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EVALUATION OF THERMAL COMFORT FOR A PROPOSED DESIGN OF A RESIDENTIAL COMPLEX IN ARID AREAS, BAGHDAD AS A CASE STUDY

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Abstract

One of the most significant goals for designers, as they address climate challenges, is to create sustainable cities in hot and dry climates. Several studies are being conducted to improve the requirements for urban architecture, particularly in dry climates due to the need to improve thermal comfort. Previous studies have emphasized the relevance of vegetation, green spaces, the function of the sky view factor, and canyon architecture to reduce the influence of solar radiation in these places. Due to a lack of studies concerned with the design that meets the requirements of the climate in hot environments, as well as the recent increase in population, particularly for an important historical and urban city such as Baghdad, and the increasing need for residential buildings, this research adopted as one of its objectives to highlight on fundamental factors in the design of residential complexes in hot weather and to improve the thermal comfort of pedestrians during the long summer season of the year. Several requirements were considered in the design of a proposed residential complex in a city with a hot and dry climate, including building shape, aspect ratio, vegetation, and the significance of albedo for pedestrian passageways. In the face of severe climate change, a new design for residential complexes was developed in Baghdad on the longest day of summer. ENVI-met software (version 2022) was used to calculate the mean radiant temperature, sky view factor, and air temperature. The Predicted Mean Vote is used to quantify thermal comfort (PMV). The results of the simulation for the residential complex design revealed that at noon, the temperature drops by a noticeable 3 °C. Regarding the results of the thermal comfort indices, the sky view factor, with a value of roughly 82.4%, is less than 0.65. The results of the simulation indicated the PMV values for the thermal comfort index; we noticed an improvement in the thermal sensation because of the moderate PMV values, which ranged from 4.5 to 6.5. Finally, the researcher concluded that the simulation results of the proposed residential complex design within the parameters and essential sustainable construction principles.

Keywords: Aspect ratio, Climate change, ENVI-met software, Mean radiant temperature, Predicted mean vote, Sustainable cities, Sky view factor.

1. Introduction

According to United Nations reports, sustainable development studies have recently become an urgent necessity that the entire world is working to attain by the year 2030. Goal Eleven (SDG 11 or Global Goal 11), entitled "sustainable cities and communities" is one of the 17 Sustainable Development Goals set by the United Nations General Assembly in 2015 [1]. It is one of the most crucial 17 goals that the UN focuses on. Make cities inclusive, safe, resilient, and sustainable.

The objective of this research is to highlight on the most crucial aspects of developing a residential complex with sustainable building requirements in a hot, dry climate. As a result of drought, a lack of vegetation cover, an increase in concrete structures, and haphazard city construction, there is an urgent need to consider the importance of thermal comfort for humans, particularly in hot and dry cities such as Baghdad. The albedo factor, street orientation, vegetation effect, aspect ratio, and sky view factor all play significant roles in building design to improve pedestrian thermal comfort.

Several variables, including the mean radiant temperature (Tmrt) and the Predicted mean vote (PMV), will be thoroughly examined and analysed to investigate thermal comfort enhancement using ENVI-met software. The relative humidity, wind speed, and air temperature will also be taken into account.

2. Literature Review

The researcher conducted a literature review based on two aspects: fundamental requirements for improving thermal comfort and indicators of thermal comfort. The requirements for the first aspect include the following: aspect ratio, which describes the relationship between building height and distance; sky view factor; albedo effect; vegetation effect; and the influence of courtyards and pergolas. The second aspect focuses on the concept of thermal comfort and the indicators used to assess thermal comfort in this study, such as mean radiant temperature and predicted mean vote.

2.1. Requirements for improving thermal comfort

In this section, the researcher clarified several criteria that were used to create the design for the proposed residential complex. Table 1 depicts the criteria used by the researcher to develop design principles for the proposed residential complex in accordance with the thermal comfort requirements.

Table 1. Design requirements for improving thermal comfort.

The Requirements	The kind of the requirements
Geometric Buildings Design	Aspect Ratio (H/W) The canyon aspect ratio is defined as building height (H) divided by street width (W). Sky View Factor (SVF) SVF is a percentage of the visible sky. SVF is critical in determining the surface radiation balance.
The effect of coatings on walls and walkways	Albedo (percentage of solar energy that a surfaces)
The effects of Vegetation	Trees, Green areas
Shading techniques	Physical elements such as patios, courtyards, and pergolas

These criteria are relevant to geometric buildings design like aspect ratio (H/W), which denotes the proportion between the average height of surrounding structures (for example, building facades) and the typical width of the space , describes the sectional proportions of the urban canyon. The researcher observed that the Sky View Factor (SVF), which also specifies the cross-sectional proportions of the canyon, is closely related to its aspect (H/W) ratio.

The Sky View Factor (SVF) is the percentage of the sky dome that is (seen) by a surface, whether from a specific point on the surface or when integrated over the full area of the surface. The ratio of long-wave radiation released from urban surfaces to the atmosphere is controlled by SVF [2]. An SVF value that ranges from 0 to 1 thereby indicates the percentage of sky view from a position on urban surfaces dependent on the interception of surrounding urban structures; this is shown in Fig. 1.

Due to multiple reflections caused by high-rise buildings and narrow streets, the heat island effect is exacerbated when the SVF value falls in urban canyons. This is because long-wave radiation loss is constrained and heat is stored [3, 4]. The sky view factor is depicted in Fig. 2 based on the canyon aspect ratio (H/W).

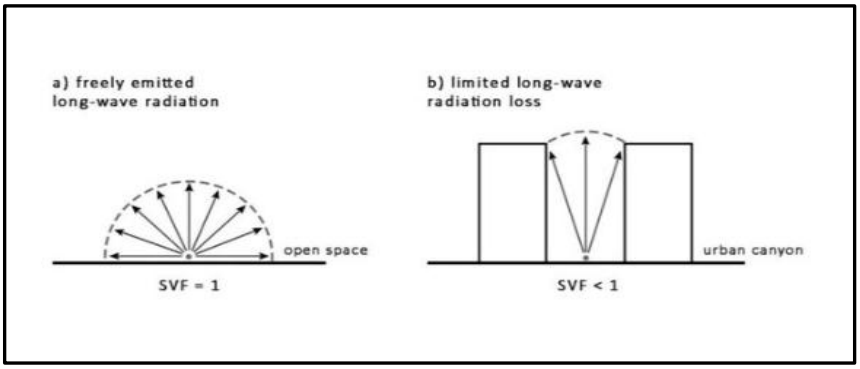

Fig. 1. The relation between SVF values and emitted long-wave radiation [2].

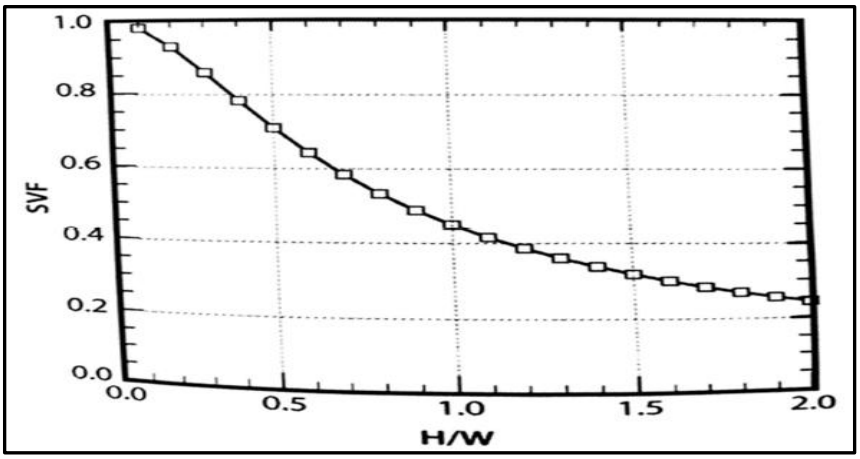

Fig. 2. The relationship between the sky view factor and canyon aspect ratio (H/W) [5].

Albedo is the percentage of solar energy that a surface or object reflects. Light-coloured roofing materials could provide some respite from local-scale heating because dark surfaces, such as those found on asphalt paving and rooftops, often have low albedo and tend to contribute to the urban heat island more than light-coloured surfaces.

For buildings with light-coloured roofs, estimations of the reduced energy costs associated with reduced cooling show that significant savings can be made for crowded urban regions [6]. Urban surfaces that reflect sunlight, such as white roofs and light-coloured pavements, can raise an urban area's albedo by roughly 0.1.

Consequently, higher albedo in urban and populated regions can lower air temperature and mitigate some of the expected temperature rise brought on by global warming. As a result, this may be a useful tactic to support attempts at climate mitigation to further limit the pace of increase in global temperature because of continuous greenhouse gas emissions [7].

Regarding the effects of afforestation, the improved thermal comfort is greatly influenced by vegetation. Even though vegetation has very little effect on air temperature, it nonetheless helps to improve human thermal comfort.

Although many researchers focus on lowering air temperatures, the radiative exchange is frequently the main element determining thermal comfort in a hot, arid area. Along with immediately sheltering a person from the sun, vegetation also reduces long-wave emissions from surfaces and limits the quantity of solar radiation reflected from them [8].

Urban green spaces are crucial for ecosystem services, according to a recent study [9]. On environmental cooling and humidification, the impact of urban green spaces was assessed. The three-dimensional green volume and plant canopy closure had a substantial impact on the overall cooling effect in the green area. More consideration should be given to the plant designs in the parks to produce an urban park and green space that is more ecologically beneficial.

According to conclusions from a recent study on the value of afforestation for enhancing thermal comfort for residential complexes, thermal comfort is most definitely improved by green space for a residential garden, regardless of the type of green space.

The thermal comfort of more areas will be increased if a green area is positioned in the block's centre or a downwind area [10].

In hot climates, consider shading techniques that lessen the effects of solar radiation and so improve thermal comfort for people. The use of physical elements like patios, courtyards, and pergolas in some buildings are examples of such strategies. Shade is essential for keeping outdoor places cool [11].

Below are two justifications for shading's significance [12]:

- Protection from sun radiation, which reduces heat stress physiologically more than simply lowering the air temperature in open areas without giving shade.
- Another method for lowering air temperatures outdoors is shading, which doesn't require any energy or water use for irrigation.

2.2. Indicators of thermal comfort

The state in which satisfaction is thermal comfort is known as human thermal comfort. Mean radiant temperature (Tmrt) is a key indicator that precisely measures human thermal comfort in an outdoor urban area [13]. The quantity of fluxes of both short-wave and long-wave radiation absorbed by the human body are also referred to as Tmrt, and it has an impact on both the body's energy balance and thermal comfort [14].

The Predicted Mean Vote (PMV) considers the measure of outdoor thermal comfort, which depends on characteristics related to heat balance and perceived temperature [15]. It is noteworthy that the Predicted Mean Vote (PMV), which is derived from the human energy balance, and other physiologically significant thermal indices, are assumed to be most affected by the mean radiant temperature.

3. Methods

3.1. Study area

The main factor influencing Iraq's climate is its astronomical location, that is, the location of the latitude circles, because it defines the angle of sunlight falling and the length of the day, that is, the time when the sun shines. Because of the orbital similarity, this location influences the shape of the prevailing winds blowing on it. In winter, the winds blew west because of this location.

The second factor is its proximity to water sources, where it is noted that the Arabian Gulf and the Arabian Sea are water areas that influence Iraq's climate and are located on the severe south-eastern side, while the Mediterranean Sea is located more than 1000 kilometres to the west.

The third factor influencing Iraq's atmosphere is the height and shape of the mountains. Because of their altitude, they play an important role in northern Iraq. They alter the temperature and increase the amount of precipitation. The terrain of the countries surrounding Iraq also has a significant impact on its resolve (high or low) (https://climateknowledgeportal.worldbank.org/country/Iraq).

Baghdad is in the centre of Iraq, on both sides of the Tigris River as shown in Fig. 3. It is located at 43 degrees East and 34 degrees north. Baghdad is the capital of Iraq which is located in the central part of it. The environment of Baghdad is semi-arid, with hot and dry summers and cold winters. Several factors, particularly in recent decades, have played a significant role in changing Baghdad's climate; the researcher summarizes these factors as follows:

- An increase in desertification and a lack of vegetation cover.
- Drought and a severe lack of rain.
- An increase in the number of pollutants, fumes, and gases in the atmosphere due to a number of factors, including an increase in the number of electric power generators and a lack of oversight of factories and the allowable percentage of pollution.
- Random construction and increased use of concrete structures.
- Lack of motivation and support for using eco-friendly materials.

Fig. 3. Baghdad is central on a map of Iraq. (https://www.infoplease.com/atlas/middle-east/Iraq-map)

3.2. Numerical modelling software

Michael Bruse, University of Mainz, Germany, and his team created ENVI-met in 1994, beginning with the design of the microclimate model and continuing to develop it since then. ENVI-met is software that simulates the interactions of urban surfaces, vegetation, and the atmosphere at the microscale. ENVI-met allows for the investigation of the effects of small-scale changes in urban design (trees, backyard greening, new building) on microclimate under various mesoscale conditions. This program was selected as simulation software. because of its ability to mimic the microclimate of urban area and because it has a sound physical basis [15, 16].

Numerous investigators demonstrated the dependability of ENVI-met results in a wide range of applications for researching urban comfort conditions. The simulation's results appeared to correspond to data collected at regional meteo.

According to research conducted by Ghaffarianhoseini et al. [17], numerous studies indicate the dependability of using ENVI-met to simulate the thermal performance of outdoor spaces. The data measured or observed at local meteorological stations agreed with the simulated air temperature in these studies. Another investigation [18] came to the same conclusion, asserting that the ENVI-met simulation validated the field measurement data.

3.3. Climate description for the proposed model

The Iraqi Meteorological Organization and Seismology provided important data required to simulate the proposed design. The researcher chose the hottest day during summer season in Baghdad, which was July 12th. According to a previous study conducted in 2015 [19], which proved that July 2010 was the hottest month of the year, the researcher relied on this study despite obtaining data from Iraqi Meteorological Organization and Seismology proving that the temperature was also 50 ºC in 2020, but the researcher did not depend on these data due to epidemic conditions and complete closure, which may have affected the accuracy of the readings somewhat.

As a result, simple forcing for air temperature and relative humidity was used for one day, demonstrating that the maximum temperature was 50 ºC at four pm and the minimum air temperature was 35 ºC at six am. Wind speed is 5 m/s with a wind direction of 315º. Once upon a time, the minimum relative humidity was 24% and the maximum relative humidity was 36%. The simulation work takes 24 hours.

The model area was created with grid sizes of x = 50, y = 50, and z = 20. These grid sizes are described in grid cells with sizes of dx = 0.5 m, dy = 1 m, and dz = 2 m. The grid sizes chosen to depend on the version of ENVI-met 2022 that provides these sizes, while the accuracy of the simulation result depends on the grid cell that represents the dimension of buildings and the area of pedestrian walks and roadways.

The researcher assumed ten receptors in various locations throughout the proposed model to improve the accuracy of the extracted results, which are used to evaluate the performance of the proposed model. Figure 4 depicts the proposed residential complex design with the location of the ten receptors. Receptors are places within the model area where data on the atmosphere and soil can be collected. Receptors are used to measure air temperature, wind speed, mean radiant temperature, relative humidity, specific humidity, and sky view factor.

Receptors are selected points within the model area where processes in the atmosphere and soil are recorded in detail. These receptor readings aid in increasing the accuracy of the results, particularly at the specific points chosen, which are usually important for clarifying changes in the results after the simulation because of the use of trees or shading, or a change in the dimensions of the buildings or material.

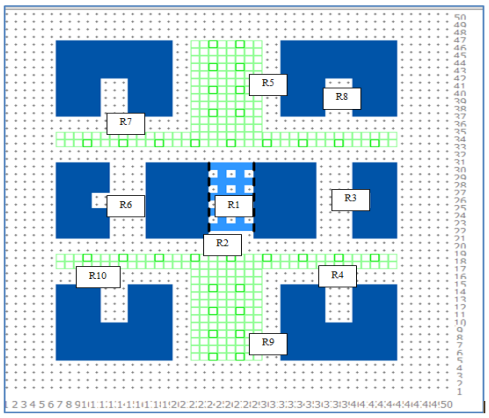

Fig. 4. Proposed residential complex design with the location of the ten receptors simulated by ENVI-met software. Source: Designed by the researcher.

3.4. Configuration for the proposed residential complex

3.4.1. Design of the residential and commercial buildings

The researcher relied on the proposed city design on several essential requirements to be considered in the design of sustainable cities, significantly in hot and dry climates. Four buildings with a height of 18 m in the shape of a letter U were constructed to study the effect of the open courtyard on improving thermal comfort. These Four buildings were placed on the four corners see Fig. 5 Building 1, 2, 3,

and 4. The idea's main goals are to take advantage of the buildings' symmetrical placement and to achieve the suitable shade that these buildings provide for pedestrian walkways.

Regarding the two buildings 5 and 6, which were proposed to be located on the sides to verify the surroundings of the place from all sides and to take advantage of the principle of shade and the cooling of the hot air, the two buildings were likewise constructed in the shape of a letter U and were 18 m in height. Each of the six stated buildings, which are multi-story residences, has six stories.

The Seventh and Eighth buildings are meant to be commercial and service buildings of 15 m in height. The three-dimensional distribution of buildings, their positions, and their heights are clearly depicted in Fig. 6.

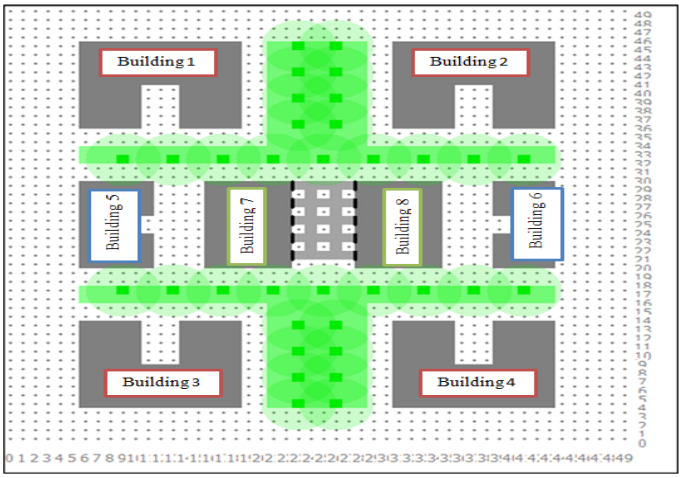

Fig. 5. The distribution and locations of the buildings were designed and modelled by ENVI-met. Source: Designed by the researcher.

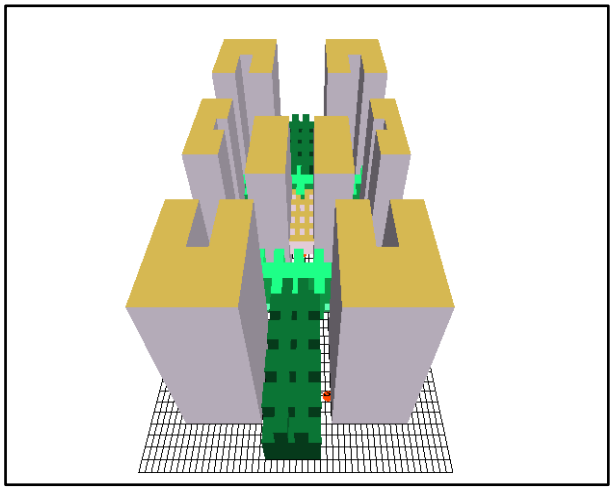

Fig. 6. The three-dimensional distribution of buildings, including their locations and heights. Source: Designed by the researcher.

3.4.2. Design of main streets and pedestrian walkways

Figure 7 depicts the arrangement of the principal streets and walkways. The idea of employing substances that don't absorb as much heat from direct sunlight has been adopted. The main roadways were paved with dark concrete pavement and the pedestrian sidewalks with light concrete pavement. Albedo is equal to 0.20000 for dark concrete pavement and 0.80000 for light concrete pavement.

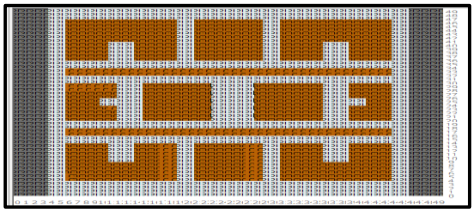

Fig. 7. Distribution of main streets and walkways of the proposed design simulated by ENVI-met. Source: Designed by the researcher.

3.4.3. Design of the landscape and canopies

The afforestation strategy used in this residential complex was based on the idea of planting trees and creating green spaces in all the open areas between the buildings as shown in Fig. 8. Palm and citrus trees consider the most prevalent in Baghdad city were planted in hot and arid places and are evergreen and offer considerable shade during the hot and long daytime hours Therefore, we adopted to use of these types in the proposed model design to provide shade and adequate ventilation.

The researcher connected the two service buildings Seven and Eight with canopies that were raised 4 m to apply the shade concept to contribute to boosting and improving thermal comfort. This area, which is planned to be between the two buildings, will benefit from it as a cafe and rest place because these canopies are meant to be in the shape of a perforated ceiling that permits providing suitable shading as well as ventilation.

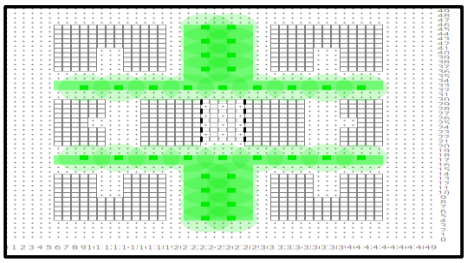

Fig. 8. Distribution of trees and green spaces in the proposed design. Source: Designed by the researcher.

4. Discussion and Analysis of the Results

The researcher opined arranging the analysis of results into two parts. The first part focuses on the model's output, including the meteorological results, which were created using the ENVI-met software, such as the potential air temperature and wind speed. The second part has crucial variables that can be used to estimate

outdoor thermal comfort. ENVI-met was designed for micro scale analysis, with a typical horizontal resolution of 0.5 to 5 m and a time step of a few seconds. This resolution enables micro-scale studies of interactions between individual buildings, surfaces, and plants. Also.

Additionally, ENVI-met is a micro-scale three-dimensional software model designed to simulate complex metropolitan settings using fundamental thermodynamic rules (temperature calculations, for example), generic atmospheric physics (turbulence prediction), and fluid mechanics (wind field).

The study focused on three important variables, each of which might provide an assessment of the outdoor sensation, especially on the pedestrian level on sidewalks at noon, such as sky view factor, Predicted mean vote, and mean radiant temperature. These variables have a direct relationship to the effect on pedestrian thermal comfort, especially at noon, because they indicate the level of radiation received by the human body.

Radiation includes all radiative fluxes (direct, diffuse, reflected solar radiation, and long-wave emissions from surfaces). The researcher identified a variety of factors that can be used to measure thermal comfort; it is noteworthy that many researchers selected only one parameter that is adequate for this purpose.

However, the researcher wanted to provide a thorough evaluation of the proposed housing complex in order to investigate the sustainability-related characteristics.

4.1. Meteorological results

According to the simulation procedure carried out on the proposed design in 24 hours, the findings show that the temperature has decreased by about 3 ℃. According to Fig. 9, the initial meteorological data that provided as the simulation's input data; we observed that the temperature was 50 ℃ in hour 16.

Manually adjust values

Time	T	rH
00:00	41.43	30.40
01:00	40.36	31.20
02:00	39.29	32.00
03:00	38.21	32.80
04:00	37.14	33.60
05:00	36.07	34.40
06:00	35.00	35.20
07:00	36.50	36.00
08:00	38.00	34.67
09:00	39.50	33.33
10:00	41.00	32.00
11:00	42.50	30.67
12:00	44.00	29.33
13:00	45.50	28.00
14:00	47.00	26.67
15:00	48.50	25.33
16:00	50.00	24.00
17:00	48.93	24.80
18:00	47.86	25.60
19:00	46.79	26.40
20:00	45.71	27.20
21:00	44.64	28.00
22:00	43.57	28.80
23:00	42.50	29.60

Fig. 9. The initial meteorological data calculated by ENVI-met.

However, once the simulation is complete, we noticed that the temperature in this hour has dropped to 47 ℃ by a percentage of 82.1%, as indicated in Figs. 10 and 11.

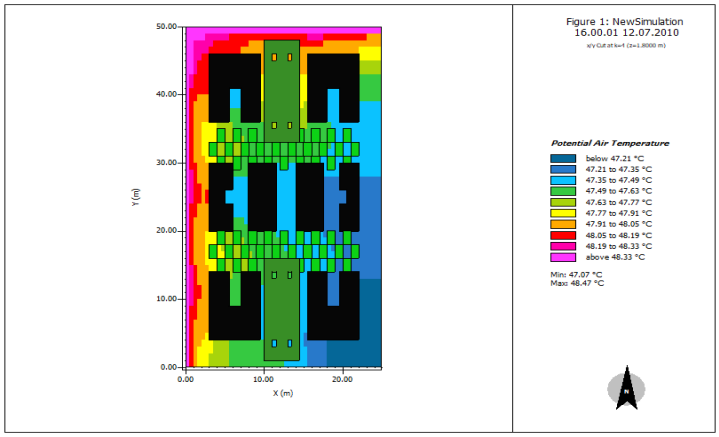

Fig. 10. Air temperature distribution for the proposed design after simulation.

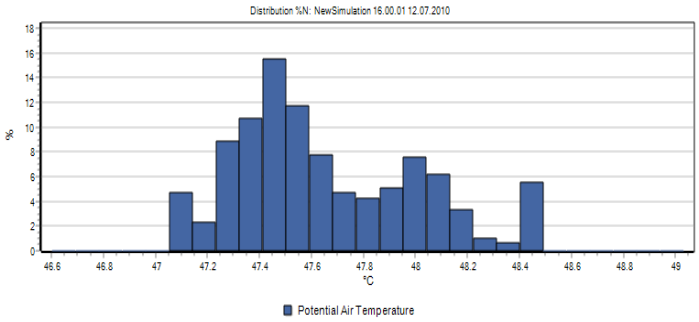

Fig. 11. Air temperature percentage value for the proposed design at midday noon.

The actual wind speed considered in the modelling study was 5 m/s, and as can be shown in Fig. 12, the wind speed is approximately (0.89-5.27)m/s, especially on the pedestrian sidewalks. This is because of the existence of a regular distribution of afforestation in open areas, as well as the impact of the presence of high buildings, particularly in the direction of the prevailing winds. Figure 13 reveals the distribution of wind speed at noon at level 1.8 m above ground with the pedestrian level.

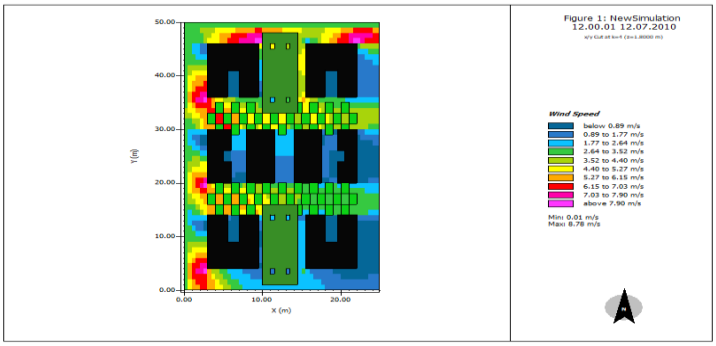

Fig. 12. Air temperature distribution for the proposed design after simulation.

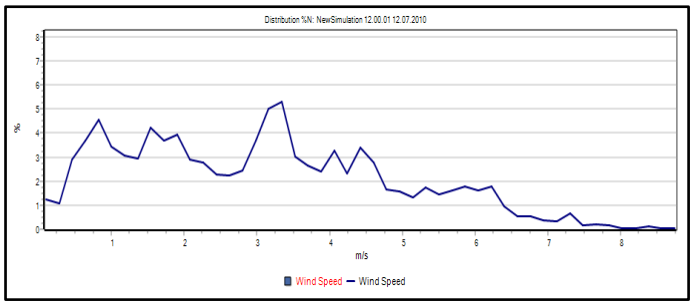

Fig. 13. Wind speed percentage value for the proposed design at midday noon.

4.2. Outdoor thermal comfort results

The most important aspect of the research is the assessment of pedestrian thermal comfort, which evaluates the proposed design of the Baghdad residential complex. The researcher adopted the following factors to evaluate pedestrian thermal comfort.

4.2.1. Sky view factor

According to Fig. 14, we observed that the value of the sky view factor varies between (0.01-0.65) with a percentage of 82.4%, this indicates that approximately 82.4% of the sky view factor is less than 0.65 indicates that the sky's openings are closer together because of the foliage and patios, increasing shading and improving thermal comfort. The distribution of the sky view factor is shown in Fig. 15, and the researcher noticed how the presence of trees whose placement was coordinated over large areas has an impact on the amount of sky display.

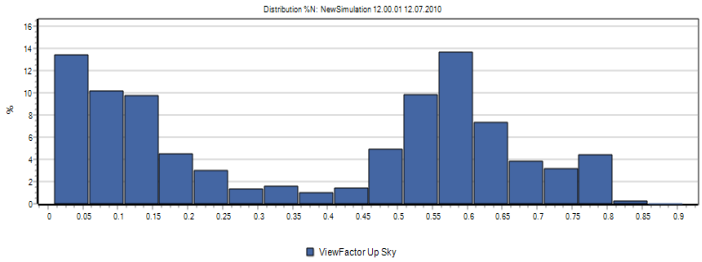

Fig. 14. Sky view factor percentage value for the proposed design at midday noon.

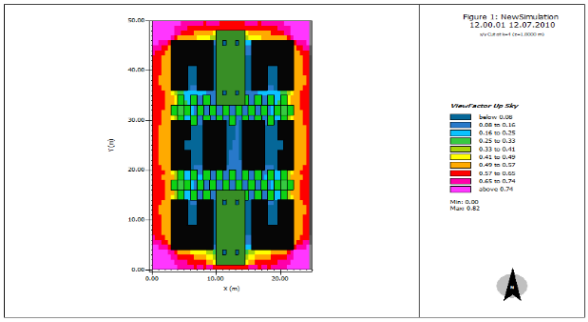

Fig. 15. Sky view factor distribution for the proposed design after simulation.

4.2.2. Mean radiant temperature

The mean radiant temperature (Tmrt) is the most crucial meteorological input parameter for the human energy balance in sunny summer weather because the combined effect of radiant and convective heat gains and losses significantly affects the human energy balance in outdoor environments [20]. As a result, the researcher focused on this essential factor when calculating the level of thermal comfort for the proposed design model, using values that were determined from the receptors that the researcher imposed in various aspects of the proposed model.

The researcher observed that the existence of the canopy, which had a significant role in boosting thermal comfort by providing shade during the day, resulted in the highest value of mean radiant temperature being recorded for receptor number one. Referring to Fig. 16, we noticed an increase in the values of mean radiant temperature that were recorded by receptors one, six and eight.

Based on the locations of those receptors in Fig. 17, we observed that is characterized by a location that was influenced by the shadow of the nearby tall buildings as well as the presence of the courtyard, which plays a significant role in reducing the intensity of heat stress and improving thermal comfort.

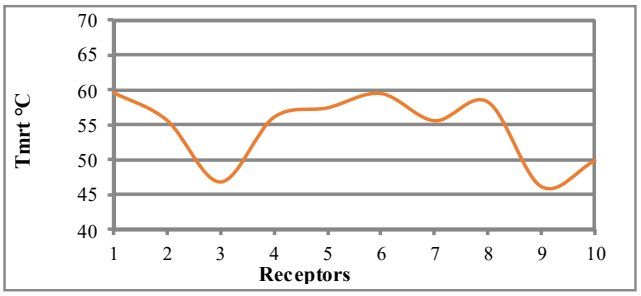

Fig. 16. Mean radiant temperature values for the ten receptors.

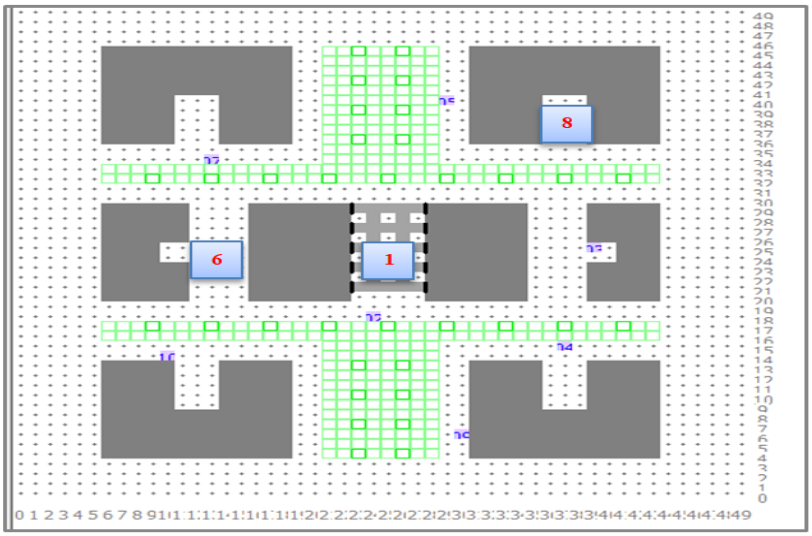

Fig. 17. The location of receptors one, six, and eight.

4.2.3. Predicted mean vote (PMV)

PMV range is typically defined as [-4] very cold to [+4] very hot, with 0 being the thermal comfort value neutral. The American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) standard 55-2004 elaborates on the use of Fanger's heat balance equation for calculating PMV to determine the scale of thermal comfort. As shown in Fig. 18, ASHRAE thermal sensation (ASH) is a 7-point scale based on Fanger's heat balance equation. [21]. Even while the local environment's mathematical function determines PMV values, in most applications, it can also provide values above [-4] or below [+4]. PMV equation can effectively provide values of PMV high over +4 [+8 and more] when applied to outdoor settings under summer temperature stress conditions, especially in hot and arid climates. These results exceed the range of PMV approach even though they are mathematically correct (www.ENVI-met.com).

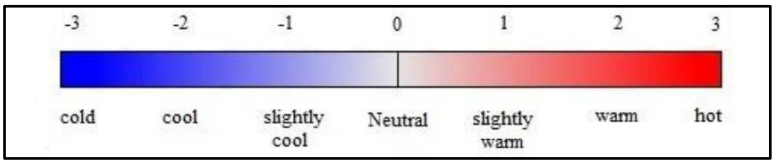

Fig. 18. ASHRAE thermal sensation scale- PMV scales [19].

According to the histogram in Fig. 19, PMV values range from (4.5 to 6) and indicate a percentage of 41.5%. While PMV values range from 6.5 to 6, its proportion is 58.5%. Referring to the results obtained in references [11, 22, 23], we observed an improvement in the thermal sensation because of recording modest amounts of PMV values for the thermal comfort index that have been deduced from the simulation's findings.

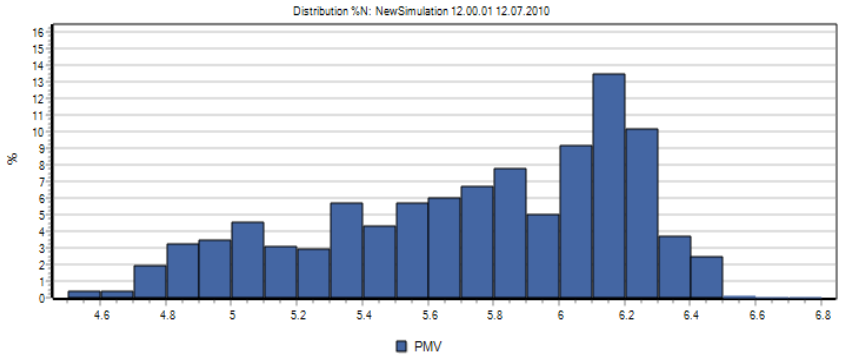

Fig. 19. PMV percentage value for the proposed design at midday noon.

The distribution of PMV values is illustrated in Fig. 20, we noted that the courtyard area and green spaces with trees, as well as the corridors in buildings with a letter U design, recorded the lowest values of PMV. This may be explained by the fact that the properties of vegetation directly affect the outcomes of thermal perception. For example, leaves absorb and transmit solar radiation, and evapotranspiration enhances thermal perception.

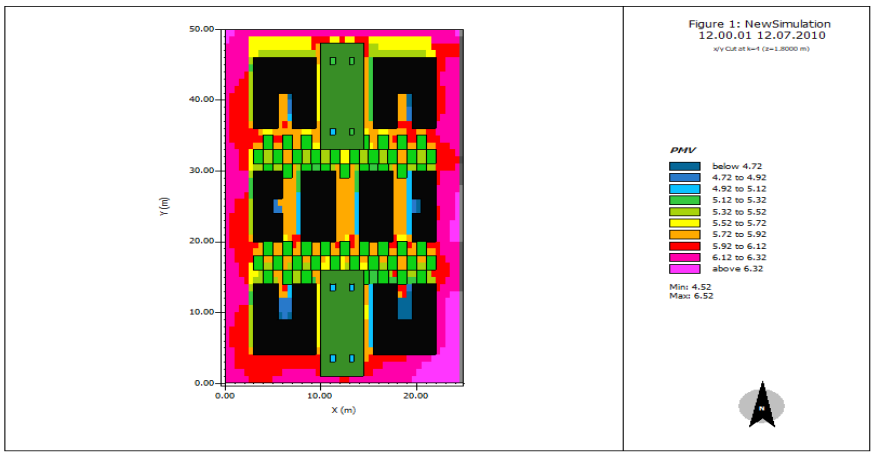

Fig. 20. PMV distribution for the proposed design after simulation.

5. Conclusions

According to the simulation results, there is a noticeable 3°C temperature decrease at noon. This decrease in temperature is a significant predictor of the impact of the parameters that the researcher considered while developing the proposed design. We concluded that the temperature decline is concentrated in areas with trees and greenery, and that this drop in temperature can be attributed to the impact of afforestation, which creates the necessary shade by obstructing the sun's rays, particularly at noon when they are most intense and vertical.

Regarding the results of the thermal comfort indices, the researcher found that a sky view factor of roughly 82.4% of the sky view factor is less than 0.65 indicates that the sky openings are closer together due to the presence of vegetation and pergolas, which increases shading and enhances thermal comfort. The values of PMV for the thermal comfort index were revealed by the simulation's outcomes; the researcher observed an improvement in the thermal sensation as a result of the moderate PMV values, which ranged from 4.5 to 6.5.

According to Tmrt results, the researcher clarified the effect of the shadow of the neighbouring tall buildings as well as the presence of the courtyard, which significantly contributes to decreasing the severity of heat stress and enhancing thermal comfort. It is also generally recognized that roads and walkways' albedo play a crucial role in reducing the amount of heat absorbed by these surfaces during the day and holding onto them for a long time, which affects how comfortable it is for people to walk on these surfaces.

The results of the simulation process for the proposed design model for the residential complex are summarized by lowering the value of the sky width factor and decreasing the openings that allow sunlight to pass through, which affects the amount of heat acquired by the surfaces and walls. Furthermore, the improvement in the values of PMV and Tmrt obtained from the effect of the shadow of the buildings, as well as the use of light-reflecting materials for the walls and surfaces, all of these variables improve the thermal comfort of pedestrians within the proposed model of the residential complex and works to increase ventilation and reduce thermal emissions of the surfaces that enhancing human thermal comfort.

Based on the simulation results of the proposed residential complex's design in light of the criteria that were studied and tested in the program, and in light of the program's positive results in improving the thermal comfort of pedestrians in the proposed design, it is possible to trust these results, taking into account the proposed design and the possibility of its implementation in Baghdad. Identifying the sites proposed by municipalities affiliated with the Municipality of Baghdad, taking into account population needs.

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