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Modeling Airflow in Urban High-Rise Building Areas and Climate Comfort

Tahmineh Zahedifar[1] | **Hassan Darabi**[2]✉

1. Kish International Campus, University of Tehran, P.O.Box 79416-55665 Kish, Iran.
2. Graduate Faculty of Environment, University of Tehran, P.O.Box 14155-6135, Tehran, Iran.

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ABSTRACT

Urban morphology impacts micro-climates, solar energy absorption, air flow, wind patterns, energy consumption, and air pollution concentration. Temperature control in public spaces reduces heat island formation, while ventilation corridors potentially improve air quality. However, despite the literature on airflow and urban tall buildings providing valuable insights, further research is needed to understand the complex relationship between airflow patterns and urban high-rise buildings. This research should consider factors such as landscape types, building height, density, and orientation. This research aims to examine airflow patterns in high-rise buildings that are influenced by nearby land use, which can impact ventilation and climate comfort. To investigate these objectives, we utilized the Universal Thermal Climate Index (UTCI) and Predicted Mean Vote Index (PMV) by conducting simulations using ENVI-met software. The results revealed that buildings with narrower widths have better wind warded front conditions, while those with an unfavorable wind angle or a narrow facade are less comfortable. Public spaces that face the wind benefit from improved ventilation. It is essential to consider the optimal arrangement, ventilation, and height of buildings to ensure the favorable airflow. Factors such as the placement of trees, the use of porous walls, water features such as fountains and sprinklers, and the local climate all contribute to creating better wind conditions. Investigating the reciprocal interaction between the landscape, high-rise buildings, and climate comfort could be considered in future research.

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INTRODUCTION

Temperature control in public open spaces has many effects on the urban environment, including the temperature of the interior spaces of the building and a reduction in the formation of heat islands on a regional and urban scale (Afshar, et al., 2018; Merabet et al., 2021). This is due to the numerous effects of airflow in the urban landscape. This is why effective design criteria for climate comfort have received attention as population and urban density have grown along with the heat of the earth (Jafarpur & Berardi, 2021).

At the same time, urban wind patterns can reduce the pressure brought on by heat at high temperatures (He, 2018; Nazarian, et al., 2017; Van Moeseke, et al., 2005), and if urban wind speeds rise, heat islands may not form for a while (Soydan, 2020; Zong et al., 2021). On the other hand, upon closer inspection, the wind speed may increase close to tall buildings, which could be problematic because it would cause turbulence at the buildings' edges (Al-Obaidi, et al., 2021; Soydan, 2020). A suitable design strategy can be used to control this phenomenon, which is brought on by the way that buildings are constructed (Jafari & Alipour, 2021a; Megahed & Ghoneim, 2021). As a result, it is possible to state that an urban plan can effectively

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*Corresponding Author Email: *darabih@ut.ac.ir*

control wind at various levels, particularly at the pedestrian level (Givoni, 1998; Jamei, et al., 2016; Bouketta, & Bouchahm, 2022). This issue is more crucial and necessary because it has a significant impact on climate comfort in areas with special climates and heat islands.

Urban ventilation corridors are widely used in cities all over the world and are effective at enhancing urban air quality and lowering heat island issues (Gu, et al., 2020; et al., 2022). The contribution of urban ventilation corridors to air pollution was examined by Lee Han et al. in 2022. This research revealed that urban ventilation corridors run the risk of worsening air pollution in the city's central areas, which calls for careful planning. Previous researches had found that urban ventilation corridors improve the quality of the air in central urban areas (Ren et al., 2018; Shi, et al., 2022).

Tsichritzis et al. (2019) investigated the degree of comfort along with the wind in the streets of London, taking into account the morphology and its interaction with the vertical characteristics of the buildings. In 2019, Papazoglou et al. conducted an experimental and objective-mental investigation of students' perceptions of the climate between the ages of 16 and 18. Sadeghi et al. (2020) studied the residential wind deflector cooling efficiency in various urban arrays.

According to continuous field measurements made by Yu et al. (2020) at the Kent Ridge Campus of the National University of Singapore, there is a distinct diurnal pattern of urban morphological influence on air temperature. Urban configuration is crucial in the current energy crisis because it creates thermally more favorable local micro-climates that enable the efficient operation of building systems. By examining the simultaneous impact of urban morphology and density on the micro-climate near the building and the effectiveness of cooling systems installed in open spaces, Hadavi et al. (2021) have addressed a significant research gap in this area. Fontenelle et al. (2021) analyzed the climate comfort benefits of natural ventilation during the retrofitting of an office building in downtown Rio de Janeiro and assessed the cooling potential of biomimicry-based strategies for the micro-climate in the historical region of Panama.

The morphological characteristics of the area have a significant corrective effect on the ventilation of the area, claim He et al. (2020). According to them, the breeze's indoor ventilation can significantly lower UHIs (He, Ding, & Prasad, 2020). The comfort of the outdoor climate can also be significantly improved by indoor ventilation performance, which can significantly increase relative humidity.

Using a medium-scale weather research and forecasting model, Heidiki and Tekbiyashi (2022) examined the distribution of thermal environmental indicators during summer days. They came to the conclusion that moving closer to the coast, urban ventilation, and fog spray are less effective than the effect of solar shading. Kang et al. (2020) investigated how the presence of trees improves the comfort of pedestrians on the urban campus of Pukyong National University by conducting a thorough evaluation of pedestrian wind comfort with respect to observed wind direction and frequency using a computational fluid dynamics (CFD) model and a tree-stretching parameterization scheme.

In Yai's research (2021), the contribution of five factors to the urban heat island and air quality was qualitatively and quantitatively analyzed. The breathability of the city was measured in terms of air change rate per hour. According to numerical results, the following factors greatly affect the intensity of urban heat islands and air quality: heat flux, temperature cycle rate, urban scale, building height, urban density, and urban heat flux (Jing et al., 2021). Ramyar et al. (2019) conducted a research using ENVI-met modeling to analyze UHI mitigation scenarios in Tehran, proposing cooling neighborhoods, and designing effective cities with drier environments. Similarly, a research conducted in Tehran found that increasing the height of blocks increases wind speed and tunnel formation in corridors at zero and 45 degrees. Building blocks that are parallel to the wind direction have an average wind speed 20-30% higher (Ghobadi et al., 2022).

Researches generally show that factors like building height, density, distance, shape, direction, and facade design affect air flow patterns in high-rise urban buildings. Designing and managing tall buildings to increase indoor air quality, ventilation, and energy-efficiency can be made easier by being aware of these factors and how they affect airflow patterns. There is little data on how various types of urban landscapes affect the airflow patterns in tall buildings, despite the fact that the reviewed literature offers useful insights into the relationship between airflow and tall urban buildings. Studies could, for instance, look into how airflow patterns differ in high-rise structures situated in cities with various types of greenery, such as parks or urban forests.

Overall, even though the reviewed literature offers insightful information about the connection between airflow and urban tall buildings, more research is still required to close the knowledge gaps and advance our comprehension of the complex relationship between airflow patterns and tall buildings. The absence of research on the impact of various urban landscape types on airflow patterns in tall buildings constitutes a gap in the literature. This research was conducted by modeling a real-life case study involving the dimensions of a very large residential town. The study was carried out on an area of 23 hectares, which is equivalent to 515 meters east-west and 445 meters north-south. The timing sequence was measured using Envi-met software.

MATERIAL AND METHODS

The case study is the residential area of Chitgar, which is located west of Tehran capital of Iran (Figure 1). The area has a variety of public spaces with varying sizes and is surrounded by high-rise residential buildings with various floor counts. This region's proximity to the Chitgar weather station reduces the impact of various factors that alter the information from the weather station used in the simulation process. This urban block, which is approximately 515 meters long and 445 meters wide, has wide streets, little greenery, 21 towers, and buildings for sports, services, and multi-story parking in addition to cultural, religious, commercial, and educational buildings. Another reason people choose this town is the high number of floors; in this residential complex, there are towers with 15, 16, 18, 19, 27, and 36 floors. As a result,

Fig. 1. The geographical location of the case study

it has a variety of forms and body of building blocks, which has led to the formation of open public spaces surrounded between the towers.

Educational, cultural, religious, commercial, sports, multi-story parking, and service buildings are located on the north, south, and west of the area. The floor covering was modeled using the ENVI-met software and consisted of asphalt, concrete paving, soil, and vegetation. The center points of neighborhoods, access and parking axes, and 10 other points in the site were designated as virtual receptors of environmental data. To comprehensively investigate the impact of open space geometry on the comfort of pedestrians, the points are positioned so that a different range of output data is obtained. The location, compass direction, and surrounding elements are displayed in table 1.

The first stage involved gathering data on the conditions at the ten chosen sites (Figure 2 & Table 1), on July 14, 2021 (Table 2 &3), and the second stage involved calculating and estimating climate comfort using a simulation of explanatory conditions. The correlation method, evaluation, and optimal points were used in the final stage to define the influencing factors in climate comfort and the physical characteristics of the environment in the formation of micro-climates.

In this research we try to measure two main indexes that are common in examination the

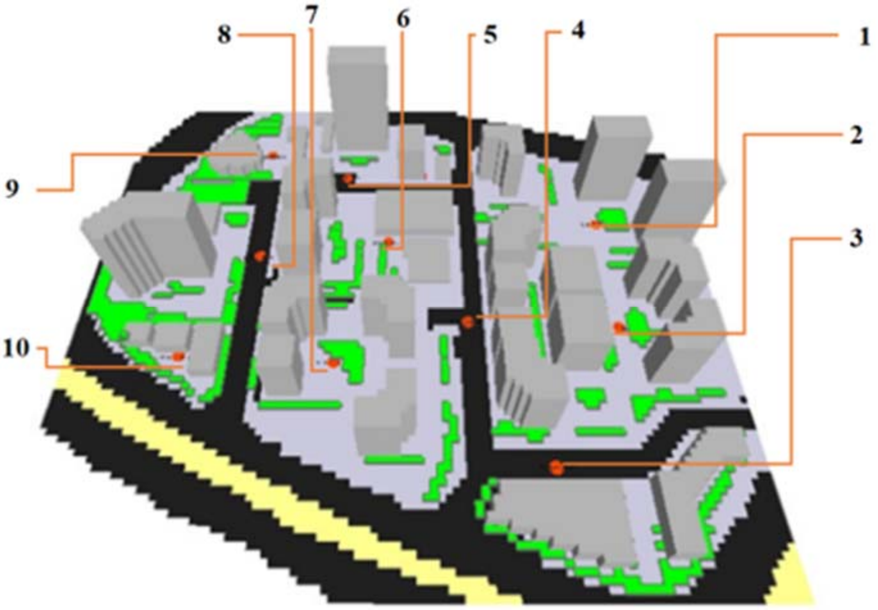


Fig. 2. The location of data loggers (Receptors) in site

Table 1. The location of data logger in area

Data logger	Location in site	Land use of area	The number of floor
1	North East	Open Space	27
2	East	Open Space	15 and 19
3	West	Street	3
4	North	Street	15 and 19
5	East	Street	3, 13, 19, 34
6	Center	Commercial area	1 and 3
7	South	Open Space	16 and 19
8	South	Street	16 and 27
9	North west	Cultural land use	4
10	South west	educational land use	3

Table 2. Information on three variables of temperature 2021

Month	Minimum temperature			Maximum temperature			Average temperature		
	Temperature	Long term	Difference	Temperature	Long term	Difference	Temperature	Long term	Difference
July	22.1	22.2	-0.1	35.3	34.4	1	28.7	28.3	0.4

Table 3. Direction and speed of dominant wind and maximum wind, July 2021

Month	Dominant wind		Maximum Wind		windy days speed of 9 to 17 (m/s)	windy days speed more than 17 (m/s)
	Direction	Percent in month	Direction (Degree)	Speed m/s		
July	North	10	240	12	5	0

climate comfort (Błażejczyk et al., 2013; Roffe, van Der Walt, & Fitchett, 2023; Zhang et al., 2023): Predicted mean vote Index (PMV) and the universal thermal climate Index (UTCI).

PMV (Predicted Mean Vote) is a measure of thermal comfort that predicts the average sensation of a large group of people in a given environment, based on a set of environmental factors such as air temperature, humidity, air speed, radiant temperature, and clothing insulation. PMV index is premeditated by equation 1:

Equation 1. $PMV=(0.303e^{-0.036M}+0.028)\{(M-W)-H-E_c-C_{rec}E_{rec}\}$

M: body metabolic rate (W/M^2)

W: constant mechanical force (W/M^2)

H: dry heat losses in the form of convection, conduction, radiation, (W/M^2)

Ec: evaporative heat exchange on the surface of the skin when it is in a neutral temperature state (W/M^2)

C_{rec}: convective exchange of transpiration (W/M^2) and

E_{rec} is the evaporative heat exchange of transpiration (W/M^2).

In the above equation, the values of E, Erec, Crec, and Ec are calculated as follows: 2- E=3.05 * 10-3 (526tsk-3373-Pa)+Esw 3- Ec=3.05 *10-3(5733-6.99 *(M-W)-Pa)+0.42(M-W-58.15) 4- Crec=0.0014M(34-Ta) 5- Erec=1.72 *10-5M(5867-Pa). Moreover, H is directly calculable and can be premeditated by equation no. 2:

Equation 2. H=Kc1=tc1-tc1/Ic1 (Momeni & Edeali, 2014)

The PMV value ranges from -3 to +3, with negative values indicating that the environment is too cold, positive values indicating that the environment is too warm, and values close to zero indicating that the environment is thermally comfortable (Dyvia & Arif, 2021; Ye, et al., 2003).

UTCI (Universal Thermal Climate Index) is a measure of thermal comfort that takes into account several environmental and personal factors, including air temperature, humidity, wind speed, radiation, and clothing insulation (Park, Tuller, & Jo, 2014). The formula for calculating the UTCI is as follows:

UTCI = f(Ta;Tmrt;Va;vp)= Ta+offset(Ta;Tmrt;Va;vp)

This index is calculated based on the following equation:

UTCI=3.21+0.872.T+0.2459.Tmrt+(-2.5078.V)-0.0716.RH

Where: Ta is the air temperature in degrees Celsius, RH, is the relative humidity as a percentage V is the wind speed at 10 meters above the ground in meters per second, M is the metabolic rate in watts per square meter, and Tmrt is average radiant temperature in degrees Celsius (Błażejczyk et al., 2013; Mölders, 2019).

The UTCI value ranges from -50 to +50, with negative values indicating that the environment is too cold, positive values indicating that the environment is too warm, and values close to zero indicating that the environment is thermally comfortable. The UTCI is a more comprehensive measure of thermal comfort than the PMV, as it takes into account a wider range of environmental and personal factors (Nie et al., 2022).

PET (Physiological Equivalent Temperature) is a thermal climate index based on the human thermoregulation system. It estimates core temperature, skin temperature, and skin wettedness (Walther, Q. Goestchel, 2018). Outdoor thermal comfort models are crucial for urban design and use. This research proposes adaptive-logical thermal comfort models that calculate heat balance and thermal adaptation simultaneously. Using PET and UTCI indices, adaptive and expansion methods were developed to improve accuracy and robustness. Validation results show PET-based logical models improve accuracy and robustness by 86%, while UTCI-based models achieve 87% improvements. These models contribute to the development of livable urban environments

Also these UTCI-based 87% and 87%, respectively. The proposed adaptive-rational outdoor thermal comfort models contribute to the development of livable urban environments.

The elements of the urban environment are represented in this model as buildings with various positions, angles, and heights. This model also takes into account the type of land in terms of asphalt, concrete, and soil. Compared to the volume of input data, the outputs of this model are very large. In this work, the space is 515 meters long, 445 meters wide, and 129 meters high with the number of cells x = 103, y = 89, z = 43, dx = 5, dy = 5, and dz = 3 and the existing vegetation cover was simulated (figure 2). The characteristics of the area are as follow:

According to Figure 3: Area=555*445 m^2 Height=129 m x=103 Grid, y=89 Grid, z=43 Grid dx=5, dy=5, dz=3

Meteorological data, such as mean radiant temperature in degrees Kelvin or Celsius, wind speed at a height of 10 meters above the ground in meters per second, wind speed and direction in degrees, and percentage of air humidity, are required in order to perform simulations in ENVI-met software. Based on the climate data from the Chitgar climatological station, the analysis was conducted. It goes without saying that gathering meteorological data in the field is also necessary for the results to be verified. The time is July 2021. The need to investigate the area during periods of high air temperature, low humidity, and unfavorable wind is the driving force behind this decision (Table 2 & 3). The time set for modeling in the software is from 6:00 am to 6:00 pm, and the analysis for July 2021 were completed at 2:00 pm.

RESULTS AND DISCUSSION

According to Beaufort Scale, receptor 2 is in a safe area in Figure 4 at y=357m, while

Fig. 3. Model of site and data loggers (Receptors) in site

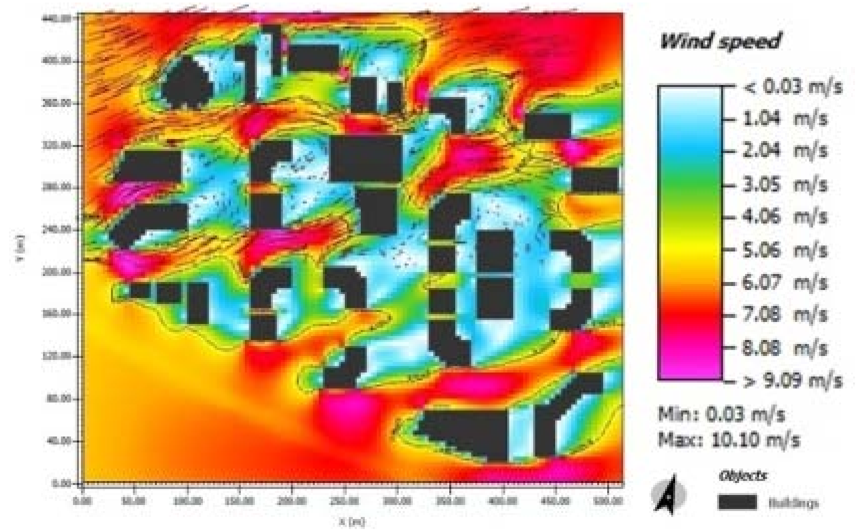


Fig. 4. The wind speed in site

receptors 3, 8, and 10 are problematic because the wind speed in these areas has increased relatively. They are placed at the borderline of comfort at wind speeds of 9.26 ms-1 and 10.8 to 13.19 ms-1, respectively.

Analysis of this series of maps shows the behavior of the wind around the building blocks. When there is no one-story building nearby, the only place for the wind to find a way to continue on is through the corners of high-rise buildings because they act as a strong and high barrier against the wind. Therefore, we will see the highest speed plots in these areas and the wind speed will increase in comparison to the mean base wind because the density of wind vectors has increased in these points.

When passing between two buildings or through an urban canyon, the intensity of the wind in a building's corners causes the wind speed to increase. In the opposite case, when the wind direction of a building is disturbed, the wind speed decreases. However, in other open spaces of the region, where there is a lack of suitable vegetation, such as trees, the decrease in wind speed will not be visible. However, when there is no wind and the air is calm, the climate comfort is not very favorable, especially in the hot seasons. When the wind blows, it can reduce the amount of heat received by the human body and provide more favorable conditions. The spaces facing the wind of the buildings are naturally safe from the impact of the accelerated wind. The inability to move the air around polluting sources is another reason why the lack of wind is unfavorable. These areas run the risk of accumulating polluting particles due to stagnant air.

The ground floor and lobby of a building that faces the wind can be protected from the accelerated wind up to the part of the building that is covered by tall trees, but the wind speed increases at higher altitudes, especially at the top floors of the building.

The results in Figure 5, The wind speed in X-Z profile, indicate that as a building's height increases, so does the wind speed. Due to both the high wind speed and the resulting noise pollution, this is annoying to those who live on higher floors.

To evaluate thermal comfort indicators, in addition to wind speed, the air temperature variable must be considered. Figure 6 shows that in the western area of the site, shading of buildings and the ground has contributed to a decrease of one degree Celsius in the air temperature. Positioning trees to align with wind and ventilation paths, using porous walls for wind flow, and implementing effective shading methods like water features and sprinklers can also reduce temperature and increase thermal comfort. However, it is important to note that the success of these techniques depends on various factors, such as climate and time of day, and requires

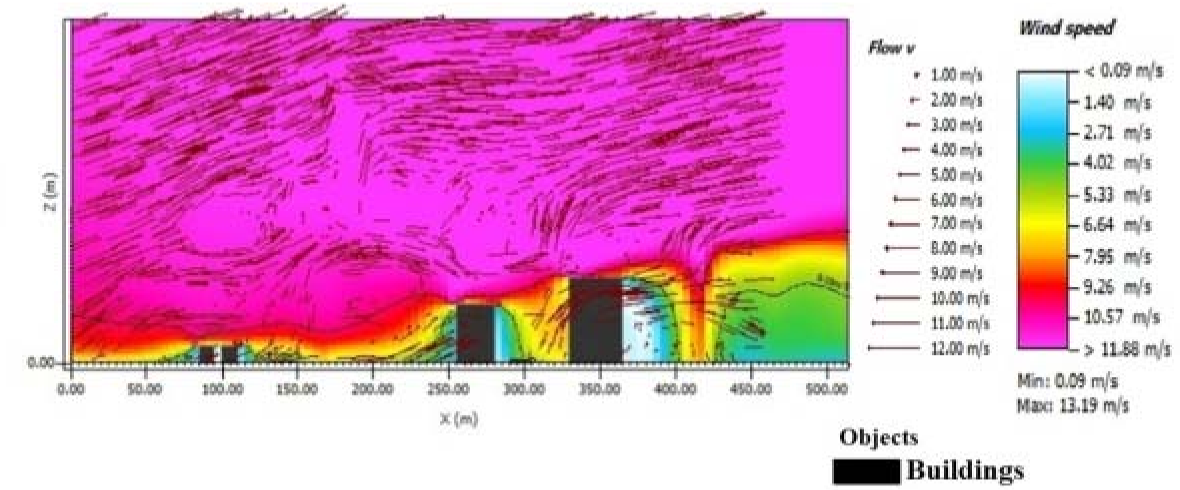


Fig. 5. The wind speed in X-Z profile

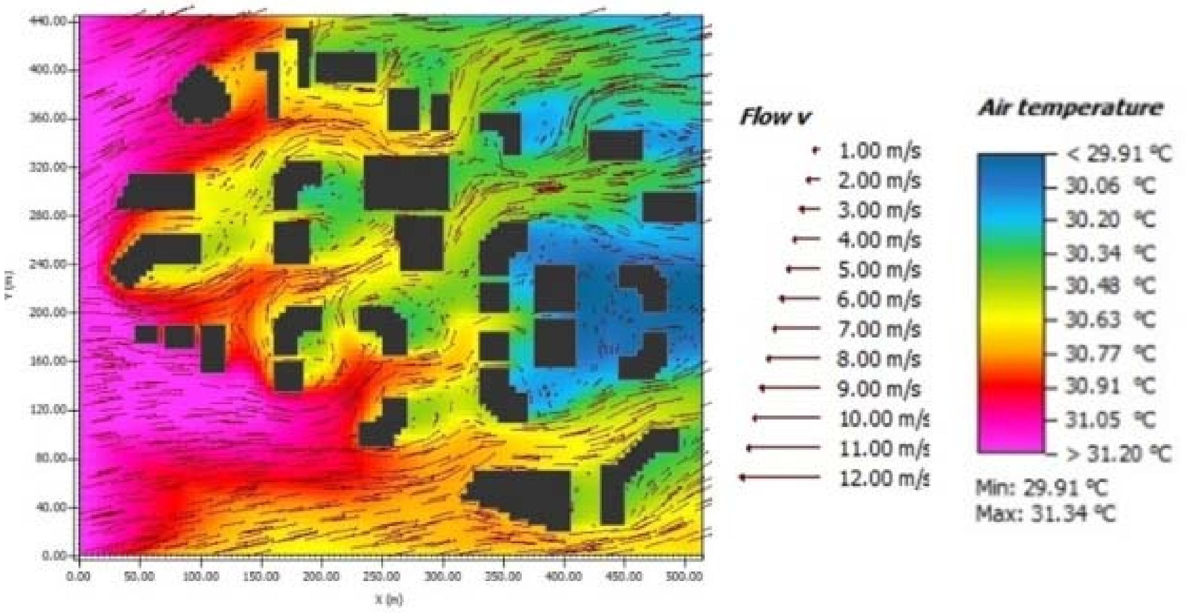


Fig. 6. The Air flow and temperature simulation

careful analysis beforehand (Cilek and Uslu, 2022).

The possibility of a local climate comfort is made possible by the use of materials that can retain water, the covering of passages with grass and trees, the use of green parking, and the use of concrete and porous materials. Planners and urban designers can better address comfort needs in the design of residential settlements with high-rise complexes and public spaces nearby by applying solutions.

As result indicates, in region 1.48 of figure 7 and 8 there is moderate physiological stress and hot weather, in region 2.57 there is severe heat stress and hot weather, and in region more than 2.85 there is very severe heat stress and hot weather, necessitating the use of the measures listed below.

In areas where the wind flow collides with the building, the wind direction frequently changes on the sides of the building. This direction change can swing up to 180 degrees in some places. Based on the outcomes of the simulation of this model with the receptors in ENVI-met software, the most suitable public space in the case study can be seen in figures 7, 8, and 9,

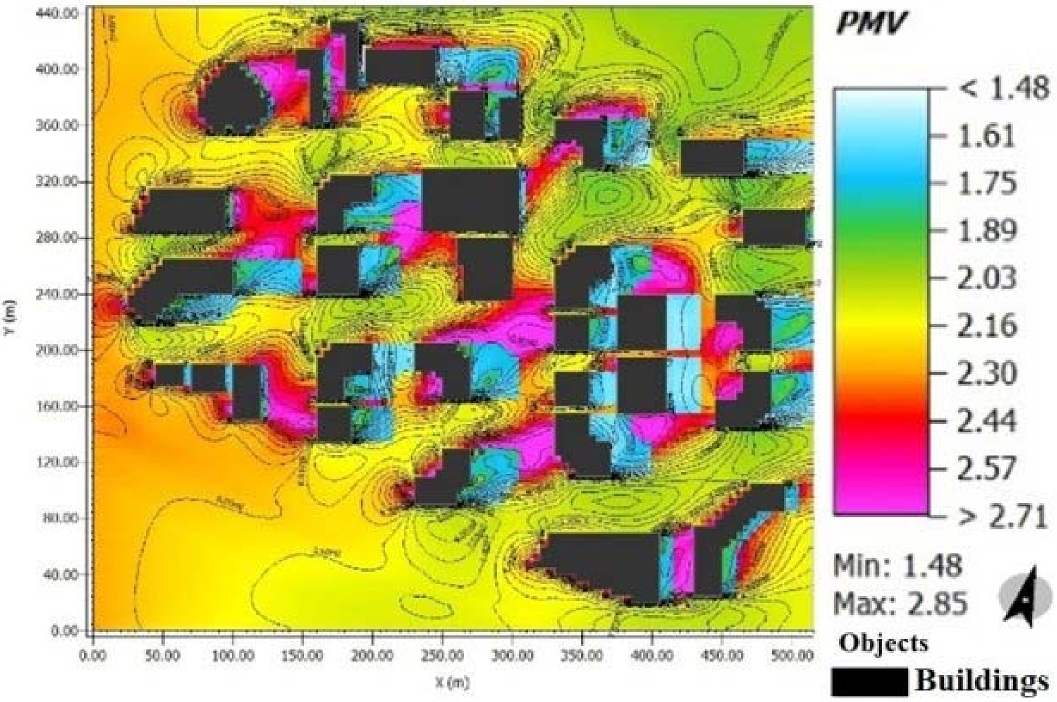


Fig. 7. PMV index

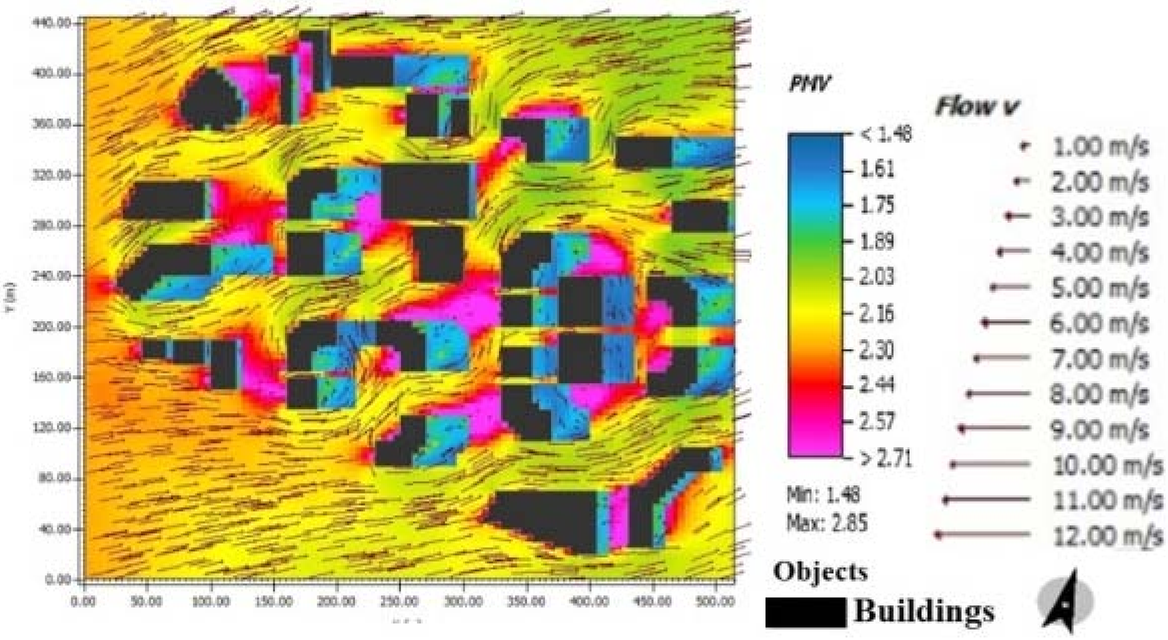


Fig. 8. PMV index and wind direction and speed vectors

according to PMV and UTCI (Universal Thermal Climate Index) indices.

According to the UTCI index range from 9 to 26 is free of thermal stress. By looking at the output of figure 9, we can see areas where there is no thermal stress between 21.75°C and 25.23°C, moderate heat stress between 26.39°C and 31.02°C, and high heat stress between 32.18°C and 33.34°C in site.

Figures 10 at y=352m and 11 at x=357m clearly demonstrate the changes in PMV in altitudes, as well as the spaces facing the wind. A PMV value of zero indicates a region without

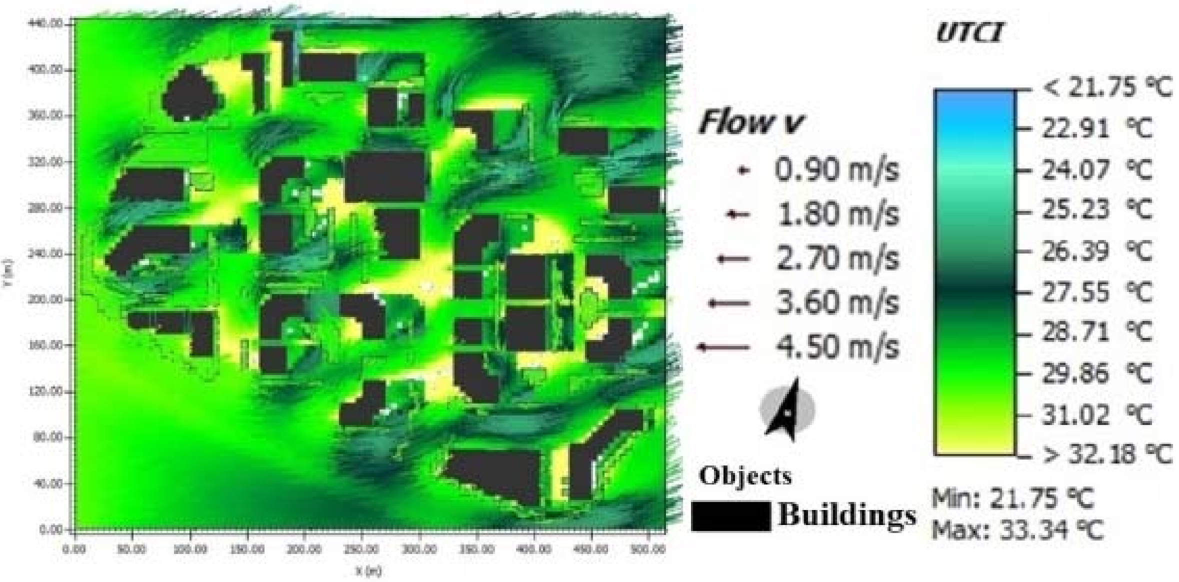


Fig. 9. UTCI index and wind direction and intensity vectors

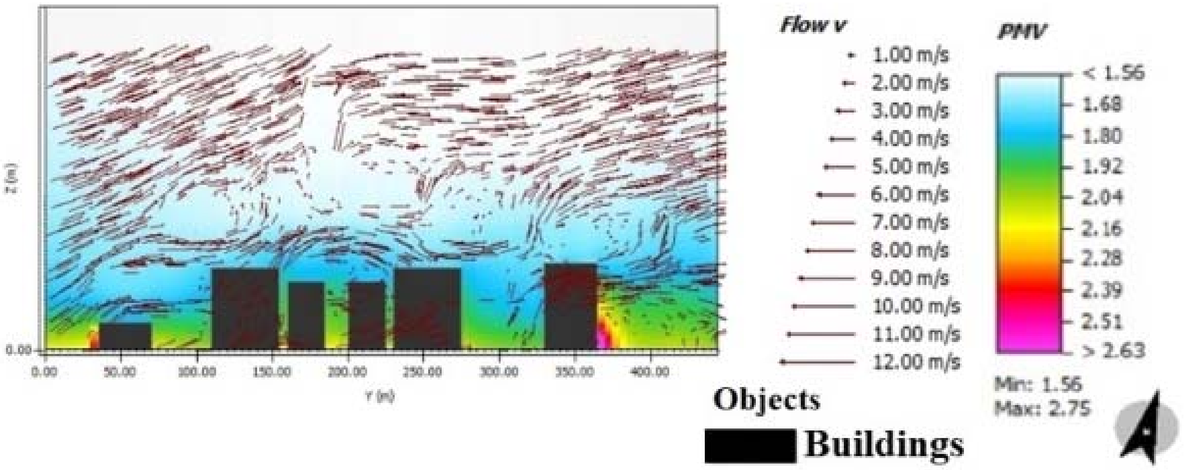


Fig. 10. PMV index and wind speed vectors in Y-Z section

physiological stress, referred to as comfortable in terms of thermal sensitivity. The greater the value becomes and the more positive it gets, the greater the thermal stress and, naturally, climate discomfort.

The studies conducted by Du et al. (2022) reveal that the physical structure of a residential area, including the orientation of passageways and building masses along with the height-to-width ratio, all significantly influence the behavior of the wind, resulting in varied levels of comfort and discomfort. The output images of wind behavior illustrated that areas having different building heights could have better ventilation than those comprising buildings of similar heights (Figure 10 and 11.) In Figure 10, where the buildings have an identical height, a PMV of at least 1.56 was obtained, located above the ground level, whereas PMV less than 1.40 was observed at the ground level (Figure 11). This finding is consistent with the observations made by He et al. (2020) in their research.

Jafari et al. (2021b) argue that it is challenging to create a comfortable environment in high-rise buildings because the wind speed increases in the corners of buildings, reaching its maximum on higher floors and close to the roofline. As wind speed and altitude are inversely

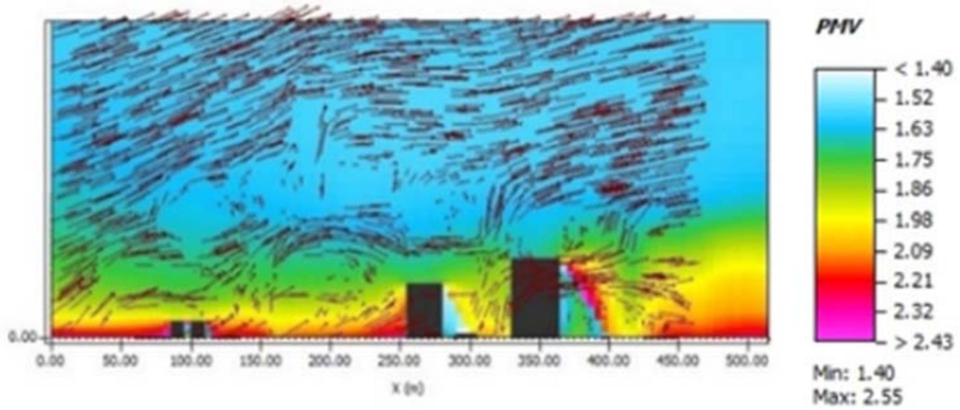
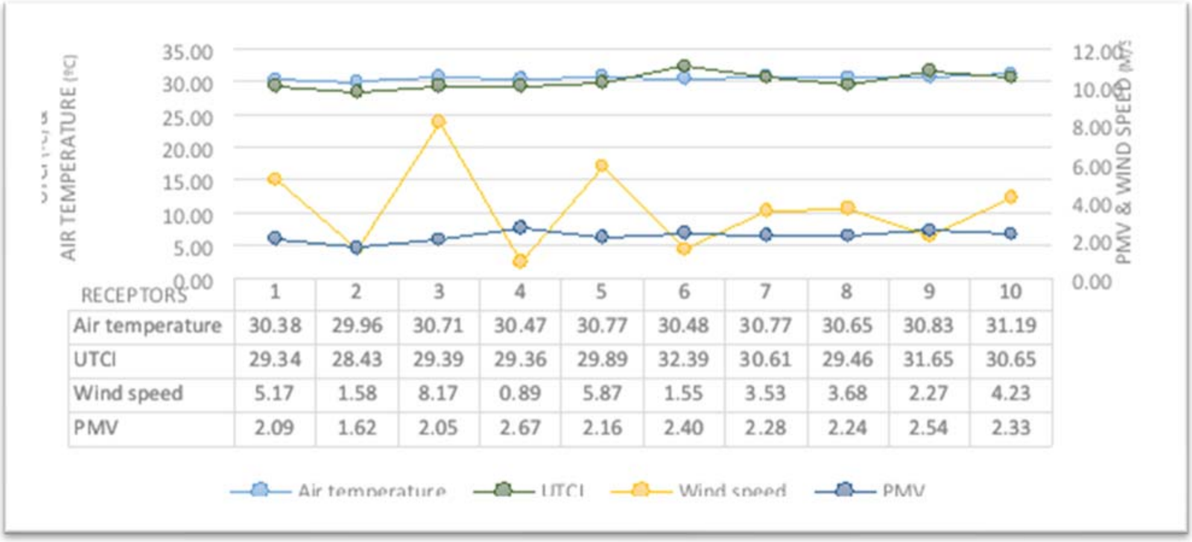


Fig. 11. PMV index and wind speed vectors in X-Z section



RECEPTORS	1	2	3	4	5	6	7	8	9	10
Air temperature	30.38	29.96	30.71	30.47	30.77	30.48	30.77	30.65	30.83	31.19
UTCI	29.34	28.43	29.39	29.36	29.89	32.39	30.61	29.46	31.65	30.65
Wind speed	5.17	1.58	8.17	0.89	5.87	1.55	3.53	3.68	2.27	4.23
PMV	2.09	1.62	2.05	2.67	2.16	2.40	2.28	2.24	2.54	2.33

Fig. 12. UTCI, PMV, Air temperature and wind speed at location of data logger

correlated, the higher the altitude, the higher the wind speed increase. This issue is confirmed by the findings of the studies by Ma and Chen (2020) and Li Han et al. (2022). Councils and urban planners could use the current model and research findings on urban building density as a guide to rationally plan the layout of urban buildings, with the aim of reducing the urban heat island and air pollution (Gu et al., 2020; Qaid et al., 2016). Accordingly, urban planners are advised to consider the following

guidelines: Buildings with a smaller width offer better windward conditions than those with wider widths. Therefore, buildings with narrow facades facing the wind or those with an adverse wind angle are more comfortable than buildings with wider facades that face the wind, as noted by Nugroho et al. (2022).

Wind speeds are very low and occasionally nonexistent in the areas behind buildings, causing disturbances in wind direction along the edges and sides of building blocks. Liang et al. (2020) confirmed that such disturbances and direction changes are more noticeable in spaces facing the building's wind than in other areas. To create undisturbed areas in front of buildings, blocks positioned at an angle to the wind instead of vertical can produce quiet zones. Compared to other blocks, integrated blocks offer less favorable conditions because they accelerate wind speed. Additionally, public spaces located away from the corners of buildings perform better than those located in these areas, according to Ignatius et al. (2015). For optimal ventilation, planners should arrange buildings to avoid obstructing wind paths, direct them to create ventilation and wind flow, and ensure that the buildings' height is appropriate relative to their distance from one another. These factors are critical to ensure that favorable winds are not blocked, as confirmed by Ignatius et al. (2015).

Metropolitans such as Tehran face increasing pollution density due to their dense and checkered texture, which traps local winds and affects air purification and blinds' speed. To address this issue, urban designers in Tehran should avoid compact, dense, and interwoven layouts and instead create open spaces and wide passages to discharge pollution and purify the air. High and interconnected buildings in narrow passages can prevent pollution discharge and trap heat. However, despite increasing density and high-rise buildings, it is essential to mitigate still wind, pollution, and heat density in the city.

One possible solution is to prioritize different strategies based on building conditions in various parts of the city, with the ultimate goal of reducing heat island formation and ensuring climate comfort of urban open spaces. The simplest method is to align the physical geometry of the design space with the direction and speed of the wind. Appropriate solutions will vary depending on the conditions of the urban development site, the configuration of urban blocks and buildings, and matching these factors with the wind's direction and speed.

Airflow modeling could enhance high-rise design coordination by evaluating air circulation, climate comfort, and lowering air pollution stagnancy, among other factors. Future research could involve modeling urban areas, simulating and analyzing various climate comfort indicators such as PET, taking into account different seasons, hours of the day and night, and examining cities with different climates. This topic could benefit in addressing the rise of factors that contribute to heat islands and their associated adverse effects in metropolitan areas, as well as assisting in the reduction and prevention of these contributing factors.

CONCLUSION

This research focuses on examining airflow patterns in high-rise buildings that are influenced by nearby land use, which can have an impact on ventilation and climate. To achieve this goal, the researchers utilized Env-met software and studied two primary indices: PMV and UTCI. The findings indicated that the wind behavior in high-rise buildings is largely influenced by their geometry, orientation, and height-to-width ratio, which, in turn, affects comfort and discomfort. For example, buildings with different heights create better ventilation than those with uniform heights. The wind speed is generally higher in the corners of high-rise buildings and reaches maximum on higher floors and near the roof line. Narrow facades facing the wind provide greater comfort compared to wide ones, and building blocks angled toward the wind create quiet, undisturbed areas in front of the building. Public spaces situated away from the corners of the building generally perform better than those located in these areas. The use of water-retaining materials, vegetation, and porous materials can enhance local climate comfort. Coordination and alignment of building designs with wind direction and speed can help mitigate heat islands and ensure climate comfort in urban areas. In addition, it suggested that airflow modeling could be employed to improve the coordination of high-rise designs in terms of air circulation, climate comfort, and reducing air pollution stagnation. This would lead to an overall improvement in the building's air quality. Future research in this area could include additional climate comfort indicators and take into account various seasons and cities.

GRANT SUPPORT DETAILS

The present research did not receive any financial support.

CONFLICT OF INTEREST

The authors declare that there is not any conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/ or falsification, double publication and/or submission, and redundancy has been completely observed by the authors.

LIFE SCIENCE REPORTING

No life science threat was practiced in this research.

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