphy-Dunning, Relationships between bole and crown size for young urban trees in the northeastern USA, Urban Forestry and Urban Greening Volume 12 (2) (2013) 144–153.

[49] Z.A. Zeleti, H. Haario, J. Hamalainen, Experimental validation of a porous medium modeling for air flow through forest canopy, Poster presented at the annual European Wind Energy Association (EWEA) conference, Barcelona, Spain, 2014.

[50] J.D. Wilson, Numerical studies of flow through a windbreak, Journal of Wind Engineering and Industrial Aerodynamics, 21 (2) (1985) 119-154.

[51] G.J. Mayhead, Some drag coefficients for British forest trees derived from wind tunnel studies, Agricultural Meteorology 12 (1973) 123-130.

[52] A. Koizumi, In-situ evaluation for drag coefficients of tree crowns, in: J.D. Pereira (Ed.), Wind tunnels: aerodynamics, models and experiments, Nova Science Publishers, New York, 2011, pp. 147-166.

[53] B. D. Amiro, Drag coefficients and turbulence spectra within three boreal forest canopies, Boundary-Layer Meteorology 52 (3) (1990) 227-246.

[54] R. Queck, A. Bienert, H.-G. Maas, S. Harmansa, V. Goldberg, C. Bernhofer, Wind fields in heterogeneous conifer canopies: parameterization of momentum absorption using high-resolution 3D vegetation scans. European Journal of Forest Research 131 (1) (2012) 165–176.

[55] J. Cao, Y. Tamura, A. Yoshida, Wind tunnel study on aerodynamic characteristics of shrubby specimens of three tree species, Urban Forestry and Urban Greening 11 (4) (2012) 465–476.

[56] V. Masson, Y. Seity, Including atmospheric layers in vegetation and urban offline surface schemes, Journal of Applied Meteorology and Climatology 48 (7) (2009) 1377–1397.

[57] M. Kanda, M. Hino, Organized structures in developing turbulent flow within and above a plant canopy, using a large eddy simulation, Boundary-Layer Meteorology 68 (3) (1994) 237–257.

[58] C. Gromke, B. Blocken, W. Janssen, B. Merema, T. van Hoof, H. Timmermans, CFD analysis of transpirational cooling by vegetation: case study for specific meteorological conditions during a heat wave in Arnhem, Netherlands, Building and Environment, 2014 (DOI: 10.1016/j.buildenv.2014.04.022)

[59] TreesNY and CENYC, Citizen Pruners, and USDA Forest Service, Northeastern Research Station, 2002. (Available online at http://www.oasisnyc.net/trees/downloads/322trees-data-dictionary.pdf)

[60] C.P. Loughner, D.J. Allen, D.-L. Zhang, K.E. Pickering, R.R. Dickerson, L. Landry, Roles of urban tree canopy and buildings in urban heat island effects: parameterization and preliminary results, Journal of Applied Meteorology and Climatology 51 (10) (2012) 1775–1793.

[61] F. Meier, D. Scherer, Spatial and temporal variability of urban tree canopy temperature during summer 2010 in Berlin, Germany, Theoretical and Applied Climatology 110 (3) (2012) 373-384.

[62] P. Kastner-Klein, E. Fedorovich, M.W. Rotach, A wind tunnel study of organised and turbulent air motions in urban street canyons, Journal of Wind Engineering and Industrial Aerodynamics 89 (9) (2001) 849–861.

[63] K. Ahmad, M. Khare, K.K Chaudhry, Wind tunnel simulation studies on dispersion at urban street canyons and intersections – a review, Journal of Wind Engineering and Industrial Aerodynamics 93 (9) (2005) 697–717.

[64] S. Vardoulakis, B.E.A. Fisher, K. Pericleous, N. Gonzalez-Flesca, Modelling air quality in street canyons: a review, Atmospheric Environment 37 (2) (2003) 155–182.

[65] M.Y. Tsai, K.S. Chen, Measurements and three-dimensional modeling of air pollutant dispersion in an urban street canyon, Atmospheric Environment 38 (35) (2004) 5911-5924.

[66] WHO, Global status report on road safety, World Health Organization, Geneva, (2013).

[67] L. Ntziachristos, Z. Samaras, Speed-dependent representative emission factors for catalyst passenger cars and influencing parameters, Atmospheric Environment 34 (27) (2000) 4611-4619.

[68] R. Akcelik. Speed-flow models for uninterrupted traffic facilities, Technical report, Akcelik and Associates Pty Ltd, Greythorn Vic, December 2003.