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Assessing the effects of urban canyon's direction on air flow pattern and CO dispersion using CFD (A case study of Tehran)

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ABSTRACT

Air pollution is considered one of the main challenges of environmental sustainability. Metropolises are increasingly facing the problem of air pollution, which seriously affects people's health. There are several factors associated with air pollution in the streets including urban form, ventilation, and air pollution sources. In the present research, the effects of the street canyon direction on the wind behavior and pollutant dispersion have been investigated using CFD and the model has been validated with the wind tunnel.

The results show that, the orientation of the urban canyon affects both airflow and air pollutant dispersion patterns. In F3 (α =90°), where the wind direction is perpendicular to the street, ventilation is mostly through the street roofs, so that the amount of pollutant in the roof height is almost 183% of F2 (α=45°) and 347% of F1 (α =0°). Since near the leeward wall the velocity of airflow is decreased to zero, these spaces are highly susceptible areas for pollution accumulation. In F1, ventilation is mostly through the longitudinal displacement of pollutions and dispersion via lateral openings. In this case, the beginning parts of the urban canyon are the most well-ventilated ones, and the end of it has the highest level of pollution concentration. It was also found that the lowest level of pollution occurs in F2. Finally, the diagonal street (F2) has been recognized as the optimal direction for main streets in the residential areas of Tehran which should be taken into consideration in the Sustainable Urban Development Principles of Tehran (SUDPT).

Introduction

Street-level air pollution (micro scale analysis), which is intensely caused by vehicles, is a challenging issue that has become a hotspot of research and application (Edussuriya et al., 2014, Shen et al., 2017). Air pollution at the street level, in addition to its sources, deals with some complex variables such as ventilation and urban forms (most common variables) that have not yet been properly explored and understood (Edussuriya et al., 2014).

Generally, long-term atmospheric stability leads to the stabilization of pollutants and increases the number of air particles in an urban area (Tominaga & Stathopoulos, 2013). Airflow transports the particles from one place to another, so plays an important role in ventilation. The airflow dynamics is highly influenced by morphological factors (Cionco and Ellefsen, 1998). The dispersion and dilution processes of air pollutants in street canyons are dependent upon horizontal mean flows in opening areas, vertical mean flows, and turbulent diffusion through canopy roofs (Hang et al., 2015).

As the aerodynamic behavior of the wind at the pedestrian level around the building is the result of the interaction between the basic characteristics of the wind (wind speed, acceleration, frequency, etc.) and the physical structure of the buildings (shape, size, height, etc.) (Jackson, 1978). Therefore, there exist a threefold relationship between morphology, airflow, and air pollution. Urban morphology on the one hand directly affects the way pollutants accumulate and on the other hand, indirectly affects the behavior of pollutants through micro-climate change. In this regard, various studies have been conducted on a wide range of scales from macro (regional, urban) to micro (neighborhood, urban block, and building).

Studies that have examined the relationship between formal factors and air quality on the micro-scale (neighborhood, urban canyon) have often used two methods of statistical analysis of the relationship between variables, and causal inference analysis using Computational Fluid Dynamics (CFD) Over the last 20 years, CFD has been employed for assessment of a wide range of variables and indices including, aspect ratio (Di Sabatino et al., 2008; Eeftens et al., 2013, Shen et al., 2017; Tan et al., 2019), street continuity ratio and street spatial closure ratio (Shen et al., 2017), average height (Yang et al., 2020), difference height (Hang et al., 2012; Lin et al., 2014; Nosek et al., 2018; Tan et al., 2019; Yang et al., 2020), length of the urban canyon (Hang et al., 2012), size of Neighborhood (Lin et al., 2014; Wang et al., 2017), Neighborhood form (rectangular and square) (Wang et al., 2017), street architecture (roof configuration) (Kastner-Klein et al., 2004; Tan et al., 2019), degree of enclosure, coverage the site, plot ratio or floor area ratio (FAR) (Yang et al., 2020), open space and mineralization (yousefian et al., 2021). Aligned with the direction of the present study, Lin et al. (2014) studied the ventilation of urban canopy layers using CFD and the k-epsilon turbulence model by changing the height of the blocks, the arrangement of the blocks, the dimensions of the neighborhood and the direction of the wind. According to the results, there is better ventilation in the models that wind blows parallel to square blocks than oblique ones. Wang et al. (2017) investigated the relationship between the number of pollutants and the wind flow angle in two square and rectangular forms of the neighborhood using (CFD) and the k-epsilon turbulence model. They concluded that in the square neighborhood, ventilation in the 0 ° wind direction is better than in the oblique one, but the rectangular neighborhood is ventilated with the wind directions of 45° to 90° better than the parallel wind. Huang et al. (2019) used a 3D CFD model for investigating the effects of different wind directions on the dispersion of pollutants, based on the RANS (Reynolds-Average-Navier-Stokes) equations and the standard k-ε turbulence, in an urban canyon in which the ratio of length to height is 10. Then the results were validated by wind tunnel (WT). The result shows, the strongest air exchange occurs when this angle is equal to 30 degrees and the weakest ventilation is at an angle of 90 degrees.

The previous research works reflect the fact that the relationship between the orientation of the street canyon with respect to the prevailing wind direction and air pollution is case sensitive, and the results could not be generalized to other cases. The present study intends to study three residential streets of Tehran (that are among the neighborhoods with most repetitions in Tehran). Due to the feasibility of CFD technique, a set of validated CFD simulations are solved in order to explain the relationships between the variables and provide us with the dispersion algorithms in those investigated areas.

Materials and Methods

The main tools for the urban physical evaluation are field measurement, full-scale, and reduced-scale laboratory measurements, and numerical simulation methods such as CFD (Blocken, 2015). In recent years, many advances have been made in numerical methods, and because to the increase in computational capacity and speed, CFD, as a cheapest and fastest method, has become possible to develop complex system simulations in the field of air pollution (Vardoulakis, 2003; Lateb, 2016). Thus, in this research, CFD technique has been used. In order to have valid results, all CFD settings (including mesh arrangement and turbulence model etc.) have been validated using experimental results (wind tunnel result of a reduced scale model) (Huang et al., 2019). Generally, four main turbulence modeling approaches are used for different CFD simulation. The order of mathematical complexity and, hence, computational cost of these methods are Reynolds-Average-Navier-Stokes (RANS), Detached Eddy Simulation (DES), Large Eddy Simulation (LES), and Direct Numerical Simulation (Setaihe al et, 2014). The RANS models are formed based on temporal averaging of parameters. A valid RANS simulation is indeed capable of providing the fastest result among the other methods while maintaining the essential accuracy. Hence, RANS models are the most popular turbulence models among CFD specialists for obtaining of aerodynamics and fluid mechanics parameters of a fluid domain. Among the RANS models, the Realizable k-epsilon turbulence model has been shown to result in acceptable level of accuracy for similar simulations (Moonen al et, 2011; Setaihe al et, 2014; Ramponi al et, 2015; Gromke al et, 2015; Juan al et, 2017).

The effects of wall grid spacing is an important factor for aerodynamics. For example, while for the wind turbine applications y+ should be about one, for air simulations in indoor and outdoor spaces higher values are also acceptable (Moshfeghi and Hur, 2021; Zoka et al., 2021).

In the field of urban form modeling, some researchers have used the idealize geometry (Nosek al et, 2018; Wen al et, 2018; Huang al et, 2019); and some ones have used real geometry (Eeftens et al., 2013, Shen et al., 2017; Karra et al., 2017; Gao et al., 2018; Hadavi and Pasdarshahri, 2020; Marulanda T. et al., 2020, Hassan et al., 2020). In this research, an idealize geometry in the context of Tehran has been used. GIS software and satellite images have been applied to select a case study. The CFD simulations have been performed using Ansys Fluent.

Case study

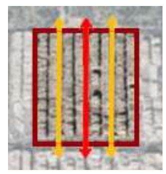
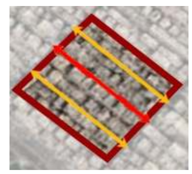
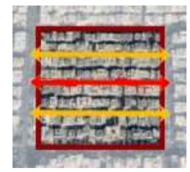
The residential areas of Tehran are the case study. Figure 1 shows the location of the case studies in Tehran. Among the local streets in the city, the two categories of East-West and North-South streets have the highest frequency which have been selected for modeling. Besides, streets with an angle of 45 degrees (northeast-southwest, northwest-southeast) have also been chosen as an intermediate angle.

Our GIS based analysis shows, 12-meter width street and four-story buildings have the highest frequency in the residential areas of Tehran (Municipality of Tehran-2020). Thus, the streets are modeled with a width of 12 meters and a height of 16 meters. The dimension of the neighborhood is assumed 300 m × 300 m and four blocks in each form have been defined (Table 1).

Figure 1- location of the case studies in Tehran

Source: Municipality of Tehran (2020)

Table 1- Selected form

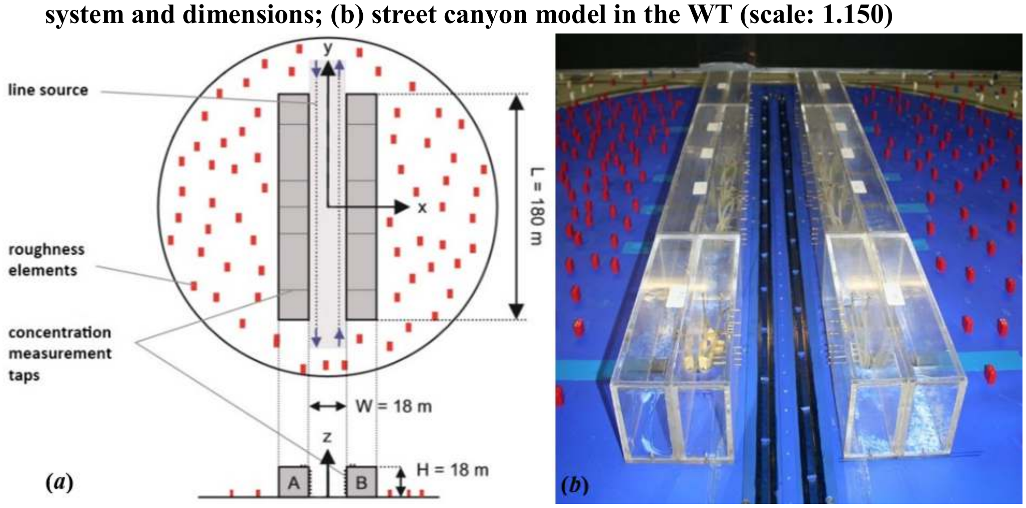
Name	**F_1**	**F_2**	**F_3**
Form			
Case study	 Moshiriyeh neighborhood	 Firuzabadi neighborhood	 Mosalla neighborhood
urban canyon's direction relative to the prevailing wind direction	0 °	45 °	90 °
Street width	12		
Block height	16		

Source: Authors

Validation of the CFD settings

Prior to the main simulations, the CFD settings have been validated, to ensure us about the accuracy of the results. For this purpose, the wind tunnel experimental dataset from the WT database (Karlsruhe Institute of Technology (CODASC). with a reduced scale (1:150) has been used the wind tunnel test consisted of two parallel buildings with dimensions of 0.12 m wide, 0.12 m high, and 1.2 m long that were located at a distance of 0.12 m from each other (Figure 2).

Figure 2- (a) Schematic of street canyon model showing the main coordinate system and dimensions; (b) street canyon model in the WT (scale: 1.150)



Source: CODASC; Moonen et al. (2013)

In the experiment, pollutant sources are linear and parallel to each others, continuously releasing SF6 tracer gas at a constant rate. The wind angle is parallel to the street. For this configuration, the concentration data is given in normalized form as:

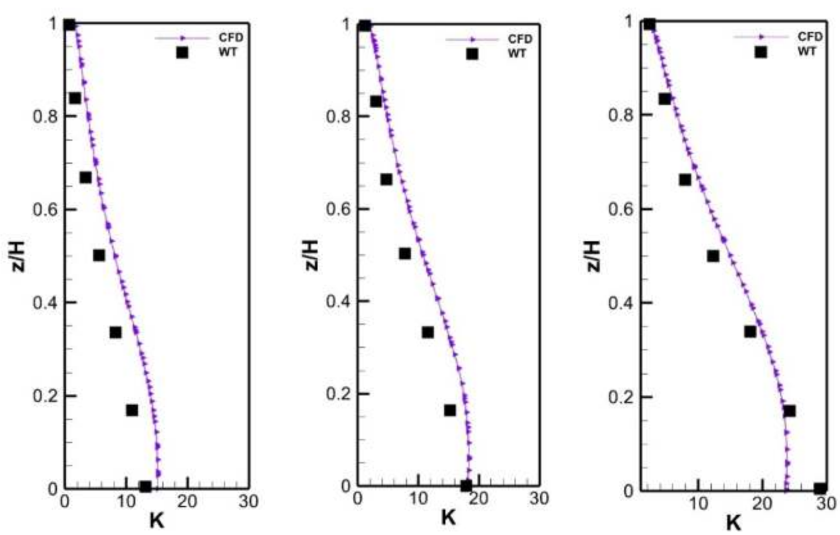
$$K = \frac{C_m H U_H}{Q/l} \tag{1}$$

where K is the normalized concentration, C_m denotes the measured concentration, H represents the building height (m) and U_H is the wind velocity (m⁄s) at the building height. Also, Q shows the pollutant emission rate from the line source (m2 ⁄s) or in other words the strength of the pollutant source and l is the length of the line source (m). For this experiment, the height of the building is 0.12 m, the wind velocity at the building height is 4.7 (m⁄s), the length of the line source is 1.44 m, and the value of Q is equal to 10 g/s (Salim et al., 2011; Huang et al., 2019).

To achieve an accurate CFD setting with acceptable results (Similar to WT), different CFD simulations with different parameters such as type of turbulence model, etc., have been implemented and the results have been compared with each other and wind tunnel results (Figure 3, Figure 4). Finally, the setting of the best model has been selected as the validated model (Table 2).

Figure 3- Comparison of dimensionless pollutant concentration (K) in three vertical lines near the canyon wall in the model and wind tunnel

Y/H = 0 **Y/H = 1.26** **Y/H = 3.79**



Source: Authors

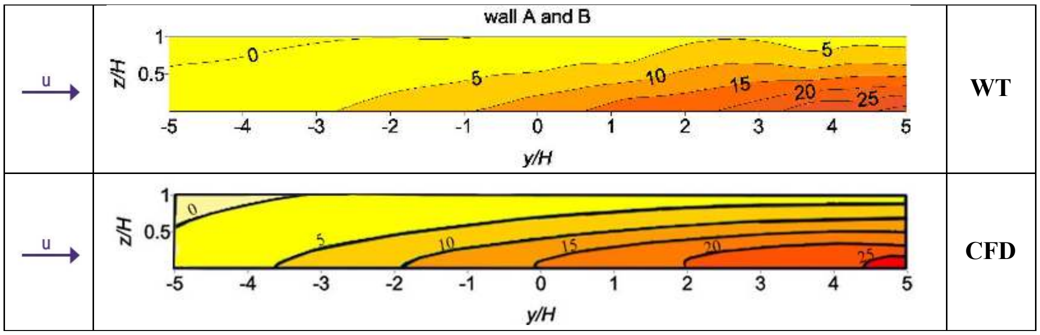
Table 2- Specifications of the final validated model

Turbulence Model	RKE
Turbulent Schmidt number	0.3
Scalable wall function	Yes

Mesh type	Tetrahedral& Hexahedral
No. of prism layers	15

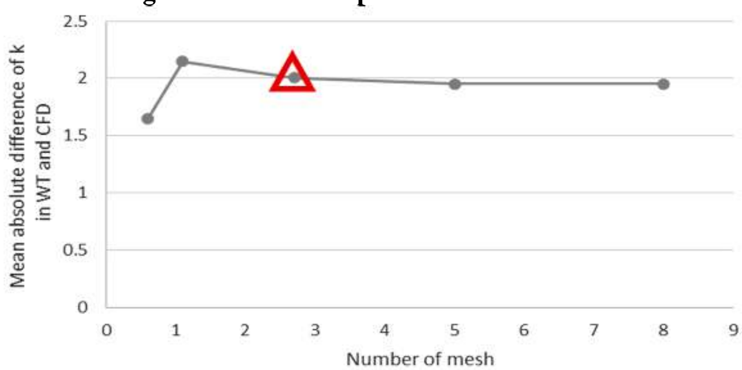
Source: Authors

Figure 4- Dimensionless pollutant concentration K in Wall A in WT and CFD



Source: Authors; CODASC

Figure 5- Mesh-independence examination



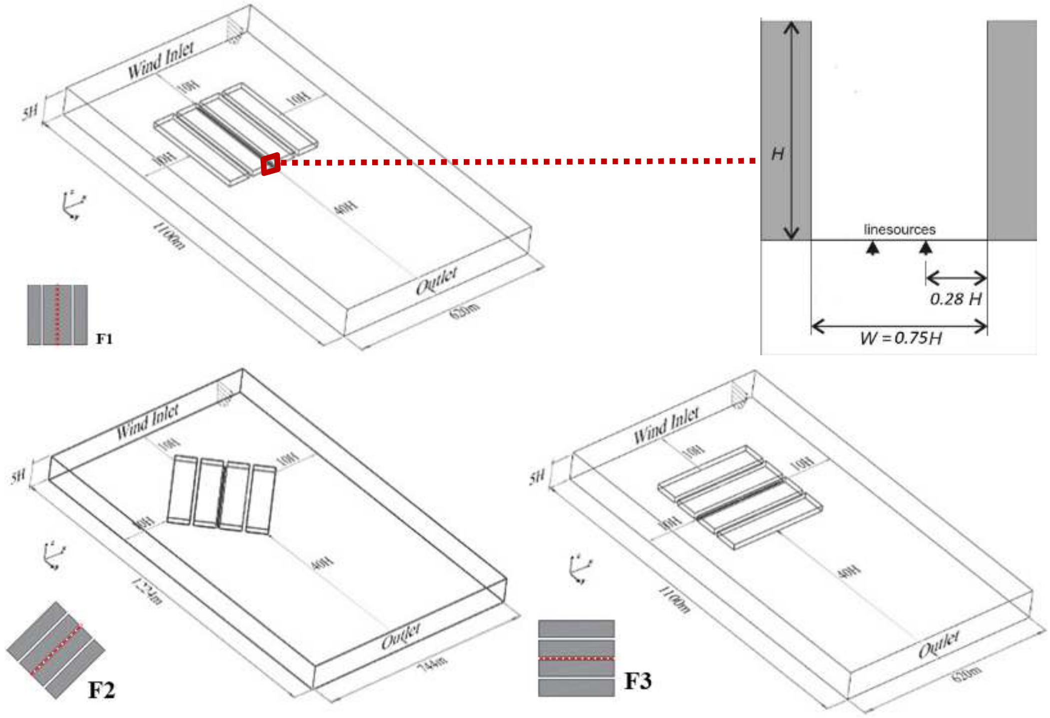
Source: Authors

CFD setting

Domain and mesh

The size of the computational domain has been determined based on the minimums mentioned by Tominaga et al. (2008) and Blocken (2015) and the dimensions of the neighborhood. The dimensions of the neighborhood are 300 m wide, 300 m long, and 16 m high. The ratio of the building height to the street width is 4 to 3 (16 m×12m). The distance upstream of the first building to the inlet boundary and side walls is10H. For the downstream, the domain outlet in assumed at a distance of 40H from the last building and the height of the domain is 5H (Figure 6).

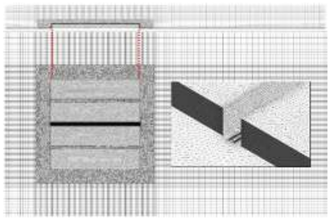
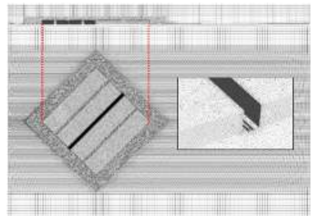
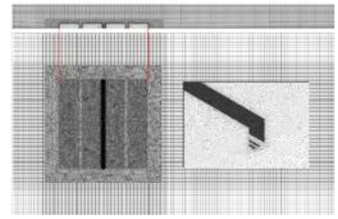
Figure 6- Geometry of F1, F2 and F3



Source: Authors

Hybrid mesh in the models have been used. For the inner region, which includes the main geometry and its adjacent space, the tetrahedral meshing, and for the outer region, the hexahedral cells have been used. The number of prism layers is 15, the aspect ratio in the whole geometry is 1.15, and in the inner region equal to 1.1. In must be noted that in order to use the results of the mesh independence and due to the similarity between the size and the form of the blocks in the wind tunnel experiment and the present model, the number of mesh along each edge has been normalized.
In order to reduce the solution time in the symmetric models with respect to the wind flow (F1 and F3), only one half of the domain is simulated (Wang et al. 2017). Number of cells in the F1 and F3 are 7.5 million and 7.3 million, respectively. The number of cells in the F2 is 16 million. Figure 7 shows the grid of F1, F2 and F3.

Figure 7- Grids of F1, F2 and F3

F1	F2	F3
		

Source: Authors

Boundary conditions

At the inlet boundary, the vertical profiles for wind velocity U(z), turbulence intensity Iu(z), turbulent kinetic energy (k), and turbulent dissipation rate (ε) are specified (Salim et al., 2011; Huang et al. 2019) (see 2, 3, 4, 5 equation). The domain output with zero gradient is defined. The symmetric boundary condition is applied at the two surrounding walls and top of the domain with constant pressure of 1atm. No-Slip Boundary Condition is used for the walls and roofs of the geometry and the domain floor.

(2) $$U(z) = U_{ref}(z_{ref})[\frac{z}{z_{ref}}]^{\alpha}$$

(3) $$I_u(z) = I_u(z_{ref})[\frac{z}{z_{ref}}]^{\alpha_I}$$

(4) $$k = \frac{u_*^2}{\sqrt{C_\mu}}\left(1 - \frac{z}{\delta}\right)$$

(5) $$\varepsilon = \frac{u_*^3}{KZ}\left(1 - \frac{z}{\delta}\right)$$

Pollutant injection

In the current study carbon monoxide (CO) is considered as the pollutant. Two lines source of the pollution is defined (5 cm wide and 40 cm high) along the main street with 0.28H distance to the wall. The pollutant is defined only at the line source with a constant rate (Huang et al. 2019; Wen et al. 2018; Shen et al. 2017). The amount of pollutant input equals 3.44× 〖10〗 ^(-4) kg/s (Appendix 1), its velocity is very small (1.02×10-5 based on inlet flow) with zero turbulence intensity (Wen et al. 2018).

Climatic data

The climatic data is based on the report of Mehrabad Airport Synoptic Station in 2020. The average annual wind speed is 3.11 m / s, and the prevailing wind direction is western which is used as the reference velocity to define the velocity profile. The average annual air temperature is 18.2 ° C, and the pressure is 1016 hPa (101.6 kPa).

Solution method

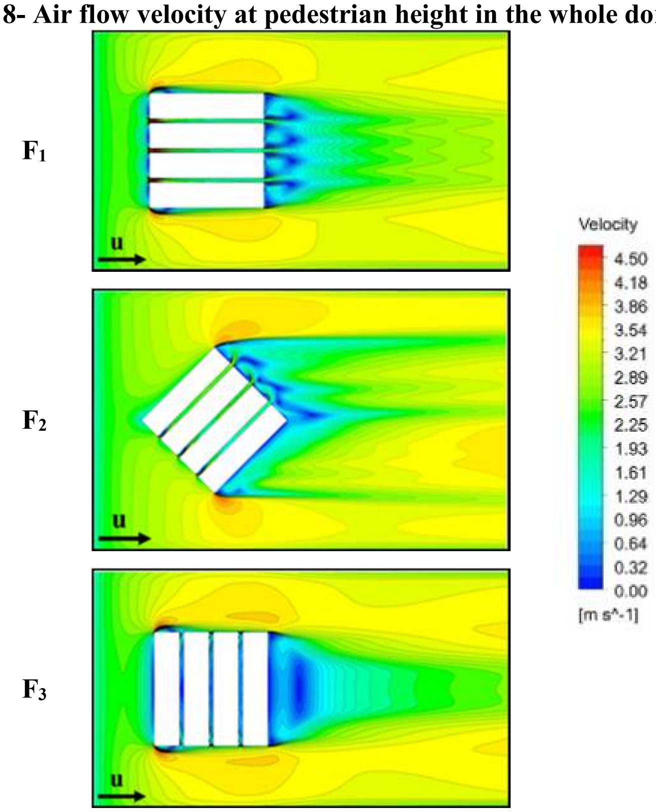
The three-dimensional, steady, isothermal, and incompressible RANS equations with the k-ε turbulence and the species transport equation (mixed-species), were solved. Among the k-ε models, the Realizable k-epsilon (RKE) model, which has achieved better results in the validation section, has been selected. The "Scalable wall function" is used in modeling and traffic turbulence are not considered here. It should be noted that the Scalable wall function generates accurate modeling of flow near the solid walls (inside the laminar and buffer layers) by effectively shifting the near-wall mesh points to Y+>11.22, regardless of their original distance from walls. This provides us with a better prediction about the exact values of pollution dispersion in those areas.

Findings

Effects of canyon directions on air flow

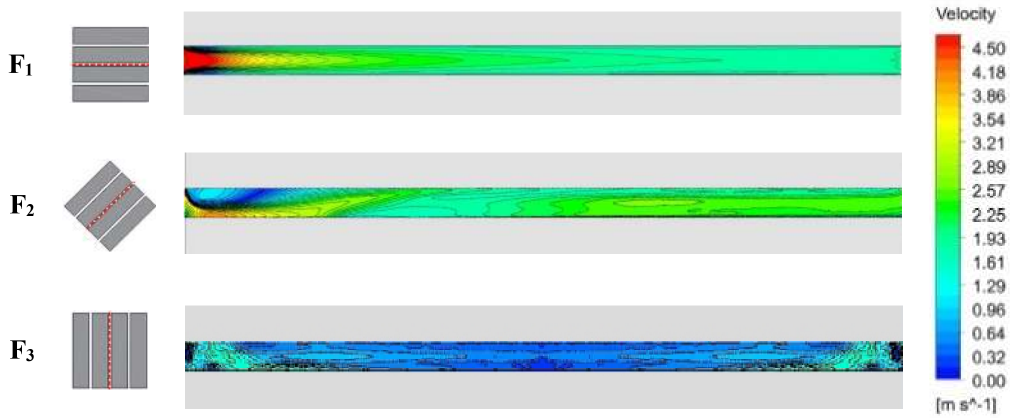
As it is in Figures 8 and 9, at the corners of the windward blocks, velocity is the maximum, and, there exists sharp decrease between these areas and walls, which is aerodynamically a separated zone. In all three forms, the maximum velocity at the height of the pedestrian (2 M) are affected by this phenomenon and are equal to 5.28 m/s, 4.56 m/s and 4.27 m/s in F1, F2 and F3, respectively. In F1, the maximum velocity is observed on the main street. In F2 the maximum velocity (4.56 m/s) in the domain is decreased to 4.18 m/s in the main street. This velocity drop is more significant in F3, from 4.27/s to 1.98 m/s.

Figure 8- Air flow velocity at pedestrian height in the whole domain



Source: Authors

Figure 9- Air flow velocity at pedestrian height in the main street



Source: Authors

Based on the maximum velocity, F1 leads to the strongest wind flow compared to other forms. As it is presented in Table 3, the domain average velocity of all three forms in pedestrian height are close to each other, but they differ in the main streets. F2 has a slightly higher velocity than F1 (0.01 m/s) and remarkably higher than F3 (1.39 m/s). It is because of the wind channeling effect and increasing velocity in F1. In F3, due to the wind perpendicular to the street, the turbulent flows cause most of the air movements, and the wind velocity in the urban canyon, especially near the leeward side and the ground is very low. It should be noted that in all three forms the minimum velocity is close to zero, which corresponds to the effects of the areas behind the blocks.

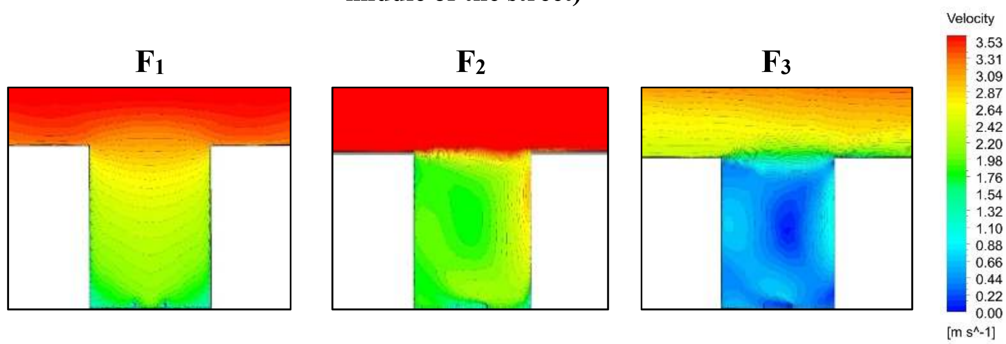
Table 3- Maximum and mean air flow velocity at pedestrian height in the whole domain and main street

Form	In the main street (m/s)		In the whole domain (m/s)	
	Maximum	Mean	Maximum	Mean
F_1	5.28	2.11	5.28	2.85
F_2	4.18	2.12	4.56	2.86
F_3	1.98	0.73	4.27	2.82

Source: Authors

As Figure 10 shows, the velocity contours in street roofs of all forms, are very close to each other and the air flow velocity increases significantly. In the F1, there is a straight correlation between the wind velocity and height, and wind velocity reaches 3 m/s in street roofs. In the F2, the maximum velocity is demonstrated in the street canyon and in the vicinity of the windward wall as well as the street roof which are about 3 and 3.7 consequently. In F3, the wind speed inside the urban canyon is very low and is accompanied by several vortices which are created as a result of the blowing of wind to obstacles such as windward walls. In this case, the highest velocity (1.1 m/s) occurs near the street roofs.

Figure 10- Air flow velocity on vertical cross sections of the main canyon (in the middle of the street)

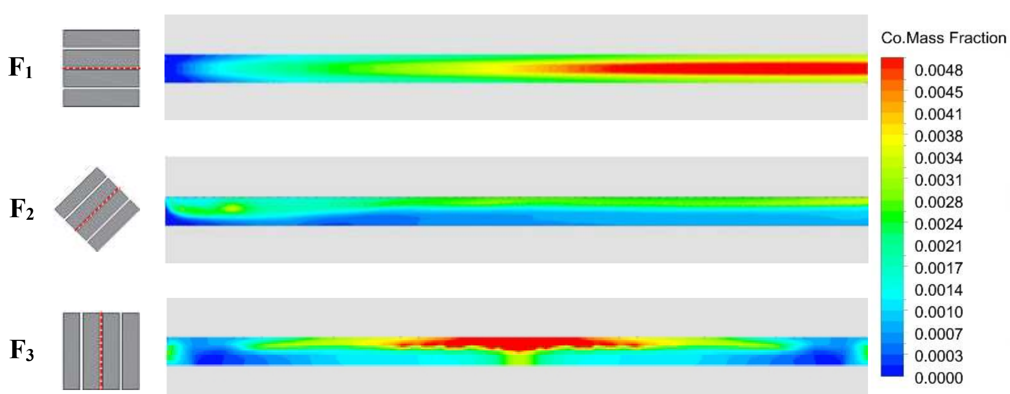


Source: Authors

Effects of canyon directions on pollutant concentration

The pollutant's mass fraction is used for the investigation. It is observed that (Figure 11) the average mass fraction of pollutants in both the whole domain and the main street of F1 has the worst condition. This amount in the whole domain of F1 is almost 230% of the F2 and 205% of the F3. The maximum mass fraction of pollutants is observed in the main street of the F3. The noticeable difference between the maximum and the average mass fraction of the F3 indicates the concentration of pollutants in a small area of the street, next to the leeward wall (western wall) in the middle part of the street. Finally, considering the average mass fraction at the height of the pedestrian, in both the main street and whole domain, the F3 shows the best performance (See Table 4).

Figure 11- CO mass fraction at pedestrian height in the main street



Source: Authors

Table 4- Maximum and mean CO mass fraction at pedestrian height in the whole domain and main street

Form	In the main street (m/s)		In the whole domain (m/s)	
	Maximum	Mean	Maximum	Mean
F_1	0.0071	0.00287	0.0071	0.000037
F_2	0.004	0.00138	0.004	0.000016
F_3	0.0116	0.002	0.0116	0.000018

Source: Authors

According to Table 5, the highest levels of pollutants on the street roof occurred in F2, followed by F3 and F1. So that its average in F3 is about 183% F2 and 347% F1. This means that most of the vertical ventilation takes place in F3, then in F2, and finally in F1.

Table 5- Maximum and mean CO mass fraction at main street roof

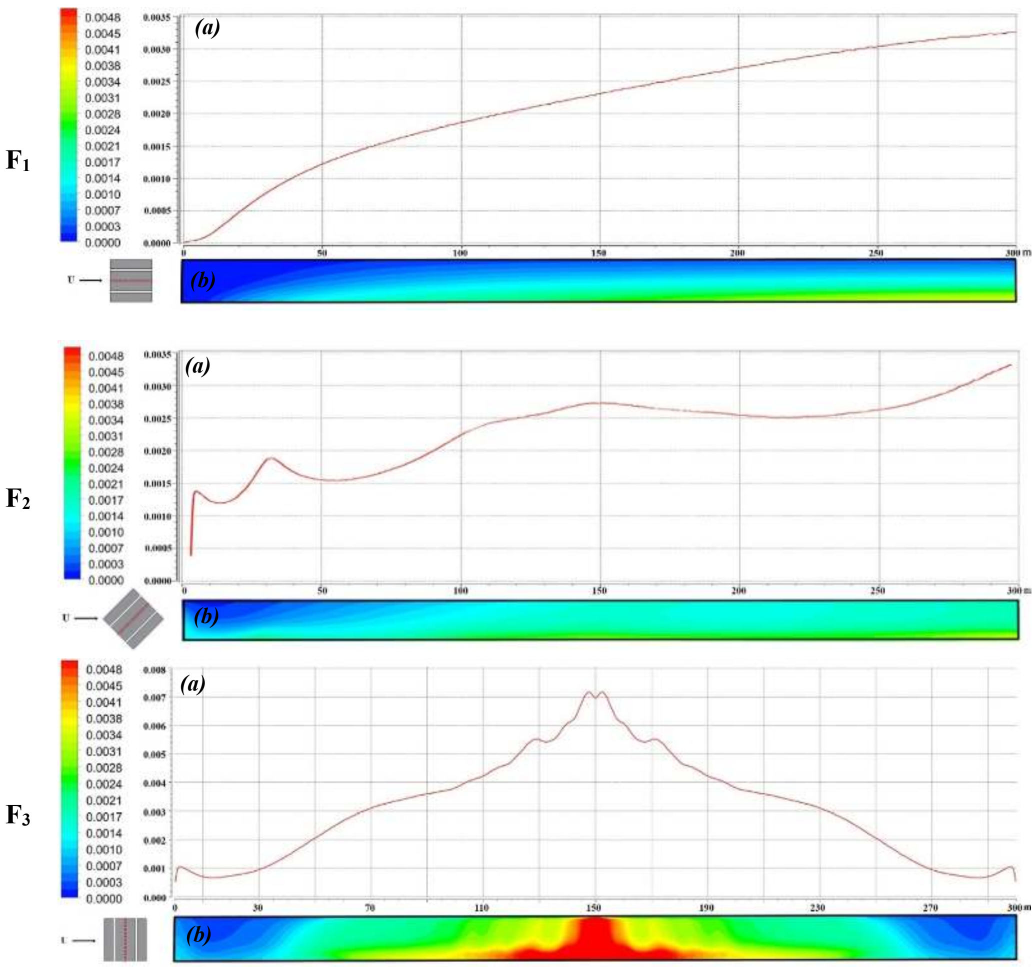
Form	In the main street (m/s)	
	Maximum	Mean
F_1	0.00046	0.00019
F_2	0.00144	0.00036
F_3	0.00643	0.00066

Source: Authors

Figure 12 shows the mass fraction contours in the longitudinal profile of the main street (in the sidewalk axis, beside the western wall). In F1, by going away from the wind inlet, the level of pollutant concentration slightly increases until its peak (0.0044) at the end of the street. In F2, at the beginning of the street, the concentration increases sharply, and then due to the turbulence diffusion the concentration shows rapid fluctuations, and reaches a peak (0.0033) at the end of the street.

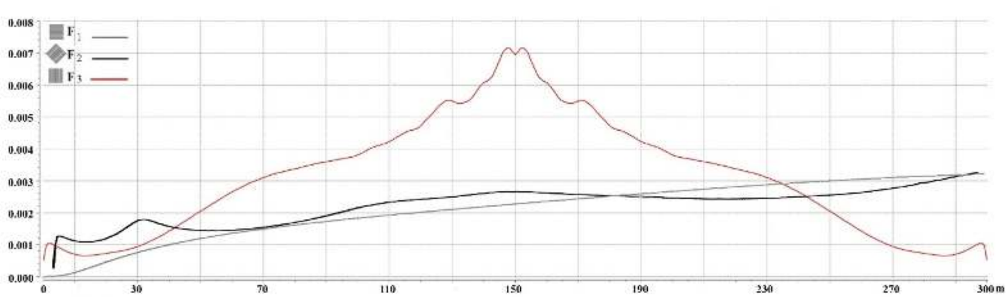
In F3, the minimum pollutant concentration is reported at the beginning and end of the street. It is mainly because of the openness next to these areas, which allows pollutants to be excreted via lateral openings. The center part of the street has the highest level of concentration (0.0072), which is almost 3 and 2 times more than F1 and F2. Besides, based on the average mass fraction, this form has the worst performance too (Figure 13).

Figure 12- (a) CO mass fraction in the longitudinal profile in the sidewalk axis of the main street– At pedestrian height; (b) CO mass fraction in the Sidewalk axis in the main street



Source: Authors

Figure 13- Comparison of the CO mass fraction in the Sidewalk axis of the main street



Source: Authors

Table 6- Maximum and Mean CO mass of fraction in the longitudinal profile in the sidewalk axis of the main street

Form	CO mass fraction in the longitudinal profile	
	Maximum	**Mean**
F_1	0.0044	0.0011
F_2	0.0033	0.0016
F_3	0.0072	0.0023

Source: Authors

Furthermore, in order to assess the effects of wind velocity on the urban canyon ventilation and the concentration of CO, the average velocity and the average mass fraction of CO in the main street and in the whole domain are compared in Table 7. As it can be read, F2 has the highest wind velocity as well as the lowest amount of mass fraction in both the main street and in the whole domain.

Table 7- Maximum and mean air flow velocity and CO mass fraction at pedestrian height in the whole domain and main street

Form	In the main street		In the whole domain	
	Mass fraction	**Wind velocity (m/s)**	**Mass fraction**	**Wind velocity (m/s)**
F_1	0.00287	2.11	0.000037	2.85
F_2	0.00138	2.12	0.000016	2.86
F_3	0.002	0.73	0.000018	2.82

Source: Authors

Although the average velocity of F3 is less than F1, the concentration is also lower. Therefore, there is not a simple direct correlation between the concentration of pollutants and wind velocity. It could be justified by these facts that ventilation is not only due to the horizontal flows but also the vertical movement of air and vortices have a significant effect on the quality of air.

Conclusion

In the present research the relationship between the orientation of the street canyon with respect to the prevailing wind direction (western wind) and pollution dispersion in three residential long streets of Tehran is investigated using validated CFD simulations with RANS equations. The important conclusions can be summarized as follows:

Wind velocity is a function of the form of urban blocks. In the corners of the windward blocks, the effect of the corner is created and the wind speed is intensified, where the presence of pollutants is often minimized. Beside the leeward walls, where pollutants accumulate, the wind blow becomes slow and sometimes reaches zero.

That is why the highest amount of pollutants is reported in F3, which the wind direction is perpendicular to the street.

The alignment of the wind flow with the urban canyon (F1) causes to create the canalization phenomenon and wind would partially accelerate. In this case, wind flow leads to better ventilation in the beginning parts of the urban canyons as well as the accumulation of pollutants at the end of the streets. Ventilation in this type of street often occurs via the pollutant dispersion in the horizontal direction through lateral openings rather than the vertical movement and the street roofs.

Generally, the vertical displacement of pollutants is a better option than the horizontal displacement, because if we consider the neighborhood as a part of the city (urban context), the horizontal transportation of pollutants, transfer them from one place to another (although these pollutants diluted during the movement), whereas in the vertical movement, the pollutants mostly evacuate through street roofs more intensely, and would less accumulate at lower heights.

One of the important results of this study is a higher concentration of pollutants at pedestrian height (lower height) rather than at 3 meters in height and above, which causes pedestrians to be highly exposed to air pollution. The reasons for this phenomenon are the presence of a permanent source of pollutants on the street, which always increases the pollution concentration, the reduction in velocity near the surface, and finally the possibility of discharging pollutants from street roofs at higher heights.

Since F2 at the pedestrian height has the least amount of pollutants (both in the whole domain and main street), it can be noted that it is the most appropriate and responsive form in terms of air quality. In this case, the pollutant disperses both horizontally and vertically. Accordingly, diagonal passages should be taken into consideration in the Sustainable Urban Development principles of Tehran (SUDPT).

Last but not the least, there is not a direct relationship between wind velocity and ventilation (the amount of CO) in the studied forms. However, there might be correlations at different ranges of velocity particularly at higher velocities, which needs further researches. At lower velocities, the way of wind behavior as well as small and large turbulent diffusions also affect the way the pollutant behaves, just like the wind speed.

Other recommendations for future research are given as below: first, investigating the relationship between different urban forms with a parametric approach (neighborhood scale) and the amount of air pollution. Second, analyzing causal relationships and behavior of other types of pollutants in specific urban forms.

Appendix

In Tehran, the amount of Co dispersion for a certain condition _which the ground slope is zero, cars' air conditioning system is off, the speed of cars is about the residential areas speed limits(25 to 35 km/h)_ is 7.5 g/km per car. Besides, the annual average daily vehicle traffic of the residential areas during the morning peak hour is about 1000 vehicles per hour (Municipalities of Tehran, 2020). Thus, an average of one car per 3.6 seconds passes through a certain section of the local street. Considering the dimension of the model (300m * 300 m), it takes 36 seconds for each car to pass the street. In the meantime, 10 cars cross the section. So, there are 10 cars, 30 meters apart in the model at any time. The equation below calculates the amount of pollutant emission. In this equation, 7.5 g is the average pollutant emission per kilometer.

$$\sum_{i=0}^{9}(300-(i \times 30)) \times \frac{7.5}{1000} \quad (6)$$

As a result, exhaust emission in ambient air is 12.375 g. Since this figure is for 10 cars passing through the street in 36 seconds, the amount of CO emission is 3.44×10^{-4} kg/s.

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