DOI: http://dx.doi.org/10.22104/aet.2015.370 Advances in Environmental Technology 3 (2015) 113-120

Advances in Environmental Technology

journal homepage: http://aet.irost.ir

Investigation of dissipation flow in the urban canyon

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ARTICLE INFO

Article history:
Received 14 March 2016
Received in revised form
18 June 2016
Accepted 19 June 2016

Keywords:
Pollution
urban block
urban canyons
TKE, CFD
Envi-met

ABSTRACT

In regard to wind flow in the cities, obtaining a minimal level of pollution in the environment is achievable. Different policies have been considered for minimizing urban pollution such as the attachment and/or reduction of building parts like air-traps, ceiling forms, and so on. Due to an increase in population in cities and an increasing need for housing, the construction of high-rise buildings is inevitable. People are forced to live in high-rise buildings to meet their housing needs and from lack of urban open spaces. A CFD based software, Envi-met, is used to acquire knowledge concerning the air pollution surrounding the buildings. In this case, we can approximate that an angle of 30 degrees, in regard to an urban canyon, is the best angle to dissipate pollution. Also, in an ideal case with imposed changes in the form, we could reduce the problem by better navigation of inside wind of urban canyons into spaces between blocks of buildings that have the capacity to trap the particles. Finally, it is found that we may be able to have more optimal results for the dissipation of pollutants by suitable orientation of blocks in regard to the wind flow.

1. Introduction

In a metropolis, the use of high-rise buildings for different purposes such as residential, office, education, entertainment, and so on is essential. Therefore, high-rise buildings are part of everyday urban life. Buildings, factories, cars, etc. contribute to urban pollution. Cars and traffic emissions are the principal origin for pollution in big cities. Although there are many advantages in using motorized vehicles, urban environments are still affected by traffic for the most part [1, 2].

For instance, the increase of motorized vehicles in India's big cities has led to problems caused by the emissions from these vehicles, which comprises about 64% of the pollution in the urban climate [3]. The local wind flow inside urban canyons is greatly influenced by mechanical turbulence caused by moving vehicles [4]. Free-flowing traffic causes more turbulence in the canyon, facilitating more dispersion of pollution [5]. Urban canyons increase overall air pollution concentrations at the street level. Yet, due to the difficulty in characterizing such geometric features over a regional area, they are rarely included in the evaluation of population exposures [6].

The air quality in street canyons is of major importance, since the highest pollution levels are often encountered in these microenvironments. The canyon effect (reduced natural ventilation) makes them "hot spots" for particulate pollution contributing to adverse health effects for the exposed population [7]. A systematic understanding of dispersion mechanisms (considering mechanical effects as well as natural movements of air) along with the impact of urban roads, streets in the canyons, and crossroads is the preferred means for the improvement and also reduction of the effects of vehicular emission. The dissipation made by vehicle movement along with the natural movements of air fundamentally lead to the dispersion of vehicular pollution, particularly at the time when the wind doesn't blow (<1m/s)

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[8]. In large cities, the discharge of these pollutants from streets, intersections, and sidewalks is dependent on the movement of the local winds. To understand this phenomenon, understanding the behavior of wind in the urban environment is essential. An urban canyon results when a street is flanked by buildings on both sides in a linear way [9]. The dimensions of urban canyons are defined by a series of elements including the ratio of the height of the building to the street width (H/W), where the ratio of elements (H/W) almost equals one (without any opening in the walls) or more. In a shallow canyon, this ratio is under 0.5 (H/W< 0.5) while the ratio of (H/W=2) describes a deep canyon. The length of the canyon (L) defines the length of the distance between the two main intersections. If (L/H=3), the urban canyon is short. If (L/H=5), then the urban canyon is average; if (L/H=7), then the urban canyon is long. If the buildings on both sides of the canyon have the same height, then this canyon is called symmetric [10]. An asymmetric canyon with tall buildings that are in a downwind direction is called "step up" and the opposite situation is called "step down". Leeward and windward are important terms when discussing canyons, where leeward is the upwind side of a canyon and windward occurs when the urban canyon is perpendicular to the wind flow. (Figure 1).

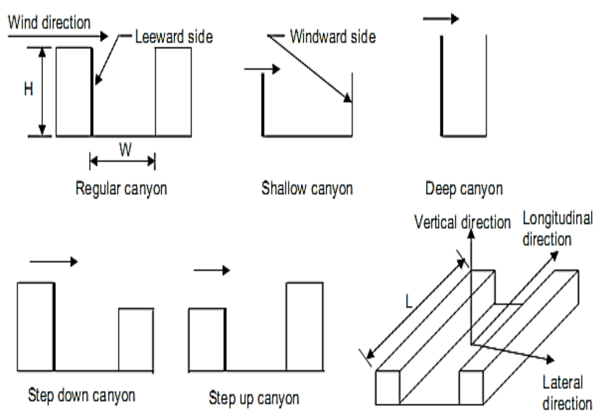

Fig. 1. Characteristics of street canyons

The aspect ratio strongly affects the initial flushing mechanics and subsequent flow regime within the canyon [11]. Wania et al. [12] studied the particles concentration and considered H/W as well as the concentration of foliage in two scenarios of perpendicular and oblique wind. They found that along with H/W and herbal covering concentration, the concentration of particles increases and therefore the quality of air and also the velocity of wind decreases. Husain and Lee [13] and Oke [14] separately described three types of wind flow direction as the functions of building geometry (with the ratio of length to depth), and the geometry of urban canyon (depth to width) for perpendicular wind flow (Figure 2). If the distance between two buildings is sizeable and the height is relatively short, the flow of air which is without any interaction is classified as an isolated roughness flow regime [15]. If the height and distances between blocks is such that they disturb the fortification and turning chamber (considering the deviation caused by downward passing of flow alongside the chamber), then the changes in the amount of established flow is known as the wake interference flow (Figure2).

The most circular eddy emerged in the deep narrow urban canyon. It might be because of the transition of movement across the cutting layer in the height of the roof. On this occasion, the majority of the flow enters the deep narrow canyon of the street in the form of a single eddy in the deep narrow canyon [16]. This kind of regime is known as the skimming flow regime (Figure 3).

In this case, the ratio is discussed in various articles. DePaul and Sheih [17] reported a threshold for symmetric urban canyons between 1.5 and 2.0 m/s and 1.4 for the proportion of (H=w). Nakamura and Oke [18] described the same digital thresholds for the proportion of (H=W).

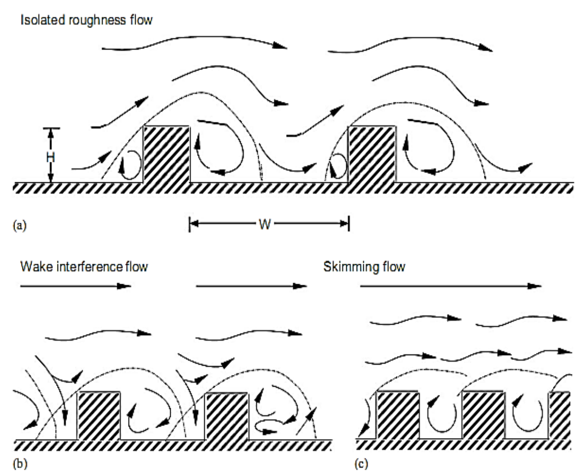

Fig. 2. Perpendicular flow regimes in urban canyons for different aspect ratios [13, 14]

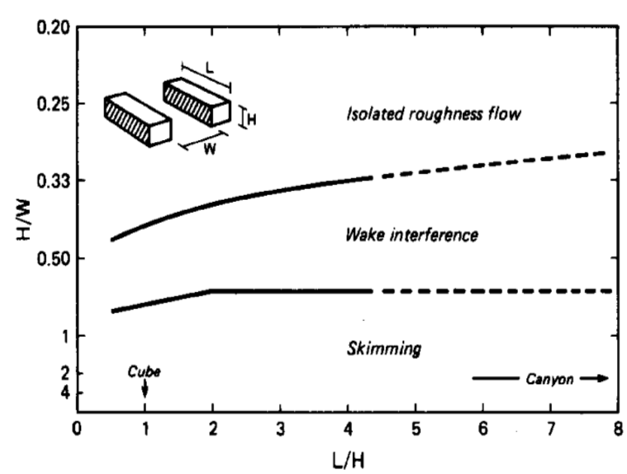

Fig. 3. Skimming flow regime [14]

The average vertical exchange of the isolated roughness flow regime for the urban canyons equals the width of the urban canyon. In the set up canyons, the isolated roughness flow regime is smaller and the average vertical exchange is 0.67 of the canyon width [19]. Yamartino and Weigand as well as Kastner Klein et al. also reported that if the L/H in the urban canyons becomes 20, it results in an isolated roughness flow regime. Hoydysh and Dabberdet reported: Isolated roughness flow regime in the corners of the structure in the relatively short canyons, with a horizontal exchange coefficient from the corners of the structure to the middle of it, causing a convergence part in the middle of urban canyon block. Meroney et al. reported that in the free case, there are unusual eddies in the urban canyons moving upward permanently. Once the isolated roughness flow regime in the urban canyon is normal, it impedes appropriate ventilation of the air, causing pollution to be trapped [19-22].

In this paper, in order to study the optimal form and to better dissipate particles from the urban canyons, the different urban blocks and directions are evaluated by Envi-met.

2. Methodology

2.1. Searching of perpendicular, 45 and 30 degree air flow

In the first case, the wind was parallel to the longitudinal direction of the blocks and the Turbulence Kinetic Energy (TKE) (m^2/m^3) and dissipation (m3/ m3) were assessed. In the following circumstance, the angle for the air flow with the direction of longitudinal direction of the blocks was in both the 45 and 30 degrees, comprising second and third scenarios. The reason for the assessment of TKE is to understand which particles are first affected by convection created by the sun (being affected by, leading into floating and convectional status) or by wind flow on the surface, which induces air movement. So due to this and the principle of conservation of energy, these particles will continue moving until their energy is consumed and they would come into a state of immobility. These particles can consist of dust, pollutions, etc. The need to assess the effects of these particles on human health gives rise to reducing these particles more quickly from the environment, optimizing parts of a block that might trap these particles. First, three scenarios were evaluated in order to realize how each of them works. A simple example to better understand this issue is throwing two balls with the same weight and different speeds in the same direction, so that the impediments are the same. We can simply conclude that the ball with more speed has more energy and moves a further distance. In the urban environment, we realize that if the initial energy, e.g. dust particles, is high, it can exit the locations that we take into consideration (Figure 4). On the average, this location is in the middle of the block.

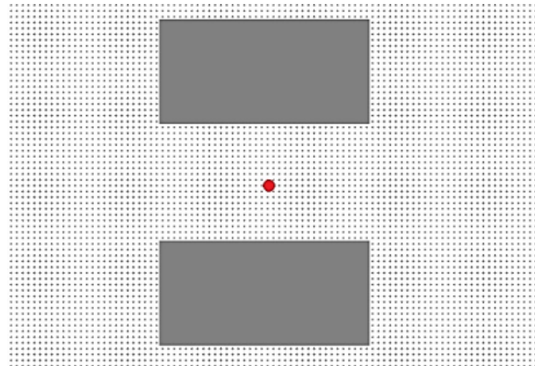

Fig. 4. Position of receptor

Via the assessment of TKE and dissipation as well as assessing particles energy changes in these locations, we can understand which location could provide better ventilation for the particles. To compute these data, we take advantage of Envi-met software. For the simulation of wind flow, the principal context of dissipation of a 3-dimentional uncompressible non-hydrostatic flow has been investigated by the Navier–Stoke equation (1c), (1b), and (1a), [23]

$$\frac{\partial u}{\partial t} + u_i \frac{\partial u}{\partial x_i} = -\frac{\partial p'}{\partial x} + K_m \left(\frac{\partial^2 u}{\partial x_i^2}\right) + F\left(v - v_g\right) - S_u \quad (1a)$$

$$\frac{\partial v}{\partial t} + u_i \frac{\partial v}{\partial x_i} = -\frac{\partial p'}{\partial y} + K_m \left(\frac{\partial^2 v}{\partial x_i^2}\right) + F\left(u - u_g\right) - S_v \quad (1b)$$

$$\frac{\partial w}{\partial t} + u_i \frac{\partial w}{\partial x_i} = -\frac{\partial p'}{\partial z} + K_m \left(\frac{\partial^2 w}{\partial x_i^2}\right) + g\frac{\theta(z)}{\theta_{ref}(z)} - \mathrm{Sw} \quad (1c)$$

in which f (=104 sec−1) is the Coriolis parameter, P' is the local pressure dissipation, and θ is the temperature potential on the Z level. The θref resource temperature and potential θ should be supplied in a 1-dimensional model parallel to the main model in the average conditions of meteorology. The density of air in the compressible Navier–Stokes equation has been deleted and the Boussinesq approximation is used. This causes an additional force, where W is the thermal force equation for perpendicular movement [2]. This model keeps time steps for the model of mass preserve. Note that the transition and distribution conditions in the 3-dimension state have been written for the Einstein accumulation (u_i= u,v,w) (i = 1,2,3). To simulate this process, a 1.5 order flow for the comprehensive model which is based on the work of Mellor Yamada, two additional equations for local dissipation (E), and its added dissipation rate to the model are needed [20].

$$\frac{\partial E}{\partial t} + u_i \frac{\partial E}{\partial x_i} = K_E \left(\frac{\partial^2 E}{\partial x^2{}_i}\right) + Pr - Th + QE - \varepsilon \quad (2a)$$

$$\frac{\partial \varepsilon}{\partial t} + u_i \frac{\partial \varepsilon}{\partial x_i} = K_E \left(\frac{\partial^2 \varepsilon}{\partial x^2{}_i}\right) + c_1 \frac{\varepsilon}{E} Pr - c_3 \frac{\varepsilon}{E} Th - c_2 \frac{\varepsilon^2}{E} + Q_\varepsilon \quad (2b)$$

Pr and *Th* conditions describe the production and waste of turbulence energy due to wind break and also thermal layering. Q and Q_E are the conditions in the local source for producing dissipation and waste in the foliage covering:

$$Pr = K_m \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\frac{\partial u_i}{\partial x_j} \quad with\ i.j = 1.2.3 \tag{3}$$

$$Th = \frac{g}{\theta_{ref(z)}} Kh \frac{\partial \theta}{\partial z} \tag{4}$$

But Th>0 under the stable case has been ignored.

The calculation of E is used for the perpendicular transition coefficient which is equal to the convergence of the used relations in the dissipation. Although cμ=0.09 and ∂E = 1.00 and ∂ε =1.3 are used for the simulation of the frontier layer flow and for the removal of coefficients interchange, the different clustering of thermal layers and under process of operations which is used by Sievers et al. and Businger et al. is needed [25,26].

$$K_m = K_h = K_q = c_\mu \frac{E^2}{\epsilon}\ ;\ K_E = \frac{K_m}{\sigma_E}\ ;\ K_\epsilon = \frac{K_m}{\sigma_\epsilon} \tag{5}$$

Considering the data presented in Figure 5, it can be concluded that TKE at the 30 degree angle is in its maximum level. In Figure 6, the dissipation of pollution at 90 degree is at its minimal level.

In Figure 7, the turbulent exchange coefficients show that the maximum changing rate is at 30 degrees. But it must be mentioned that this only applies to the building and block height which are being investigated.

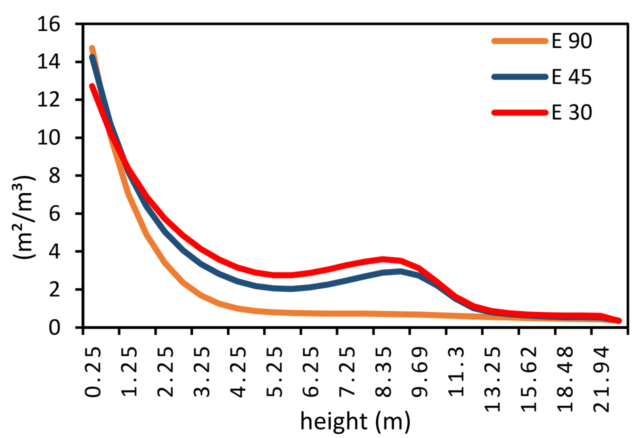

Fig. 5. TKE in 3 scenarios of wind directions

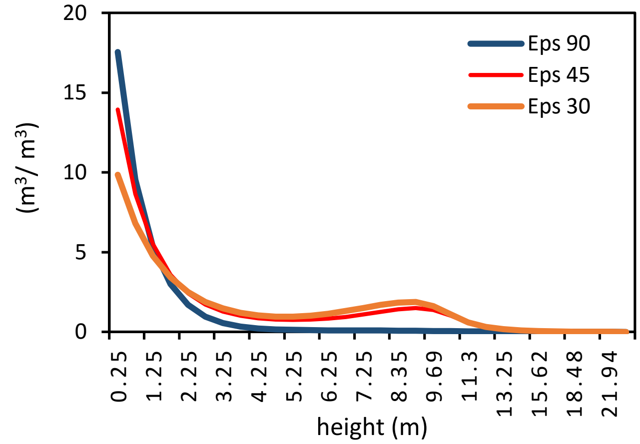

Fig. 6. Dissipation in 3 scenarios of wind directions

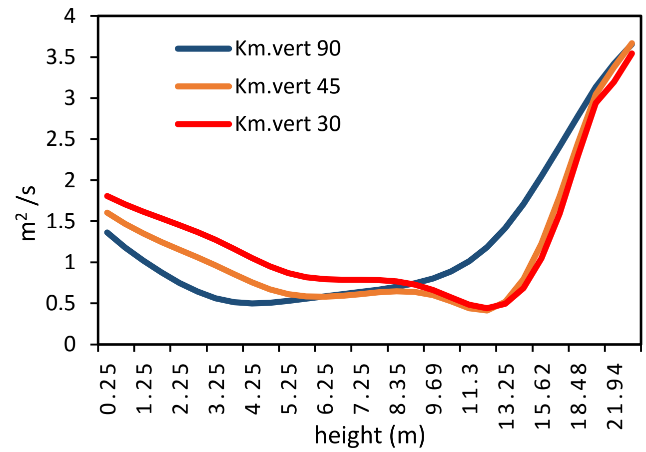

Fig. 7. Turbulent exchange coefficients in 3 scenarios of wind directions.

2-2-The wind velocity in the urban canyon

Nakamura and Oke [18] reported the parallel flow of wind along the direction of the urban canyon with the possibility of boosting along the parapets. The friction of urban parapets slows down the accessibility to the air flow. The longitude element of speed inside urban canyons is in direct proportion with the wind velocity (speed) on the roof. Yamartino and Wiegand present a relation [21] where the proportion constant is a means for access to the zenith angle of wind flow.

$$V = u\ .cos\alpha \tag{6}$$

Nakamura and Oke report the linear relations between two wind speeds. For speeds of more than 5m/s, the formula of *Ucanyon= P.uroof* (*P* is variable between 0.37 to 0.68 and for symmetric urban canyons, the proportion of H=w equals one) predicts the magnitude of the speed of U and V equal to 1.2 H and 0.06 in the depth [18]. The low constant empirical value of p is gained due to the flow deviation. According to Figure 8 and Figure 9, it becomes clear that along with the change in the angle of the wind against the longitude axis of the blocks, the wind speed in the mentioned point between the blocks would increase.

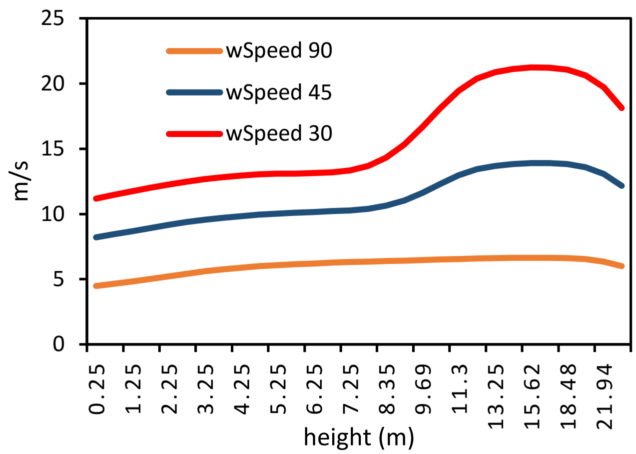

Fig. 8. Wind speed in 3 scenarios of wind directions

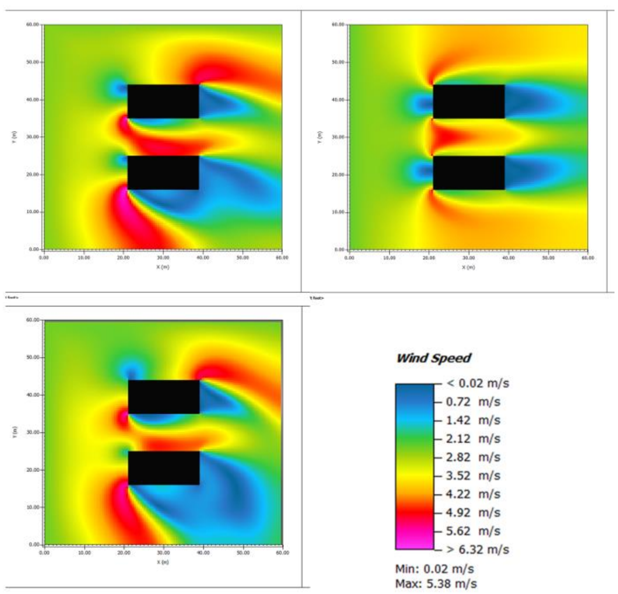

Fig. 9. Wind speed in 3 directions

It can be concluded that the best angle for the wind flow on the face of the building and block is 30 degrees. Although there are many positive instances in this situation, there are points which cannot be ventilated and thus cannot evacuate the pollution. These points are usually at the back of a building where the wind has lost its energy and therefore cannot evacuate the particles.

Strategies which could produce enough turbulence in these critical points can be employed in the following cases:

a. changes in the form of the blocks
b. changes in the height of the buildings
c. exploitation of an additional attached element

2-3-Optimization of blocks with 30 degree wind (changing in roof).

In order to improve the troubled areas, different strategies can be applied. For instance, Hoydysh and Griffiths [22] reported that in the case of single tall buildings, the longitudinal as well as latitudinal level of density in the area opposite of the wind was reduced. In addition, a single tall building is suitable for the reduction of pollution accumulation. Also, Wedding et al. [26] concluded that a single tall building could improve the overlap of pollutions in the windward side of a building when there is a very high density in the leeward side. Hoydysh and Dabberdt [15] described the distribution state (dispersion) (designed density by tracking gases) of the leeward side of buildings in two cases, even and step down of urban canyons, as almost the same. So it's practical to have a single tall construction at a hypothetical site. Nevertheless, all of the constructions in the overpopulated parts of a city must be considered in order to accommodate these people in very large housing developments [19, 18, 29]. Schatzmann, Rafailidis et al. have investigated the effects of the form of the roof on the dispersion of pollution in the urban canyons. They reported that in the urban canyons, a step roof has more effect on the dispersion than a flat one. The reduction of the parts of forms increased TKE and decreased dissipation [30,31,32]. In order to modify the form of urban blocks in accordance with previous studies, the following form was created (Figure 10, 11).

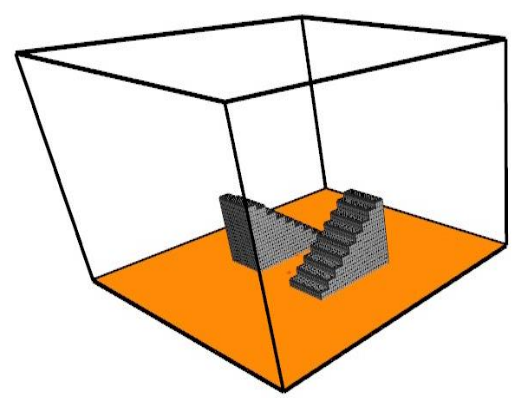

Fig. 10. Change in the roof form (30-1)

The high density of tracking gas in the mid-block shows that on the leeward sides of buildings, the lack of convergence in the state of step up canyons can be observed. Of course the 180 degree rotation of the forms for the optimization of TKE was a strategy which was assessed as well (Figure 11).

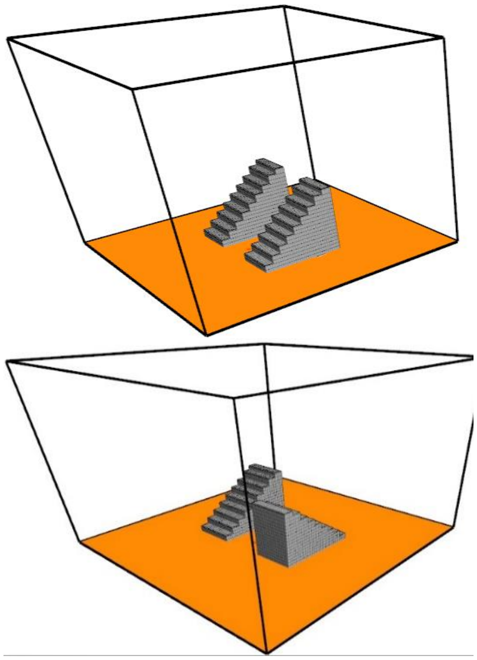

Fig. 11. Other orientations of blocks (up:30-2, down:30-3)

3.Results and discussion

According to Figures 12-15, these three cases have been compared with each other. In the case of 30-1 in Figure 12, it has a minimum amount of TKE between the blocks. The particles dispersion in the back of the block and on the windward leeward increases the storage of pollution that causes the wind to adversely affect the block facing the wind.

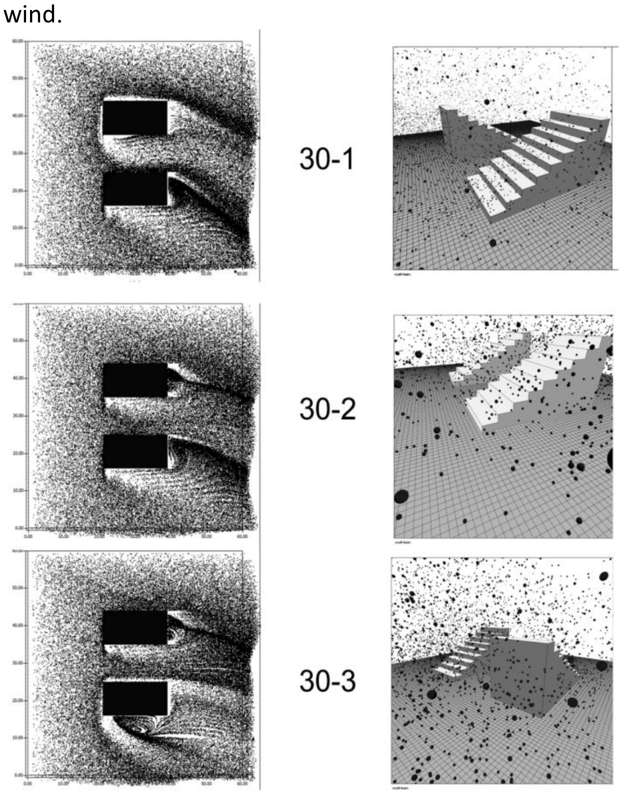

Fig. 12. Three scenarios for change in the form of the block

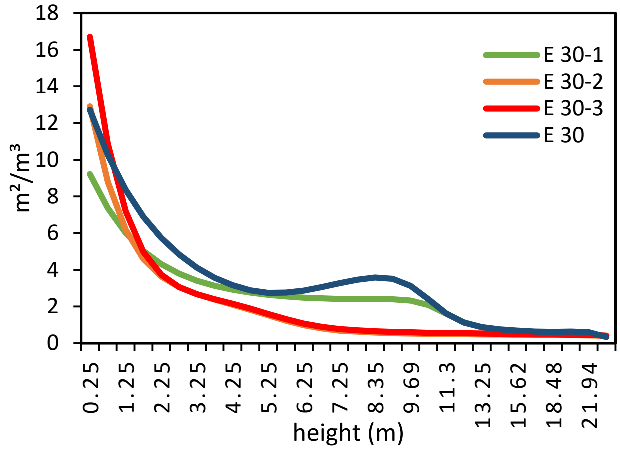

Fig. 13.TKE in 3 scenarios of change in the form of the block

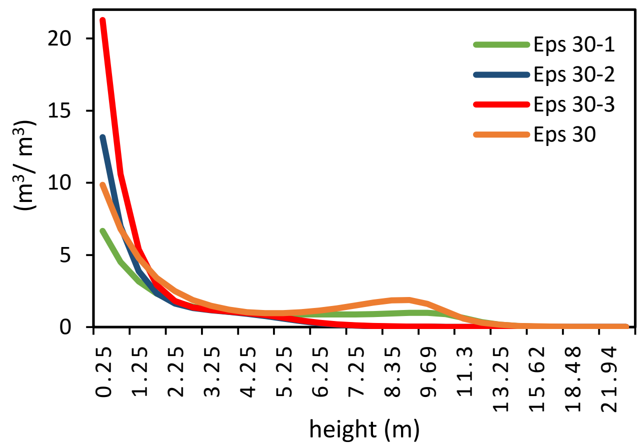

Fig. 14. Dissipation in 3 scenarios of change in the form of the block

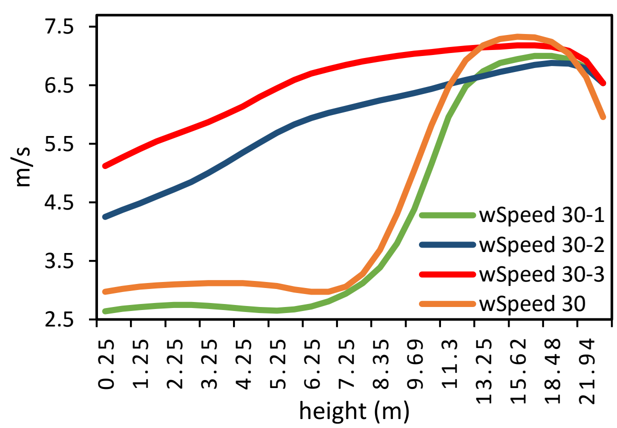

Fig. 15. Wind speed in 3 scenarios of change in the form of the bloc

In order to compare 30-2 and 30-3, we have a difficult path ahead. These two cases have similar consequences. To compare these two cases, another methodology can be considered. Along the direction of the urban canyon center (between blocks), we established a line as a criterion to compare all the existing data with each other. Supposing that 30-3 is a criteria case and 30-2 is a variable one, Figure 16 displays the consequences; it can be observed that from the place where the urban canyons start till their ending point, our horizontal exchange coefficient increases. Particles in the 3-30 case were evacuated and removed better than the 30-2 one. Of course, the fastest wind speed according to Figure 16 belonged to the 3-30 case. Perhaps it can be concluded that better navigation of wind as well as a speed increase among blocks caused such optimization. To realize an environment free of pollution with optimization of air in the urban environments, the blocks form could be changed to achieve a more uniform dispersion of clean air without pollutions.

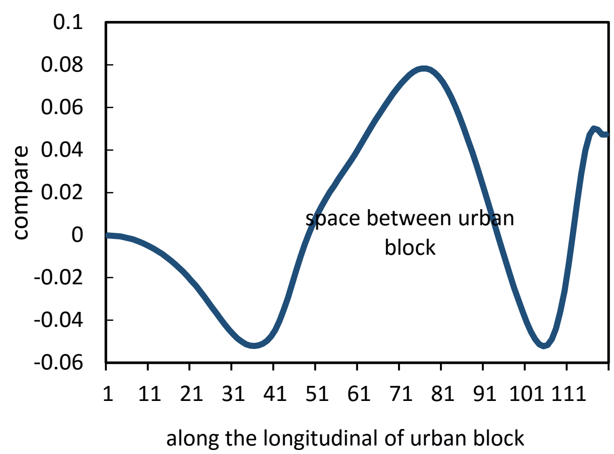

Fig 16. Comparison between 30-3/30-2

4. Conclusions

It was shown that the interactions between wind direction, urban blocks, and the atmosphere inside the urban environment are complex and can produce a distinct pattern of different flows and temperature fields. Even small changes in a building can cause a surprisingly wide range of different aspects of local climate even if we restrict our discussion to flow and temperature. The prognostic calculation over a range of several hours can reproduce more typical microclimate phenomena than a steady-state simulation. Due to the slow heat transfer inside the soil, local surface temperature and humidity are a function of different exchange and radiation conditions give or take the last few hours. These effects cannot be reproduced with a steady-state simulation by just 'observing a small time frame of the diurnal cycle. The presented case study proves that it is not possible to make a statement about the effects of changes in a complex system like the urban boundary layer at first glance. Based on the simulation results, the following main points were made:

1- The best angle of wind flow is 30 degrees that cleans the air pollution.
2- The dispersion of the particles in the urban canyon can be optimized by changing the roof of the building and block.
3- The best urban block form is 30-3 that also can minimize the air pollution.

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