A CFD Investigation on the Effect of Urban Morphology on Natural Pollution Removal in Metropolitan Areas

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ABSTRACT

City ventilation is one of the most powerful natural phenomena to reduce air pollution and control related biological problems. Air pollution is usually concentrated in densely populated metropolitan areas, especially in developing countries. Various control methods used to restrict air pollution due to numerous sources, however, most of them are not effective in many cities, so removal strategies could be helpful, especially as a prompt and mid-term solution. Therefore as a helpful strategy in establishing new sustainable cities, urban planning strategies and patterns may improve air quality in the long run. This paper reports results of a research examining the effect of different building morphology in a specific urban block in Tehran, a polluted city in Iran. In this paper the result of Computational Fluid Dynamics in five most common urban textures was investigated. The results show that by virtue of high rising, air velocity will increase in urban areas and therefore the capacity of natural pollution removal can help reduce pollutant condensation in highly populated downtown areas.

Keywords: Pollution Removal, Urban Morphology, CFD, Outdoor Comfort

1. INTRODUCTION

1.1. BACKGROUND

Industrialization has imposed new challenges on modern cities. Among them, the increase in air pollution within the inhabited environment is a critical problem in the present century. Recently, hazardous air quality has been reported in many big cities (e.g., New York, Hong Kong, and Tehran). The alarming increasing number of deaths caused directly or indirectly by environmental pollution forces authorities to control this issue urgently. The risk of air pollution is relatively low to individual health but is considerably higher to public health (KuÈnzli, N., et al., 2000). Although ensuing air pollution control strategies are of great importance, there are other ways to banish produced pollution from citizens and enhance air quality locally. One of the best ways for this mean is enhancing natural wind flow.

There are certainly some similarities between ventilating an enclosed space in order to provide the required environmental conditions, and ventilating an urban canyon. Pollutants can be carried long distances away by the natural wind flow and fresh air replaces it (Hang, J. et al., 2012). Traditionally, the city passages were designed and constructed to be ventilated naturally by local wind. As city planning changed in the modern era and lost the correlation to nature, natural ventilation techniques may not be able to provide the required conditions in urban texture anymore. (Tominaga, Y., et al., 2012) Current statutes of modern cities explicitly show the necessity of revision in the current trend of city planning and reverting to principles of sustainable cities. Modern construction of street passages with high buildings in a relatively narrow passage results in blocking the prevailing wind breakthrough. This alteration of the airflow regime can inversely increase the pollution concentration level and produce a vulnerable air quality for pedestrians (Oke T.R., et al., 1988 & Rafailidis, S., et al., 1977).
Therefore, apart from establishing control measures to decrease pollutant emissions, understanding pollutant dispersion patterns in urban areas and the effect of urban morphology on that, is necessary in order to guide policymakers, urban designers, and architects in making better evidence-based decisions.

This paper proposes a systematic approach to quantify the impact of pollution island phenomena in an urban area on pedestrian exposure. For this purpose, a Computational Fluid Dynamics (CFD) model is developed to simulate physical interactions around and inside a street canyon. The case study of this paper is a typical populated residential region in Tehran with dense construction and narrow urban canyons. The simulation models studied in this paper are designed based on the current situation of the studied region to investigate the effect of city planning on air quality. This model evaluates the effect of urban canyon form on wind velocity and its influence on urban pollution dispersion patterns.

1.2. LITERATURE REVIEW

Several studies on urban climate in the past decades have focused on air quality in urban texture, especially in the street canyons. Urban microclimate and air quality can be regarded both as the consequence and as the prerequisite of urban planning and design activities. (Li, X. X., et al., 2006). Therefore, the reciprocal relationship between them requires research on the environmental sensitivity of urban planning and design, in order to positively address their negative consequences on urban air quality.

Huang et al. studied an actual urban case of mid-density layouts (Huang, H., et al., 2008). Mirzaei and Haghighat provided a systematic approach to quantify the outside environment in the street canyon (Mirzaei, P. A., et al., 2012). Hang et al. conducted a study on the effects of varying building heights on street level air pollutant dispersion in high-rise area (Hang, J., et al., 2012) and Eefents et al. reported the effects of canyon indicators such as Sky View Factor (SVF) on the concentration of NO and NOx (Eeftens, M., et al., 2013) Buccolieri et al. Richmond-Bryant related the fluid properties and canyon geometries, such as the Reynolds number and canyon height, with air pollutant retention by field measurement data at Manhattan and Oklahoma (Richmond-Bryant, J., et al., 2012. Buccolieri, R., et.al, 2010). However, the direct understandings for design strategies behind a decrease in pollutant concentration through urban morphological mechanisms, particularly for high-density cities, remains little known yet further studies are needed to extend the study findings for practical design applications. Bridging the knowledge gap between high-density urban design and air pollutant dispersion mechanisms in the urban street canyons is necessary to provide guidance for designers and policymakers in order to limit hygienic, environmental, and economic negative impacts of air pollution.

1.3. CLIMATE OF TEHRAN

Tehran, the capital of Iran (35◦42’ N, 51◦25’E), has an area of 700 km^2 and is situated in a semi-enclosed basin in the south of Alborz Mountain range. The southern slopped down to the low-lying flat terrain. The mountainous nature of Tehran has a dominating control on low-level wind climatology (Pegahfar N., et al., 2011) so directing wind flow in desired direction is in great importance. The hottest month is July (mean minimum temperature 23 ◦C, mean maximum temperature 36 ◦C) and the coldest is January (mean minimum temperature -1 ◦C, mean maximum temperature 8 ◦C) (Keyhani A., et al., 2011). The average annual rainfall is approximately 230 mm, with most precipitation falling in the autumn and winter months. Low level of precipitation intensifies the level of air pollution, especially in densely populated central districts (Torabi et. al., 2022). Aside from the summer when the large-scale flow is easterly, a westerly direction is preferred at other times. As shown in Figures 1 and 2, the mean wind velocity of Tehran is about 5-5.5 m/s (Pegahfar, N. et al., 2011).

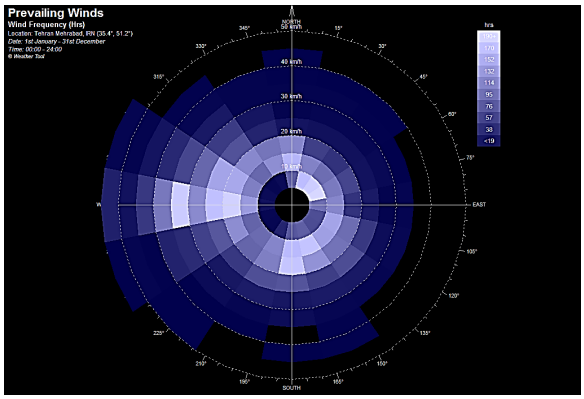

Figure 1- Wind rose diagram of Tehran

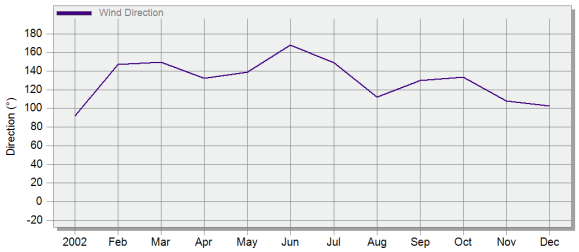

Figure 2- Wind direction

2. SIMULATION

The object of this study is to investigate the role of natural ventilation in pollution removal of big cities like Tehran. To be more detailed, we focused on the effect of urban canyon shape and its morphology on wind velocity regime and its influence on ventilation. The case study of this paper is a 680 km long and 220 km wide land located in Tehran city center in a crowded residential region. As shown in Figure 3, five geometric cases were designed to create their corresponding parametric models, establishing a total of five simulations with different building geometries and urban permeability. During the simulation process, the current population density in this area of Tehran, which is approximately 6000 people per hectare, is unchanged and based on that different sets of urban configurations are defined to highlight the airflow alteration rate. These alternatives are designed with unique Floor Area Ratios (FAR) and different Building Coverage Ratios (BCR) varying from low-rise and vast mass of buildings to high-rise and sparse construction patterns representing variable heights and forms. The detailed features of a single block of alternatives are tabulated in Table 1.

Table 1-The detailed features of alternatives

	Building Coverage area (m^2)	Height (m)	Density (%)	Distance in X direction (m)	Distance in Y direction (m)	Height to width ratio (m)
1	3840	15	60	0	22	0.833
2	3840	30	30	0	62	1.66
3	240	60	15	13.30	62	3.33
4	240	120	7.5	40	62	6.66
5	240	180	5	93.30	62	10

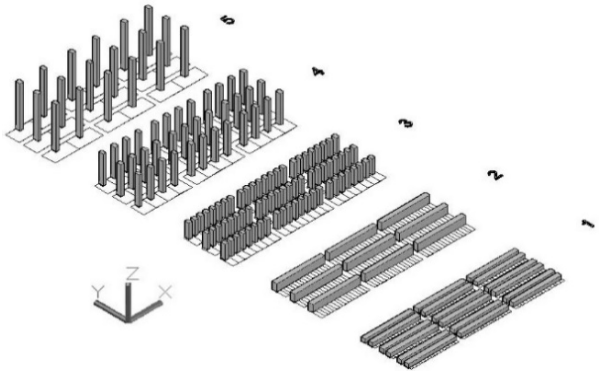

Figure 3- Simulation models.

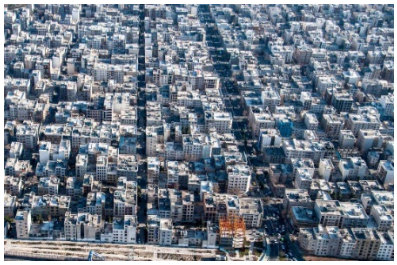

Figure 4-View of studied area.

The modelling method of this study is Computational Fluid Dynamic (CFD) simulation. This has already been used not only as an environmental research tool, but also as a design tool for urban planners and designers. CFD models of the alternatives were simulated in Design Builder software version 3.4.0.041. The simulation is performed for 15000 iterations. The width, height and downstream length of the computational domain were defined in accordance to the best practice guidelines, while the upstream length was taken 5 times the maximum height of the buildings width and length was taken 8, resulting in dimensions of W*D = 6240*1760 m^2 for the base with the height of 5h. The height of models is listed in table 1. The street canyon is oriented along prevailing wind direction. The pollution removal potential is calculated through measuring wind velocity at monitor cell located in the centre of urban passage at the height of 7.5m. Simulation modelling settings is listed in table 2. Due to generality of problem statement, any kind of subordinate modifications to the street canyon like shape of the buildings, fenestrations, materials are not considered in this study and the configuration of canyon geometry is the main issue. The aspect ratio of the street canyons is variable in this study as shown in Table 1.

In later alternatives in comparison to primary ones by the means of high-rise architecture, constructed area has decreased remarkably and wider public spaces is observed. Therefore higher amount of free spaces are reachable which can be allocated to various functions. The mentioned spaces can be used as green urban spaces, which has a significant role in improving air quality, drop in temperature and decrease in heat island effect over cities, improvement in visual and acoustic comfort are some of the other advantages. The other functions of these spaces are social and cultural use that can provide a vibrant place for social activities. Overall, the mentioned spaces are in service of the city to boost the quality of urban life.

Table 2-Simulation modelling settings

Computational Domain Factor	8*8*5
Blockage Ratio	<5%
Grid Type	uniform
Iteration	15000
Turbulence Model	2-k-e

3. DISCUSSION AND RESULT ANALYSIS

In this study, air velocity and pressure are calculated inside the pedestrian zone, on a 7.5 meter-high plane. As demonstrated in the figures horizontal slice shows the distribution of wind speed in the studied land. Simulations are performed for each scenario shown in Table 1: a total of five sets of simulations. As mentioned previously all the measures of simulation and climatic characteristics and location are the same and fluctuation of wind velocity affected by urban canyon shape and proportions is studied. Figures 5 to 9 report the results.

The first alternative represents current city planning in numerous big cities like Tehran. The relatively low height of the buildings in these cities is due to the conventional construction technology and available structural material that makes low-rise buildings economically profitable although it may alter the natural issues. The dense low-rise mass of residential buildings shapes narrow passages, which partially trap a limited volume of air among buildings. Limited volume and depressed mass of the air soon will lose the quality for pedestrians' health and comfort and pollutant density will rise up and may surpass the unhealthy threshold. BCR in the first model is 60%. As shown in the output results the wind velocity decreases through the built environment and rises up again as there is no obstacle in the way out. This study suggests the idea of enlarging urban canyons by reducing FAR and stimulating natural air flow circulation through cities. This hypothesis is investigated in later simulations of this study. In the

following figures red arrow indicates the prevailing wind direction which is toward the west and the gray arrow shows geographic north.

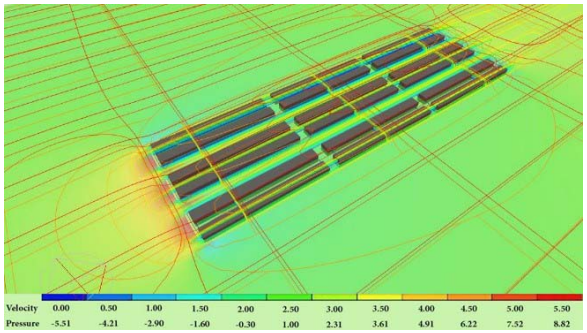

Figure 5-Horizontal slice of first case.

Other cases are examples of implemented city planning in megacities, which show less resistance along the airflow regime and therefore show better behavior in relation to air pollution dispersion. In the second case, the same as the first case, continuously constructed strips of buildings are still observed but with double the height and half BCR of the first case, a higher velocity rate is observed. Horizontal slice of the second model shows enhanced velocity of the airflow that leads in to better city ventilation at pedestrian level. In this case, by minimizing BCR, urban canyons get wider and subsequently they become better passages for natural air to remove unfavourable components of air mass.

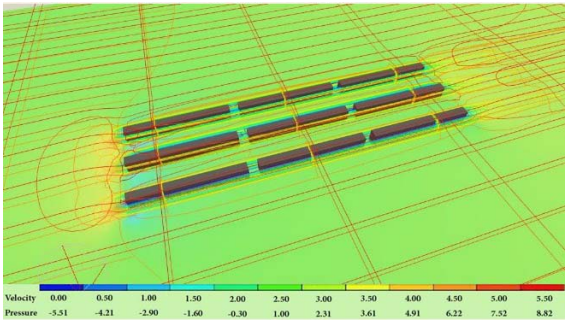

Figure 6 -Horizontal slice of the second case.

In Cases 3-5 high-rise buildings are studied. By decreasing BCR and accommodating required area in height instead of surface, we observe high and slender buildings comprising urban texture. This enables urban designers to plan buildings sparsely and an urban function among them. These large spaces can serve the city and meet the new demands of the citizens. In other words, by this means, urban canyons are actually removed and scattered buildings with urban spaces among them, integrate porous urban texture that accelerates airflow penetration. In convergence with the results from two earlier simulations, as shown in Figures 7 and 8, decreasing BCR air velocity in urban texture demonstrates a noticeable increase.

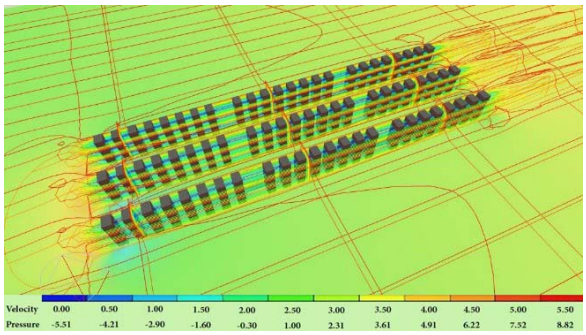

Figure 7-Horizontal slice of the third case.

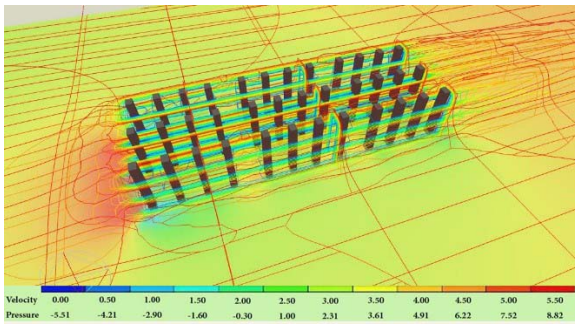

Figure 8- Horizontal slice of the fourth case.

The last model has the least BCR and the widest urban canyon in the most porous texture; consequently as illustrated in Figure 9, wind speed reaches to maximum of 5.5 m/s among all the alternatives. This model explicitly suggests the advantages of high rising. By the means of high rising designers can not only accommodate desired floor areas and help the habitants to live in a better and cleaner atmosphere, but also they can provide a vibrant neighborhood and meet many social needs of modern cities.

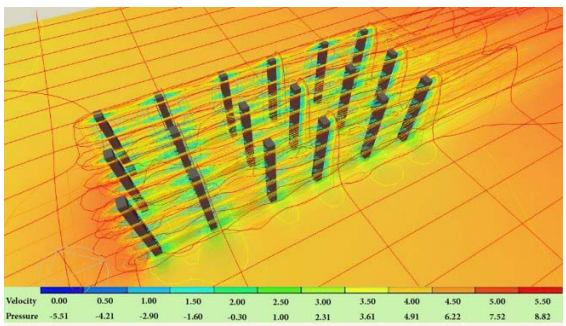

Figure 9-Horizontal slice of the fifth case.

Figure 10 indicates wind velocity in the main axis of the city plan (X direction). The monitor point defined in the canter of the canyon. As illustrated in the graphs, by reducing BCR and widening the space among them, we observe a significant increase in wind velocity and its natural potential to distract pollution. Fifth model represents the maximum annual mean speed of 4.9 m/s, which is almost equal to the average wind speed of Tehran, while other show a higher decrease in velocity due to dense urban planning. This noticeable measure of wind velocity is a design tool, as the designer either can use it in favour of boosting

air quality and providing thermal passive comfort, or control it by limiting to desire amount by using windbreakers.

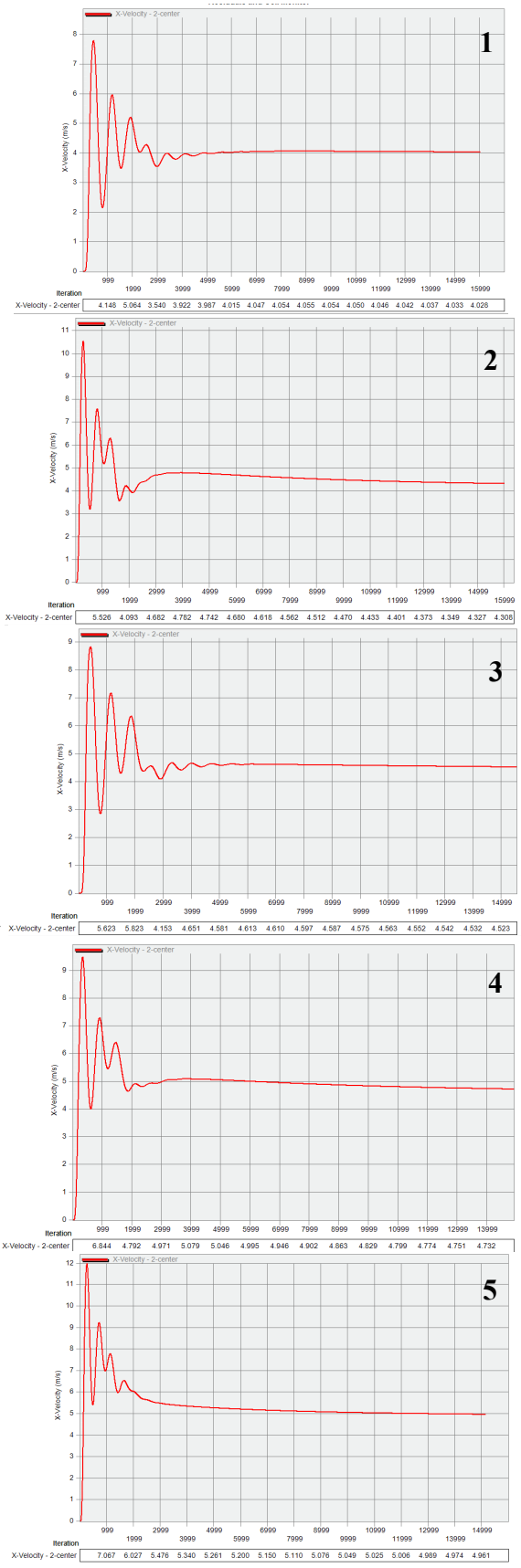

Figure 10- Wind velocity in monitor cell of studied scenarios

Figure 11 shows the comfort zone in psychometric graph with (red zone) and without (yellow) the effect of natural ventilation. It is concluded from the graph that by utilizing natural ventilation designers can provide remarkably larger range of comfort for pedestrians, even in higher temperatures and humidity rate**.** In other words, accelerating natural ventilation not only results in better air quality but also helps to provide thermal comfort inside and outside the building.

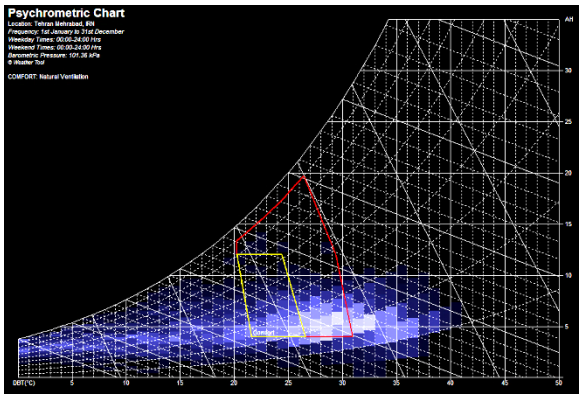

Figure11- Comfort zone with and without ventilation in Tehran

A significant factor in functionality of suggested patterns is pedestrian comfort in described urban canyons. Pendwarden and Wise report that Condition for pedestrians in outdoor is acceptable if wind velocity do not exceed 5 m/s more than 20% of the time (Pendwarden, A.D.,etal., 1975). This condition is observed in all simulation reports so it's concluded that comfort zone is provided in all cases. The high amount of wind velocity can easily be controlled by utilizing windbreakers and plants in green spaces or by presenting different building array.

Vertical resulting profiles of models explicitly shows residual rise in air speed and pressure distribution in urban texture from the first to last model. Vertical section is along XZ plane. Outputs show that the lower BCR becomes, the higher wind velocity grows. This alteration is more appreciable in lower levels. In other words by reducing BCR, we expect higher wind velocity in pedestrian level that results in better natural pollution removal procedure.

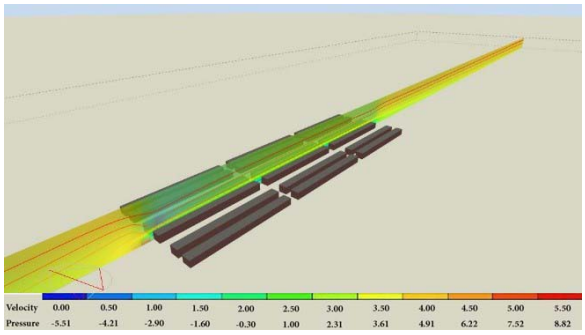

Figure 12-Vertical section of the first alternative.

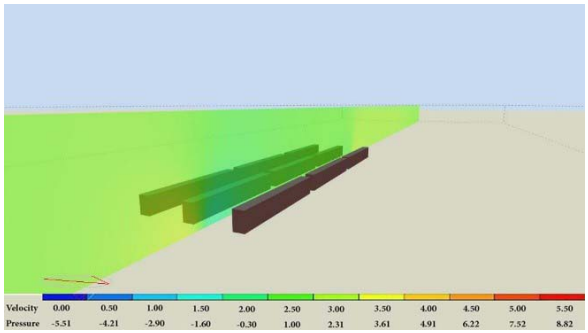

Figure 13- Vertical section of the second alternative.

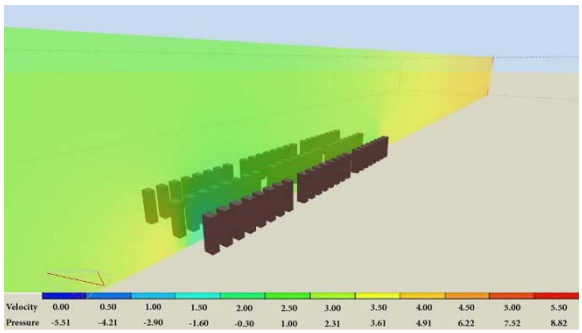

Figure 14- Vertical section of the third alternative.

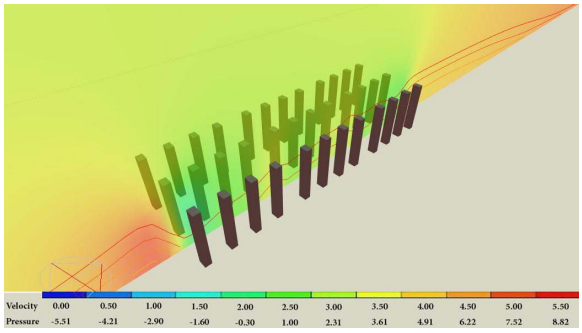

Figure 15- Vertical section of fourth alternative.

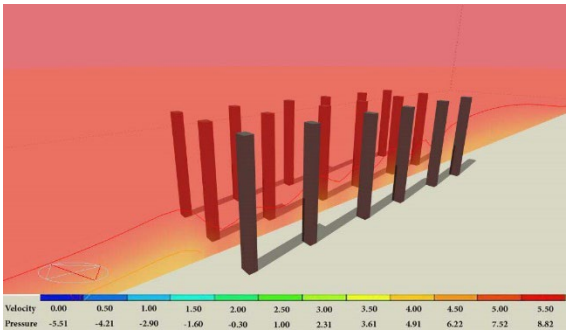

Figure 16- Vertical section of fifth alternative.

4. CONCLUSION

In this study, a CFD parametric approach was taken to investigate the impact of urban permeability and canyon geometries on air pollution dispersion in high-density urban areas. The studied case is a module Tehran city plan. The analysis and discussion of the results of this study revealed the following understandings for developing high-density urban planning and design activities in the future:

1. The current situation shows that mitigation strategies for air pollutant dispersion are necessary in the planning of high-density urban areas of Tehran. In current urban conditions, traffic air pollutants are seriously concentrated in the deep street canyon. If current planning and design activities do not change, these conditions will grow worse in future urban development.
2. In addition to mitigation strategies for air pollution, by designing cities wisely and by the aid of natural airflow, air mass in urban areas can be refreshed.
3. The geometry of the urban canyon has direct effect on city ventilation. city passages orientation along the prevailing wind and wide enough cross-section help ventilate the depressed air.
4. In order to apply appropriate geometry for urban passages and also provide enough floor area, high rising becomes the most favourable strategy.

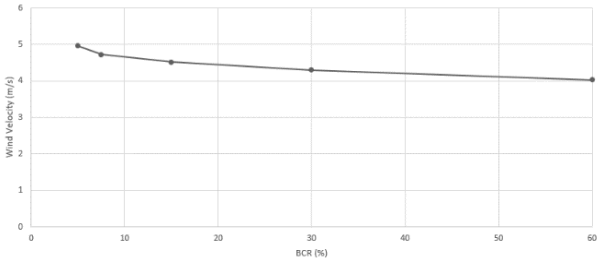

Figure 17 -Wind velocity increases as the BCR decreases.

By extrapolating the result of simulation, one concludes that generally by decreasing BCR, the velocity variable increases. It is concluded from evaluation of these models that the fifth case is highly recommended for pollution removal. If fifth case is hard to implement, then the forth case is recommended and on down, third and second case, and the first model is the least favourite for urban planners to follow.

5. LIMITATIONS AND FUTURE STUDY

This study is one of the early stages of a research program on urban design guideline for controlling the air pollution issue of Tehran. The current study is limited by the computational parametric study, which only considers the wind flow rate in proposed urban contexts. Validation of results _by wind tunnel experiment or saltwater intrusion modelling _ is expected in order to determine threshold values for design parameters. Further studies on airflow regime in high-rise urban blocks and breeze dispersion is also

recommended. Other determinants, such as building modifications and various building heights, orientation along prevailing wind are expected to reveal more insights in future works. In addition, wind speed control by applying plantation and windbreakers and investigating breeze distribution may be the next step for researchers.

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