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The influence of height/width ratio on urban heat island in hot-arid climates

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Abstract

Urbanization has a substantial impact on the microclimate of cities. The urban form is composed of urban canyons that are defined by the building's height to street's width ratio (H/W ratio) and the orientation of their long-axis. These two descriptors are controlling the absorption and reflection of the solar and emission of the thermal radiation that influence the ambient air temperature to be significantly higher than the rural surroundings (Urban Heat Island effect). Thus, the goal of this study is to investigate the thermal performance of two urban canyons, deep traditional (H/W=2.2) and shallow modern canyons (H/W=0.42) in a hot and arid city of Riyadh, Saudi Arabia. The objective is to determine if the H/W ratio is an influential factor that contributes to the formation of the Urban Heat Island (UHI) phenomenon, which in turn causes an outdoor thermal discomfort in hot-arid climatic zones. Both canyons are oriented approximately NE- SW and bordered by residential buildings. A series of field measurements were conducted over 18 summer days, 13th–30th of July, 2013, to measure the ambient air temperatures inside the canyon and at the roof level and surface temperature of walls, roofs and streets. Results show that the intensity of the UHI increases with the decrease of H/W ratio. The ambient air temperature in the deep and the shallow canyons are warmer than those in the rural surroundings by 5% and 15%, respectively. The significant temperature increase in the shallow canyon is attributed to the high exposure of the canyon’s surfaces to the intense solar radiation.

Keywords: urban form; urban canyon; H/W ratio; urban heat island; hot-arid climate

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1. Introduction

Urban microclimate is influenced by the urban form and its surfaces. Cities are featured with more impervious surfaces and a high concentration of anthropogenic activities, leading to significant increases in the ambient air \((T_a)\) and surface temperatures \((T_s)\) to be higher than the rural surroundings. This is recognized as “Urban Heat Island” phenomenon (UHI) [1], whose magnitude depends primarily upon the size of the city and the local climatic characteristics [2]. It is observed to be at its highest levels in hot-arid regions that are characterized by extreme solar radiation and heat during the summers as well as low relative humidity, contributing to an outdoor thermal discomfort. The urban microclimate is established in the urban canopy layer (UCL), extending from the ground to the buildings’ height, due to its high level of heterogeneity [3], and each urban form establishes its own microclimate [4]. An urban form consists of urban canyons, defined as linear spaces enclosed by buildings on both sides. They are characterized by three main descriptors that have been proven to have a substantial impact on the microclimate: building’s height to the street’s width ratio \((H/W)\), the canyon’s axis orientation, and the Sky View Factor (SVF) [3]. The H/W ratio, or the aspect ratio, has been found to correlate significantly and directly with the UHI effect. With the orientation, it controls the amount of the direct and diffuse solar radiation to penetrate into the canyon.

In hot and arid regions, compact urban form—typically found in old parts of the city—represents a climate-sensitive approach that responds to the intensity of the local climate, contributing to the accomplishment of outdoor and indoor thermal comfort. However, modern urban forms in such climates have been developed based on urban planning regulations that have been imported from moderate and cold climates with no consideration to the extreme local climate. These regulations have led to the formation of dispersed urban forms that are characterized mainly by wide streets and low density of buildings in which the majority of the urban surfaces are vulnerable to the extreme incoming solar radiation and therefore causing outdoor and indoor thermal discomfort. In this regard, the impact of the urban canyon geometry, defined by the H/W ratio and orientation, on microclimate and the outdoor thermal comfort for pedestrians have been evaluated extensively. In a semi-arid city of Constantine, Algeria, seven urban canyons with H/W ratios that range from 1.0 to 6.7 were compared to assess their impact on \(T_s\) and ground \(T_r\) within urban streets [5]. They found that the \(T_s\) variations in the canyons could reach about 3-6 K compared to the surrounding rural environments. In Fez, Morocco, it was found that the compact urban form with very deep canyons has cooling effect during the daytime which enhances the thermal comfort for pedestrians; while the dispersed form creates an extremely uncomfortable environment [6]. In a desert city of EL-Oued, Algeria, it was concluded that the \(T_s\) variations between the compared urban canyons are larger compared to the \(T_s\) [7]. They reported that there is a significant correlation between the \(T_s\) and the street geometry. Additionally in Ghardaia, Algeria, it was stated that the duration of the sun exposure is a function of H/W ratio and orientation [8]. They found that a street in a shallow canyon (H/W ratio = 0.5) is irradiated longer than a street in a relatively deep canyon (H/W = 1.0) by almost 3 hours. Hence, as the H/W ratio increases, the access of the direct solar radiation to the ground surfaces decreases. Finally in Damascus, Syria, it was found that the influence of H/W ratio and orientation on the ground \(T_r\) is insignificant when the street is aligned with detached buildings; however, their influence is extremely substantial when the canyon is bordered with attached buildings.

Similar to the previous cases, modern urban form in Saudi Arabia have the same impact on the microclimate, yet there is a lack of investigation. It has been reported that the adoption of modern urban regulations in Saudi Arabia has led to an undesirable microclimate around buildings [9,10]. Hence, the goal of this study is to investigate how the traditional and modern urban geometries perform in terms of thermal quality in the city of Riyadh, Saudi Arabia. The objective is to determine if the H/W ratio is an influential factor that contributes to the formation of the UHI phenomenon, which in turn causes outdoor and indoor thermal discomfort in hot-arid regions.

2. Description of the study areas

The investigation was conducted in the city of Riyadh, Saudi Arabia (24.65° N; 46.71° E). Riyadh is situated in a desert region on a large plateau, in the heartland of the Arabian Peninsula (Fig. 1). Its climate is characterized as hot and arid with extremely high solar radiation intensities during the summer, an annual average precipitation rate of around four inches (10cm), and an annual average relative humidity of around 24%. The highest recorded
temperatures are in July and August with an average maximum temperature of 45°C. All these factors contribute to the climatic severity of the city.

Two urban configurations were selected to evaluate the effect of the geometry of urban canyons on the microclimate. One urban form represents a traditional layout with narrow streets and attached houses that vary in height, one to three stories, and zero setbacks from streets (Fig. 2a). The other configuration represents a modern urban layout that is characterized by wide streets and detached two-story residential units with setbacks from streets (around one-fifth of the street’s width) (Fig. 2b). In each urban form, one typical urban canyon was chosen as a sample for investigation. The selection criterion of these canyons depended primarily on three factors: the aspect ratio (H/W ratio), the orientation, and the used materials. The traditional urban canyon has an H/W ratio of 2.2, and it is henceforth called a “deep” canyon. The modern urban canyon is called a “shallow” canyon with an H/W of 0.42. The long-axis of both canyons are oriented approximately NE-SW and bordered by residential buildings. The materials in both canyons are uniform for vertical and horizontal surfaces. Streets and roofs are covered with asphalt and white coloured ceramic tiles, respectively. The walls are made of concrete blocks covered with cement mortar and painted with similar light coloured finishing.

3. Methodology

To evaluate the effect of the aspect ratio (H/W ratio) on the microclimate, a series of measurements were carried out over 18 days, spanning from July 13th through July 30th, 2013, for each canyon. The main climatic parameters that were measured are the ambient $T_a$ at the roof and inside the canyon and $T_s$ of roofs, walls, and streets. These measurements were divided into continuous and instantaneous. The continuous measurements were performed to record the ambient $T_a$ in both canyons at two different levels: inside the canyon and at the roof. The instrument types and positions are shown in details in figure 3. All sensors were configured to save data at one hour intervals and were protected from the direct solar radiation by white painted perforated wooden shield to avoid solar absorption and allow for natural ventilation. At the same time, instantaneous measurements were performed to measure the ground $T_s$, at the center of the street. They were taken on 11 days at three different times: 7:00, 14:00, & 18:00 LST.
4. Results and discussion

In practice, field measurements could involve errors that lead to having some missing data over the time of the experiment. Therefore, the analysis covered the period from the 13th to the 16th of July.

4.1. Air temperature ($T_a$)

The quantity of the solar radiation that is received by the canyon surfaces during the daytime influences the ambient $T_a$ substantially. The magnitude of the impact of these surfaces depends on the thermal properties of their materials, such as the absorbance, reflectance (albedo), emittance, and transmittance. Urban surfaces tend to pass the majority of their energy into the atmosphere as sensible heat flux.

4.1.1. Inside the canyon ($T_{a-canyon}$)

The hourly variations in the ambient $T_{a-canyon}$ inside the two canyons are shown on figure 4. During the daytime, the $T_{a-canyon}$ in both canyons, is significantly higher than in the rural surroundings. The average differences in the maximum daytime temperature are around 6.6 K and 2.3 K in the shallow and deep canyon, respectively. The high exposure of the shallow canyon's surfaces contributes greatly to the increase in the ambient $T_{a-canyon}$. Between the two canyons, the deep canyon is cooler than the shallow one with an average variation in the maximum daytime $T_{a-canyon}$ of 4.3 K. The maximum $T_{a-canyon}$ in both canyons are observed to occur in the times between noon and 13:00 LST, where the intensity of solar radiation is at its peak. These temperature differences are attributed to the compactness of the old canyon in which the walls prevent the direct solar radiation to penetrate deeply inside it, which makes the canyon’s surfaces to be completely shaded, except at noon.

During the night-time, the differences between the two canyons are low and stable; however, they vary significantly to the meteorological data measured in the rural areas. The average variation in minimum night-time $T_{a-canyon}$ is about 6.4 K. The average minimum $T_a$ in the rural area is 29°C, compared to 35.4°C and 35.8°C in the deep and shallow canyons, respectively. Johansson, E. [6] found that the deep canyon is warmer during the night than the shallow one. This tends to be because the wind enters the wide street and thus helps remove the heat quickly up into the atmosphere, convection process. Hence, deep canyons experience stronger nocturnal heat islands and, conversely, more prominent daytime cool islands when compared to shallow canyons. It seems that the nocturnal heat island is observed significantly in the very deep canyon, which is not the case in this study (H/W=2.2).

4.1.2. At the roof level ($T_{a-roof}$)

The hourly variations in the ambient $T_{a-roof}$ in both canyons are shown in figure 4. The $T_{a-roof}$ is influenced by the surroundings surface and their materials’ thermal properties. During the daytime, the $T_{a-roof}$ in the deep canyon is slightly higher than in the shallow one. The average variation in the maximum $T_{a-roof}$ is around 2.8 K, reaching up to a maximum difference of 3.2 K in the 15th. These differences tend to be attributed to the variations in heights of the surrounding buildings in the deep canyon. The surrounding surfaces contribute to the increase of the $T_{a-roof}$ by reflecting and diffusing some of the received direct solar radiation toward the roof surface. Thus, more sensible heat is added to the air near the surface. It was reported that in dense urban areas located in hot-arid regions, the radiation exchange will occur at the roof surfaces, and negative overall radiation balance is accomplished at the roof surfaces if their reflective capacity is high [11]. In the shallow canyon, the height of the buildings, around the measurement instrument, is identical with almost no diffused radiation from the surroundings. During the nighttime, the average variation in the minimum $T_{a-roof}$ between the two canyons is negligible, reaching a value of 0.5 K. Compared to the meteorological data, both canyons vary substantially with an average variation in the maximum daytime temperature of around 9.8 K and 7.0 K in the deep and shallow canyons, respectively.

During the night-time, similar to the ambient $T_{a-canyon}$, the $T_{a-roof}$ variations between the two canyons are minimal. Nevertheless, they are significantly higher than the $T_a$ of the rural surroundings with an average variation in the minimum temperature of around 5.6 K in both canyons.
4.2 Surface temperature \( (T_s) \)

Generally, urban canyons are covered with more waterproofing materials, compared to rural areas. With the extreme direct solar radiation, the net radiation at these impermeable surfaces becomes tremendously high, making them significantly warmer than the ambient \( T_a \). Therefore, a greater percentage of the available energy at these surfaces is passed into the atmosphere as sensible heat, which plays a dominant role in the surface energy budget in hot-arid climatic conditions and leads to a significant increase in the ambient \( T_a \).

4.1.3. Walls temperatures \( (T_{s\text{-wall}}) \)

The hourly variations in \( T_{s\text{-wall}} \) of the south-eastern (SE) - and north-western (NW)-facing façades in both canyons are shown in figure 5. During the daytime, the results show that the average maximum \( T_{s\text{-wall}} \) of both façades in the deep canyon are identical. In contrast, the average maximum \( T_{s\text{-wall}} \) of the SE-facing wall in the shallow canyon is higher by 1.5 K, compared to the NW-facing façade. Additionally, it is noticed that the \( T_{s\text{-wall}} \) of both façades in the shallow canyon are higher than those in the deep canyon. The average variations in the maximum \( T_{s\text{-wall}} \) of the SE- and NW-facing walls between both canyons are around 4.5 K and 2.9 K, respectively. This is because the majority of vertical and horizontal surfaces inside shallow canyons are susceptible to extreme solar radiation and heat gains.

In comparison to the \( T_a\text{-canyon} \), it is observed that the average variations in the maximum \( T_{s\text{-wall}} \) of the SE-facing façade in both canyons are insignificant, reaching its peak around noon, between 11:00 – 13:00 LST. For the NW-facing façade, the average maximum \( T_{s\text{-wall}} \) is almost identical to the average maximum ambient \( T_a\text{-canyon} \) in the deep canyon; however, it is cooler in the shallow canyon by around 1.8 K. The NW-facing walls in both canyons reach their maximum temperatures before the sunset, between 15:00-17:00 LST. The extreme minimal variations in temperature between the ambient air and the vertical surfaces in the deep canyon are due to the narrowness of the canyon that obstructs the direct solar radiation from heating up the surface and thus reducing the sensible heat fluxes that could
have been added to the air.

During the night-time, the $T_{s\text{-wall}}$ variations between both walls in both canyons are negligible; nonetheless, they are slightly noticeable when compared to $T_{a\text{-canyon}}$. In the shallow canyon, the $T_{s\text{-wall}}$ of both walls is slightly higher than the ambient $T_{a\text{-canyon}}$ with an average variation in the minimum temperature of 1.3 K. In the deep canyon, the average minimum $T_{s\text{-wall}}$ of the NW-facing façade is lower than the ambient $T_{a\text{-canyon}}$ by around 1.0 K; while the differences between $T_{a\text{-canyon}}$ and the SE-facing façade’s $T_{s\text{-wall}}$ are insignificant.

4.2.2. Roof surface temperatures ($T_{s\text{-roof}}$)

In terms of horizontal surfaces, they are receiving more intense solar radiation during the daytime than the vertical surfaces, leading to a significant increase in their temperature. Horizontal surfaces’ temperatures are approximately 20°C higher than the highest temperature of vertical surfaces [12]. Figure 6 shows the hourly variations of the $T_{s\text{-roof}}$, compared to the ambient $T_{a\text{-roof}}$ in both canyons. The $T_{s\text{-roof}}$ in both canyons are substantially higher than $T_{a\text{-roof}}$ by an average variation in the maximum temperature of 11.1 K and 10.0 K in the deep and shallow canyons, respectively. The $T_{s\text{-roof}}$ in both canyons reaches its peak when the $T_{a\text{-roof}}$ is at its maximum, almost at noon.

Comparing the two canyons, the $T_{s\text{-roof}}$ in the old canyon is higher than in the shallow one, during the daytime, by an average variation in the maximum temperature of 4.0 K. This difference seems to be attributed to the variations in the surrounding buildings’ heights that could diffuse some of the radiation towards the roof surface and obstruct the wind flow that has the ability to eliminate some of the surface’s heat by convection.

During the night-time, the $T_{s\text{-roof}}$ in the shallow canyon is higher than in the deep one by an average difference in the minimum temperature of 2.0 K. In relation to the $T_{a\text{-roof}}$, the $T_{s\text{-roof}}$ in both canyons is lower with average variations in the minimum temperature of 4.6 K in the deep canyon and 3.1 K in the shallow canyon.

4.1.4. Street surface temperatures ($T_{s\text{-ground}}$)

Similar to roofs, streets inside the canyon are more irradiated than the vertical surfaces. While the orientation of the canyon is critical factor in determining the exposure of walls to the sunlight, the canyon’s depth (H/W ratio) is a decisive factor for the exposure of the street surface [8]. However, in shallow canyons, both factors play significant role in this regard. Figure 7 shows the $T_{s\text{-ground}}$ in comparison to the $T_{a\text{-canyon}}$ in both canyons for two days, the 13th and 15th. It is found that the highest $T_{s\text{-ground}}$ is in the shallow canyon with maximum variations between the two canyons of 11.5 K on the 13th and 6.2 K on the 15th. The average maximum $T_{s\text{-ground}}$ in the shallow and deep canyons are 62.0°C and 53.1°C, respectively. These variations are attributed to the high exposure of the shallow canyon’s surfaces to the direct solar radiation. Bourbia & Awbi [7] It was observed that in a deep canyon (H/W=1.5), almost 35% of the street width receives direct solar radiation; whereas around 65% of the street width in a shallow canyon (H/W=0.5) is exposed to direct sunlight at a rate of 846 W/m². This indicates that the street in the deep canyon receives and absorbs less quantities of solar radiation than the street in the shallow one, and eventually has lower $T_s$ and $T_a$. Nonetheless, the ground surface in the deep canyon is slightly cooler than in the shallow one in the early morning, at 7:00 LST, by an average of 0.8 K.
Compared to the ambient $T_{a,canyon}$, the $T_{s,ground}$ is higher by an average variation in the maximum temperature of 12.9 K and 7.3 K in the shallow and deep canyons, respectively. In terms of $T_{s,wall}$, the largest variations in the maximum temperature are observed between the $T_{s,wall}$ of the NW-facing façades and $T_{s,ground}$ in both canyons. The $T_{s,ground}$ is higher by an average in the maximum temperature of 15.4 K and 11.1 K in the shallow and deep canyons, respectively. Furthermore, it was found that the SE-facing façades in both canyons are also substantially cooler than the ground surface with an average variation in the maximum temperature of 13.7 K in the shallow and 8.2 K in the deep canyon. Therefore, it could be implied that the extreme $T_{s,ground}$ and $T_{s,wall}$ inside the urban canyon would affect the ambient $T_{a,canyon}$ by adding a tremendous amount of sensible heat flux to the lower atmosphere.

5. Conclusion

The study was carried out in the hot and arid city of Riyadh, Saudi Arabia. It evaluates the thermal performance of traditional and modern residential urban canyons with H/W ratios of 2.2 (Deep) and 0.42 (Shallow), respectively. The study shows that the exposure of the urban surfaces to the solar radiation is a function of the H/W ratio and orientation of the canyon. They play a dominant role in determining the quantity of the received incoming solar radiation by the canyon’s horizontal and vertical surfaces, and thus affecting the ambient $T_a$ and $T_s$ inside the canyon. These temperatures increase with the decrease of H/W ratio, and vice versa. The exposure of urban surfaces to the sun in an urban profile decreases as the profile becomes deep [13]. The more solar radiation is received by the surface, the larger the net radiation is left at the surface and the greater sensible heat is added into the ambient air, leading to a significant increase in its temperature.

In this regard, the ambient $T_{a,canyon}$ and $T_{a,roof}$ in both canyons was substantially higher than those in the rural surroundings throughout the day. During the daytime, the shallow canyon is warmer than the rural areas by around 15%, while the deep one is warmer by approximately 5%. The increase of the $T_{a,roof}$ in the deep canyon represents around 22% to the temperature in the rural areas, whereas it is about 16% in the shallow canyon. Between the two canyons, it was observed that the shallow canyon experiences higher ambient $T_{a,canyon}$ and $T_s$ during the daytime when compared to the deep one. However, the deep canyon was found to have higher $T_{a,roofs}$ which is believed to be attributed to the different height of the surrounding buildings. Thus, mutual reflection and absorption occur between the adjacent buildings’ vertical surfaces and the roof, which leads to increase the $T_{s,roof}$ and, consequently, increase the $T_{a,roof}$. Although the average variations in the minimum $T_{a,canyon}$ and $T_{a,roof}$ between the two canyons are negligible during the night-time, they are significantly higher than the $T_a$ in the rural surroundings by an average increase in both canyons of about 23% and 20%, respectively. Even though it was reported that deeps canyon experience strong cool islands during the daytime and nocturnal heat island, for instance in [6], the results of this study show that the average variations in the minimum $T_{a,canyon}$ were negligible. Hence, it is apparent that the nocturnal heat island is observed in extremely deep canyons (high H/W ratio).

In terms of $T_s$, it was observed that the average variations in the maximum $T_{s,wall}$ of the SE-facing wall in the deep canyon are minimal, compared to the NW-facing façade. Furthermore, the average variations in the maximum $T_{s,wall}$ of both walls are also insignificant, compared to the $T_{a,canyon}$. In the shallow canyon, the NW-facing façade is cooler than the $T_{a,canyon}$ by an average decrease in the maximum temperature of around 4%; while the $T_{s,wall}$ of the SE-facing
wall is identical to the $T_{a-canyon}$. Between the two canyons, it was notice that the SE- and NW-facing walls in the shallow canyon are warmer by an average of 10% and 6%, respectively, compared to the same façades in the deep one. During the night-time, both walls in the shallow canyon are warmer than the $T_{a-canyon}$ by an average increase in the minimum temperature of 4%. In the deep canyon, there were no variations in the average minimum temperature between the $T_{s-wall}$ of the SE-facing wall and the $T_{a-canyon}$; however, the NW-facing wall’s $T_{s-wall}$ is slightly lower than the $T_{a-canyon}$ by around 3%, on average. With regard to the $T_{s-roof}$, it was found that $T_{s-roof}$ in both canyons during the daytime are significantly higher than the $T_{a-roof}$ by an average increase in the maximum temperature of 20% in the deep canyon and 19% in the shallow one. Additionally, the $T_{s-roof}$ in the deep canyon was found to be higher by an average increase of 7%, compared to the $T_{s-roof}$ of the shallow canyon. Nonetheless, the shallow canyon’s $T_{s-roof}$ was observed to be higher than the $T_{s-roof}$ in the deep one during the night-time by an average of 6%. Furthermore during the night-time, the roof surfaces in both canyons were cooler than the $T_{a-roof}$ by 13% and 9% in the deep and shallow canyons, respectively. Finally, it was observed that the $T_{s-ground}$ in the shallow canyon is higher than in the deep one by an average of 17%. Compared to the $T_{a-canyon}$, the $T_{s-ground}$ is substantially higher by an average difference in the maximum temperature of 26% and 16% in the shallow and deep canyons, respectively.

Thus, compact urban form presents an influential strategy in hot and arid regions to alleviate the impact of the UHI that has a substantial negative impact on the outdoor thermal comfort. Modern urban planning regulations in these regions have to be modified in order to achieve outdoor and indoor thermal comfort.

6. Limitations and further studies

The study is limited to field observations with specific climatic parameters. The use of simulation model is needed to evaluate the energy balance at the urban surfaces with different thermal properties to determine what fluxes contribute mostly to the net radiation. The further investigation should assess the incoming shortwave solar and outgoing long wave radiation, sensible heat, latent heat, and soil fluxes. Furthermore, using a simulation model allows evaluating the vertical and horizontal temperature gradients inside the urban canyon to identify the variations in the ambient air temperature at different heights and distances from the urban surfaces.

7. Reference