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The Impact of Urban Roughness on Outdoor Thermal Comfort in Hot Arid Climate

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ABSTRACT: The proportion of the world's population living in cities is rapidly increasing, presenting new challenges to the urban environment and quality of life. Among these challenges is the urban environment's impact on residents' outdoor thermal comfort, which can affect their health and well-being. Urban roughness, which includes building and street heights, has a significant impact on the thermal environment of urban areas. Changes in these factors cause variations in temperature distribution, wind speed, and humidity, which affect how people perceive thermal conditions. The research problem is the effect of urban roughness on outdoor thermal comfort in hot arid climate, specifically the height of buildings and the density, for a case study in (Al-Bab Al-Sharqi) in Baghdad city. Measurement method that employed the computer programs (Rino8 and Grasshopper) to calculate the thermal comfort index (UTCI) and its impact on various climatic variables. The findings revealed that the thermal comfort index and the climatic factors associated with it vary depending on the configuration of buildings.

KEYWORDS: Thermal comfort; urban roughness; urban environment; hot arid climate; UTCI index

1. Introduction

Thermal comfort in outdoor urban spaces is one of the most important factors influencing people's quality of life in cities. Understanding the impact of urban roughness on comfort is essential for designing green cities and improving urban living standards. Urban roughness refers to a variety of factors affecting the urban thermal environment, including buildings, roads, and green spaces. For example, buildings can provide heat or shade, while roads and trees influence the distribution of heat and wind speed. Outdoor users' comfort levels are a key factor affecting outdoor activities in streets, squares, playgrounds, urban parks, and other spaces. The volume and intensity of these activities are primarily determined by the level of discomfort users experience when exposed to climatic conditions in outdoor spaces. The Universal Thermal Climate Index (UTCI) is a measure of the physiological response of humans to heat, expressed in degrees Celsius. It describes the synergistic heat exchanges between the human body's energy balance, physiology, and clothing, and the thermal environment. The UTCI takes into account how people adjust their clothing based on the actual temperature of their surroundings. To calculate the UTCI, four variables are needed: mean radiant temperature (MRT), wind speed at 10 meters above ground, air temperature at 2 meters, and dew point temperature or relative humidity at 2 meters (Universal Thermal Climate Index, 1979-2020). The ASHRAE standard defines thermal comfort as "that state of mind that expresses satisfaction with the thermal environment" [3].

For decades, much research has focused on the impact of environmental factors on urban comfort conditions. Urban climatologists have sought to assess thermal comfort in outdoor spaces, which has gained as much recognition as indoor comfort. The effects of urban configuration on the urban thermal climate have been investigated in a series of studies conducted under hot, arid climate conditions [4, 5, 6, 9]. The sky view factor (SVF) is the ratio of the visible area of the celestial hemisphere to the total radiated environment from the earth's surface. SVF and air temperature have a strong relationship during clear, calm nights, which affects thermal comfort at street level. SVF limits the amount of global radiation that can reach a specific point in the urban environment during the day while also accounting for radiative cooling at night.

Mean radiant temperature (MRT) refers to the radiation exchange between the human body and its surrounding environment [11]. This study aims to examine the effects of urban roughness, measured by building density, arrangement, and height, on outdoor thermal comfort in urban areas using the UTCI index, which assesses thermal sensation in outdoor environments. To achieve this, previous studies on the subject were reviewed. Most previous research has focused on studying and analyzing various thermal climatic variables, as well as human thermal comfort and its key influencing factors. However, the impact of urban roughness on thermal comfort in outdoor environments has not been sufficiently addressed, especially at the local level. Recent studies have explored many aspects related to this research scope.

The study [12] assessed the impact of urban architecture on outdoor thermal comfort and applied the UTCI index in hot and arid climates. The UTCI index was calculated using the software "RayMan Pro 2.1" and applied to the urban fabric of the Red Village Palace, Alcantara in Biskra, Algeria, to determine the most efficient urban geometry for thermal comfort during the summer. The study found that thermal comfort parameters (MRT and UTCI) at various points are significantly influenced by city configuration. The sky view factor (SVF), the H/W ratio, and the sun’s direction all significantly impact thermal fluctuations in streets, primarily by influencing wind conditions, which help regulate air temperature and provide shade. MRT and UTCI values typically decrease on north-south streets and as building heights increase. Narrow and covered streets in the north-south and northwest-southeast directions provide the best shading, which is desirable in the summer for pedestrians, as it helps maintain human thermal balance and provide optimal comfort. Shading from sun exposure is a key goal for urban streets.

Another study [13] examined the effect of building height on the urban thermal environment in summer using a case study of large Chinese cities. It aimed to understand how building height affects land surface temperatures (LST) during summer. LST was measured using a single-channel (SC) algorithm, and the heating/cooling effect caused by building height differences was assessed through correlation analysis. The study concluded that building height contributes significantly to rising land surface temperatures in urban areas during the summer. The findings also showed that areas with taller buildings had significantly higher surface temperatures than areas with fewer tall buildings. The results revealed an inverse logarithmic relationship between building height and ground surface temperature, with correlation coefficients ranging from -0.701 to -0.853. As building heights increase from 0 to 66 meters, surface temperatures significantly decrease, suggesting that taller buildings have a cooling effect up to this point. However, once buildings exceed 66 meters in height, their impact on surface temperature diminishes.

In a related study [14], remote sensing data was used to examine the impact of building shadows (BSs) on urban land surface temperatures (LST) in Beijing during different seasons. Using digital image analysis and spatial statistics, researchers found that building shadows' effects on surface temperatures vary by season. Higher solar radiation in the summer increases surface temperature, especially in densely built areas. The study demonstrated that areas with high building density tend to trap heat, leading to warmer temperatures. Urban design and building distribution significantly influence surface temperatures, and these factors should be considered in urban planning strategies to enhance thermal comfort and environmental quality in cities.

In Iraq, another study [15] focused on how urban fabric types affect thermal comfort and microclimates within street canyons in hot, arid cities. The study compared traditional and modern urban fabrics, using CFD simulations to estimate airflow speed in the street canyon. The findings showed that traditional urban fabric accelerated airflow, improving comfort. Urban roughness is influenced by various factors such as height-to-width ratio, frontal area density, roughness length, zero-plane displacement, and building plan area fraction. Urban roughness and the thermal properties of urban surfaces are the most important factors influencing urban climate. The height-to-distance ratio (H/W) between buildings affects incoming and outgoing radiation and wind speed, influencing thermal conditions in urban areas.

Previous research on outdoor thermal comfort in urban climates has identified many key aspects. However, there remains a lack of understanding about the impact of urban roughness on thermal comfort in outdoor environments. This research seeks to address that gap, focusing on the relationship between urban roughness and the UTCI index. The study proposes that increasing urban roughness, as represented by building height, plays an important role in providing thermal comfort and improving external environments in response to climate change. The study examined samples using both experimental and analytical methods, employing Rino8 and Grasshopper software to calculate the UTCI and its impact on various climatic variables.

2. Materials and Methods

2.1 Study area

The study area in Baghdad specifically in the Al-Bab Al-Sharqi neighborhood within the Al-Bataween district. The study area is characterized by being a vital center in the city of Baghdad, which includes many major activities and is visited by people. It also includes buildings of various heights, densities, and urban spaces, which makes it a appropriate for testing the research problem (Figure 1). The area's urban fabric is made up of 8-meter-wide streets and buildings ranging in height from 1 to 4 floors. The orientation of the streets in relation to the vertical streets (northwest to south-east) and the transverse streets (northeast to southwest)

Observing the area's planning, we can see that the urban blocks are distributed elongated in the direction of the prevailing winds, acting as wind buffers, preventing the urban fabric from benefiting from the wind's effect in improving thermal comfort.

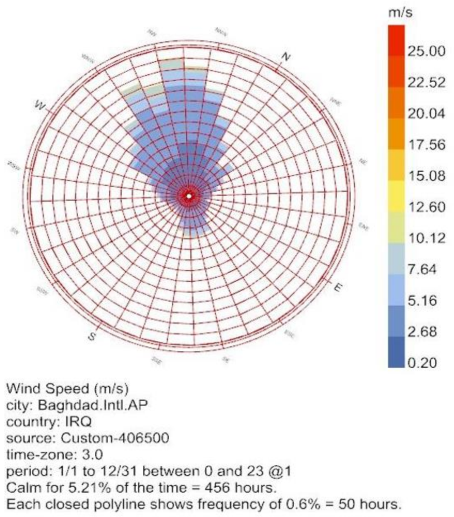

Figure 1. Climatic conditions for the study area (Rino8 and Grasshopper).

Figure 2 depicts the sun's movement and position relative to the site for months (7, 8, and 9), which are the hottest and most exposed to sunlight during the year (Simulated with Grasshopper program).

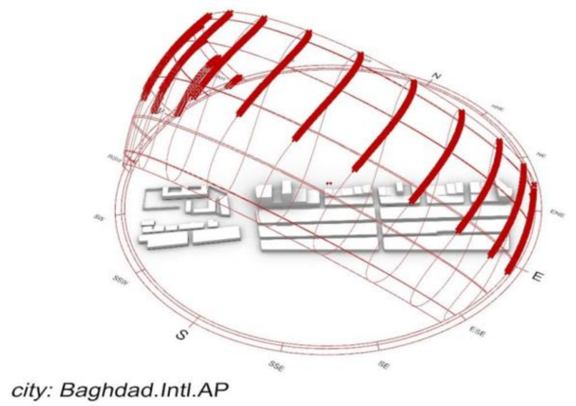

Figure 2. The sun's movement and position (Rino8 and Grasshopper).

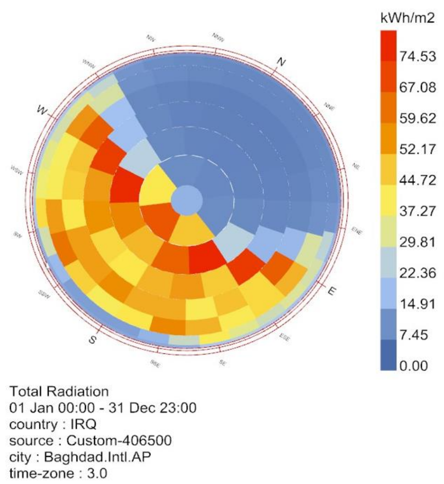

Figure 3. The solar radiation in the study area.

Figure 3 depicts the solar radiation to which the site is exposed throughout the year at a rate ranging from (0 - 74.53) KWh/m2. Figure 4 shows the subjective temperature of the study area ranges from 0 in winter session and 50 degrees Celsius in summer sessions.

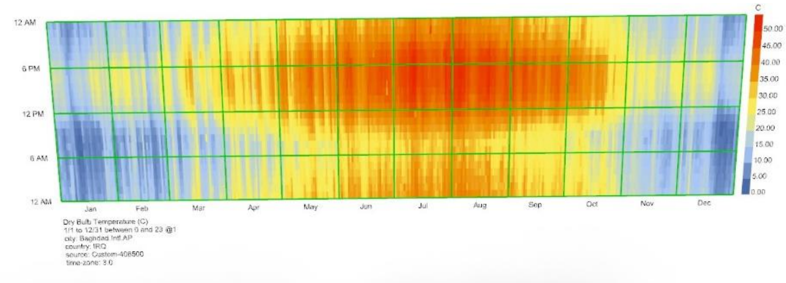

Figure 4. The subjective temperature of the study area ranges from 0 to 50 degrees Celsius(Rino8 and Grasshopper).

2.2 Measurement methods.

To investigate the urban fabric of the Al-Bataween area in Al-Bab Al-Sharqi, Baghdad, thermal comfort was measured using the UTCI index, and the results were obtained using the Rino8 & Grasshopper program, which calculated the effect of wind and the average thermal radiation factor (MRT) on perceived temperature in the urban space. Figure 5 depicts the study location and shape of the region's urban fabric.

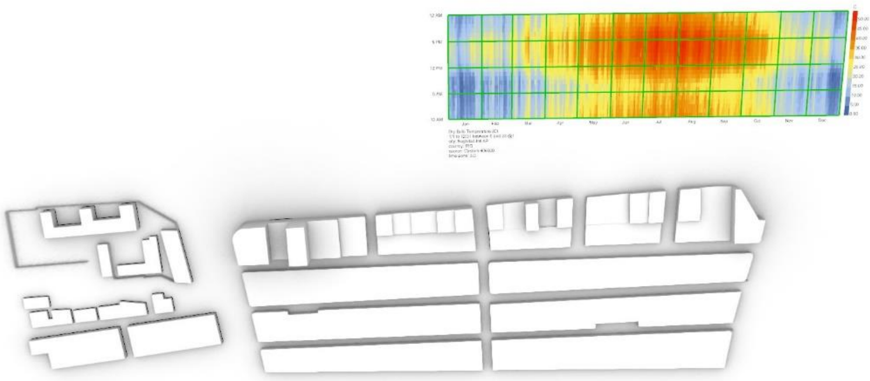

Figure 5. The sun's movement and position(Rino8 and Grasshopper).

3. Results and Discussion

The Figure 6A shows that the perceived temperature in urban spaces for humans varies throughout the year, ranging from (1.02 in winter session and 47.41 degrees Celsius in summer sessions). The results were obtained without taking into account the average radiation temperature or the effect of the wind, as this rate varies depending on the indicators listed above [13,14].

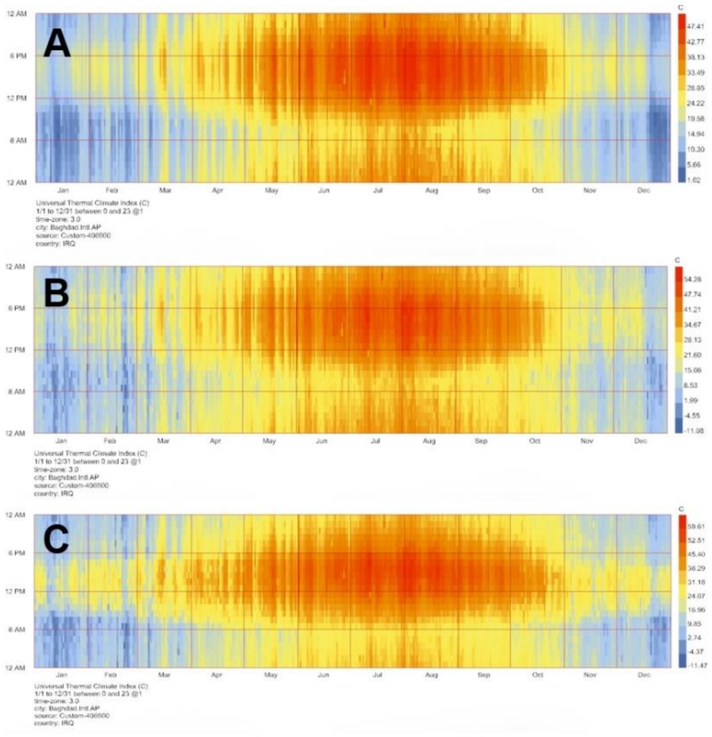

Figure 6. The UTCI factor in urban spaces (A), in urban space with wind effect (B), and in urban space with MRT effect (C) (Rino8 and Grasshopper).

When the effect of the wind was considered when calculating the UTCI factor shown in Figure 6B, it was discovered that the perceived temperature in the urban space ranged between (-11.08 in winter session and 54.28 in summer session) throughout the year, implying that the effect of the wind caused a 10-degree Celsius difference in felt temperatures [13, 14]. When the effect of the average radiation temperature and the effect of the wind were combined in calculating the UTCI factor, a perceptible temperature in the urban space was obtained ranging between (-11.47 in winter session and and 59.61 in summer session) throughout the year, implying that the effect of the wind and the MRT caused a change in the perceptible temperature by a difference of 5 degrees Celsius in the case of feeling the temperature increase, but its effect on the decrease was slight and hard (Figure 6C). The study found that areas with high urban roughness and an altitude of less than 60 m tend to have lower UTCI values, indicating higher levels of thermal comfort. These areas have increased shading at street level, which reduces the average amount of radiation reaching street level and increasing wind speed as a result of the disruption of wind pressure around tall buildings [13, 14].

4. Conclusion

The impact of wind on perceived temperatures, as measured by the UTCI index, shows significant variations of up to 10 degrees Celsius, but the current urban fabric limits its potential to enhance thermal comfort. Similarly, mean radiant temperature (MRT) influences temperatures by up to 5 degrees Celsius. Taller buildings can create cooler microclimates at street level by providing shade that lowers MRT, fostering "cool islands" and improving pedestrian comfort. Additionally, taller structures can generate cooler airflows, further enhancing thermal comfort through a combination of shading and improved air circulation. To maximize these benefits, strategies such as optimizing urban roughness to improve wind flow, promoting natural ventilation, using heat-reflective materials, strategic afforestation for shading, encouraging mixed land uses to increase building height and airflow, and incorporating shading and green infrastructure can help reduce heat stress, mitigate the urban heat island effect, and enhance outdoor thermal comfort for pedestrians.

Author Contribution

Zainab Abdul Kareem Abdul Lateef : writing, methodology, data analysis; Susan Abed Hassan: data collection, conceptualization, methodology.

Competing Interest

The authors declare no conflict of interest.

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