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EFFECTS OF SUNLIGHT AND SHADOW ON THE SURFACES OF PIGEON TOWERS IN CENTRAL ASIA: CASE STUDIES IN IRAN, QATAR, EGYPT AND SAUDI ARABIA

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Abstract. In many parts of the world, especially Central Asia, pigeon towers have been constructed as traditional buildings with different forms and types to keep pigeons. These buildings are cylindrical, cubic, dome-like and multi-cylinder in shape. This study was conducted to identify the effects of sunlight and shadow on the surfaces of pigeon towers in Iran, Qatar, Egypt, and Saudi Arabia with hot and dry or humid climates. Several pigeon towers with different types and structures in these countries were selected and modeled in detail in Rhino 5. Radiance and Ecotect were then employed to measure solar radiation and shadow on the surfaces of the pigeon towers on the hottest day of the year. According to the graphical and numerical results obtained, sunlight and shadow differently affected the surfaces of the different pigeon towers. The effect level of sunlight and shadow on the single-form pigeon towers was higher than on the vaults. In fact, solar radiation was lower and shadow was higher per square meter of the surfaces of the vaults constructed as pigeon towers in close proximity. These houses were therefore found to be the optimal type for the hot and dry or humid climate in Central Asia.

Keywords: pigeon tower, solar radiation, Radiance, Ecotect, shadow, Central Asia.

Introduction

Ongoing research on thermal energy in old buildings aims at analyzing radiation and shadow on historical buildings, especially domes of mosques, reservoirs and markets (Sedighi et al., 2017; Shiri et al., 2021). In recent decades, a growing number of articles have been devoted to solar radiation on the outer surfaces of buildings in a way that outers surfaces and forms increase thermal comfort in spaces.

Certain strategies are commonly adopted to control the effect of sunlight on the surfaces of buildings based on the shape of their outer surfaces (Mohajeri et al., 2016).

A study examined the use of renewable energy sources and determined the effects of sunlight on the surfaces of buildings from physical, geographical, technical and socioeconomic perspectives. Global solar radiation on the selected buildings was also obtained by performing a solar radiation analysis (Montavon et al., 2004; Compagnon, 2004). Today, a large body of literature is assigned to building surfaces using solar radiation measurement tools such as ArcGIS, Radiance, Ecotect, Lidar (Hachem et al., 2011; Urbanetz et al., 2011; Liu, 2014). The photovoltaic potential of Apeldoorn, (the Netherlands) was estimated at high resolution and feasible areas for photovoltaic installations and their power output were calculated (Kausika et al., 2015). Several studies also analyzed the potential of the outer surfaces of buildings for receiving sunlight (Košir et al., 2014). Moreover, numerous studies investigated the effects of sunlight on the outer curved surfaces of traditional buildings, including the domes of water reservoirs, mosques and bazaars. The effect of solar radiation on these surfaces was simulated in Radiance in dry and hot or cold climates (Shiri et al., 2019b; Shiri & Momeni, 2020; Shiri et al., 2019a). Building orientation, solar radiation, shading and natural ventilation were included in the study of thermal comfort in buildings by performing a weather data analysis in Ecotect (Haase & Amato, 2009; Petersen & Svendsen, 2010; Newell et al., 2012).

As the epitome of traditional architecture in Iran and Central Asia, pigeon towers were mainly built with curved

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and dome-like surfaces to meet the needs of locals in the hot and dry climate of these regions (Olgyay & Hainline, 2003). This functional concept is used in traditional architecture to create diverse structural forms of pigeon towers (Pratt, 1954; Ishraqi, 2000). Pigeon towers have been built with different structures and forms to keep pigeons in many parts of the world, including Central Asia. Indigenous materials were used in pigeon towers to meet the requirements of hot and dry or humid climates (Rafiei, 1974; Damirchi, 2004; Mirdanesh, 2007; Bourgeois & Pelos, 1983). Pigeon towers in Iran were divided into eight groups by their physical structure (Amirkhani et al., 2010). Five out of these eight forms still exist.

With a major effect on the surfaces of buildings, solar radiation should be considered in the design of buildings. The forms of pigeon towers were analyzed by regional conditions and climate. Given the hot and dry or humid climate of Central Asia, investigating solar radiation and shadow on the surfaces of pigeon towers is crucial.

The forms of these pigeon towers can be based to develop the roofs of houses and buildings in this area and therefore design houses that suit the local climate. Thermal simulations can be also performed to analyze the absorption of radiation and creation of shadow on the surfaces of pigeon towers.

Research questions

To answer the following questions, the present study examined several types of pigeon tower in Iran, Qatar, Egypt and Saudi Arabia with distinct forms, including single-cylinder, multi-cylinder and single-cube.

1. What role did the shape of pigeon towers play in absorbing sunlight and casting shadow?
2. What were the differences between the single-cylinder and multi-cylinder pigeon towers in terms of receiving sunlight and casting shadow?

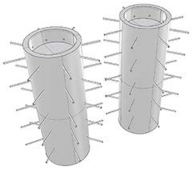
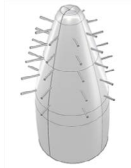
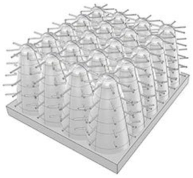
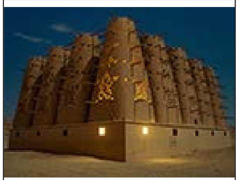
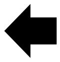
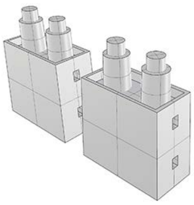
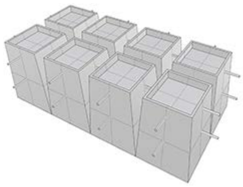
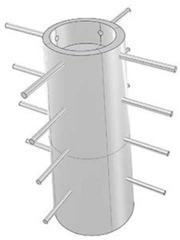
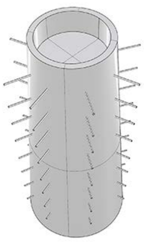
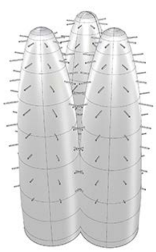
1. General discussion on pigeon towers

The effect of sunlight on the surfaces of traditional buildings depends on parameters such as the form and height of the building. Buildings with more surfaces exposed to sunlight absorb more heat. The shape and height of buildings thus play a key role in the amount of heat and shadow they receive (Shiri et al., 2019b). Unfired clay brick and glazed brick constitute the main materials used with utmost delicacy and creativity in building pigeon towers. Wooden beams have been also used in the structure of pigeon towers to increase their lateral and axial strengths (Bourgeois & Pelos, 1983; Amirkhani et al., 2010; Mattewes, 1951). Pigeon towers in Central Asia have square, rectangular, circular or multiple plans. Pigeon nests are built inside the towers that lie on ground surface in Central Asia and lie underground in Central Anatolia, Turkey (Altina, 2001; Özen, 2012). This study recruited real-world examples of pigeon towers with different shapes and structures in the hot and dry or humid climate of Central Asia. The structures examined included single-cylinder, multi-cylinder and single-cube towers in Isfahan (32°39'N, 51°43'E, h 1577m), Iran, and the Siwa Oasis (29°62'N, 25°54'E, h -14m), Egypt, as well as single-cylinder and tower of multi-cylinder in Doha (25°46'N, 51°53'E, h 104m), Qatar, and Riyadh (24°82'N, 46°65'E, h 741m), Saudi Arabia. Figure 1 shows the locations of the selected pigeon towers on a map of Central Asia.

An accurately-scaled model of all the pigeon towers was developed as a surface in Rhino 5. The three-dimensional images, models and locations of the selected pigeon towers presented in Table 1 were used to simulate the effects of sunlight and shadow cast on the surfaces of all types of the pigeon towers.

Figure 1. Locations of pigeon towers in Central Asia on Google map (source: www.google.com/maps)

Table 1. Specifications of the pigeon towers in Central Asia used in their simulations (Zarghami et al., 2010; Google, n.d.-a, n.d.-b, n.d.-c)

Orientation to the north	Location	Model	Actual picture of pigeon tower	Name	Location	Model	Actual picture of pigeon tower	Name	Orientation to the north
	Doha, Qatar			Qatar cylinder Tower	Siwa, Egypt			Egypt cylinder Tower	
	Riyadh, Saudi			Multi-cylinder tower of Saudi	Siwa, Egypt			Multi-cylinder tower of Egypt	
	Isfahan, Iran			Iran Cube Tower	Siwa, Egypt			Multi-cube tower of Egypt	
	Riyadh, Saudi			Saudi cylinder tower	Isfahan, Iran			Iran cylinder Tower	
	Doha, Qatar			Multi-cylinder tower of Qatar	Isfahan, Iran			Multi-cylinder tower of Iran	

2. Methodology

2.1. Materials and methods

Pigeon towers in these regions show a harmony between human needs and a nature-based approach to architecture. The present findings can be used to construct buildings and pigeon towers of proper forms in terms of receiving sunlight and shadow and also develop cultural buildings in Central Asian cities with hot and dry or humid climates.

This study aimed at determining the amounts of sunlight and shadow on the dome shell of pigeon towers and heat absorption in each dome.

A method was required for accurately simulating solar radiation on the outer surfaces of the buildings. Data such as time, place and climatic conditions of the region were also necessary, and effects of shadow on these surfaces were to be analyzed. Radiance, Daysim, ArcGIS and Ecotect are powerful tools for evaluating sunlight and shadow on building surfaces (Brito et al., 2012; Freitas et al., 2015; Andersson et al., 1985; He et al., 2021b; Aldhshan et al., 2021; He et al., 2021a). On the other hand, highly-accurate analyses of solar radiation can be performed at small scales in Radiance using the Perez diffuse irradiance model (Perez et al., 1987, 1990). Surfaces are modeled in this software with high diffuse reflections. Radiance functions based on a visual algorithm written in the Grasshopper environment for the analysis of solar radiation. The results of analyzing solar radiation on three-dimensional models are presented with a high accuracy in this software, which is even recommended for the analysis of complex curved geometries (Ward, 1994). Ecotect can be used to analyze the effects of shadow, orientation and natural ventilation on building surfaces in different climates (Yang et al., 2014; Bekkouche et al., 2011). These software packages have been frequently validated been applied in many programs to evaluate the effect of solar radiation on the roofs and facades of buildings and use daylight and electricity generation. Rhinoceros5 software requires that a visual algorithm be written in the grasshopper environment using Honeybee and Ladybug tools. Solar radiation is therefore analyzed by adding the standard EnergyPlus weather file to Ladybug in the Grasshopper environment. After performing the initial step-by-step Ladybug setting, the result of analysis is graphically illustrated in Rhino 5. The four credible simulation engines integrated into this software to evaluate building energy consumption, thermal comfort and daylight include EnergyPlus, Radiance, Daysim and OpenStudio (Roudsari & Pak, 2013). The present study proposed the use of Rhino 5 (http://www.rhino5d.com/) and Grasshopper (http://www.grasshopper3d.com/) with built-in Honeybee and Ladybug (http://www.grasshopper3d.com/group/ladybug) plugins Radiance (http://radsite.lbl.gov/radiance/) and Ecotect (https://autodesk-ecotect-analysis) were therefore employed to simulate solar radiation and shadow. The present findings were also validated using Ecotect as a reliable shadow analysis tool. The samples were modeled in Rhino 5 based on their exact dimensions, orientation and body details. The areas of the outer surfaces of the individual pigeon towers were obtained in the Grasshopper plugin using Area as an algorithm. Table 2 presents the associated data, suggesting the lower surface area of the single-cylinder tower than that of the multi-cylinder towers.

2.2. Methods

Each model was placed at the zero-ground level. The algorithm of simulating solar radiation on the individual pigeon towers was written after adjusting Ladybug and Honeybee. After assigning the corresponding climatic conditions (EPW) (https://energyplus.net/weather) to the individual models in Rhino 5, solar radiation on the surfaces of the pigeon towers was simulated in Radiance. Ladybug and Honeybee were used to perform the analyses on the hottest day of the year at 13:00 and 16:00. These analyses were then conducted in Ecotect to determine the amount of shadow cast on the surfaces of the pigeon towers. Figure 2 Stepwise analysis of solar radiation and shadow on the surfaces of Central Asian pigeon towers.

To obtain solar radiation on the surface of each pigeon tower (E_{RT}), the outer surface of each pigeon tower was obtained using the grasshopper plugin as per Equation (1). Solar radiation on a legend (R_L) in kWh/m^2 was multiplied by the receiving area of the legend of the corresponding pigeon tower (S_L). These analyses were performed using ten-part legends.

Legend refers to any color receiving solar radiation in kWh/m^2. Each analysis involves 10 legends, as shown next to the analysis. A specific kWh/m^2 is assigned to each legend or color.

$$E_{RT} = (R_L \cdot S_L)_1 + (R_L \cdot S_L)_2 + (R_L \cdot S_L)_3 + (R_L \cdot S_L)_4 + \ldots (R_L \cdot S_L)_{10}. \quad (1)$$

The surface of the pigeon towers exposed to sunlight was then determined as the percentage of the total outer

Table 2. Area of the outer surfaces of pigeon towers in Central Asia

Cylinder towers in Qatar	Multi-cylinder towers in Qatar	Cylinder towers in Saudi Arabia	Multi-cylinder towers in Saudi Arabia	Cube Towers in Iran	Iran cylinder Tower	Multi-cylinder towers in Iran	Cylinder towers in Egypt	Multi-cylinder towers in Egypt	Multi-cube towers in Egypt	Pigeon tower characteristics
236 m^2	510 m^2	109 m^2	2257 m^2	287 m^2	165 m^2	670 m^2	66 m^2	264 m^2	1065 m^2	Surface area

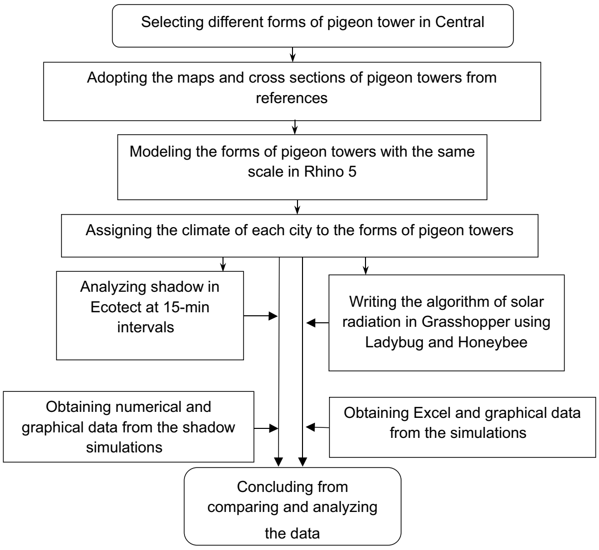


Figure 2. Analytical diagram of solar radiation and shadow on the surfaces of pigeon towers in Central Asia

surface of the tower (X_{Pr}) as per Equation (2). Sum of the solar radiation associated the individual legends was multiplied by 100 and divided by the total surface of the pigeon tower (S_{LT}).

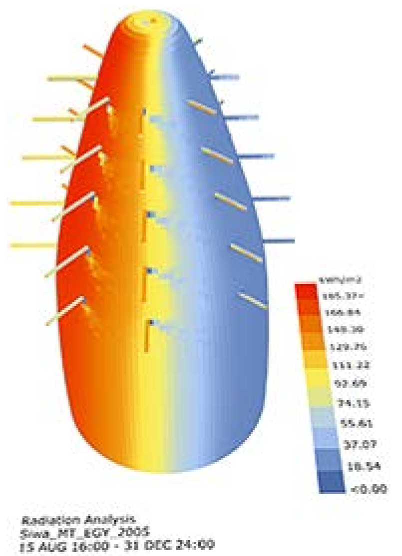
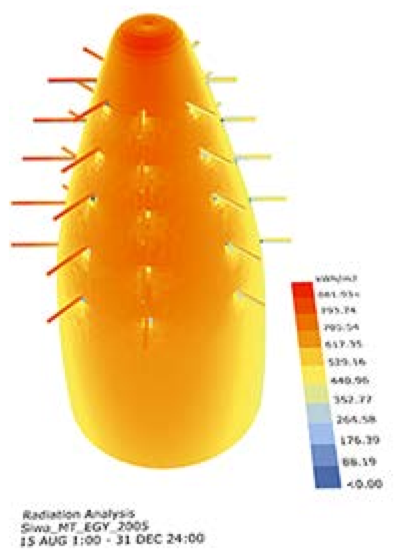
$$X_{pr} = \frac{E_{R1} \cdot 100}{S_{LT}} + \frac{E_{R2} \cdot 100}{S_{LT}} + \frac{E_{R3} \cdot 100}{S_{LT}} + \ldots \frac{E_{R10} \cdot 100}{S_{LT}}. \quad (2)$$

3. Results and discussion

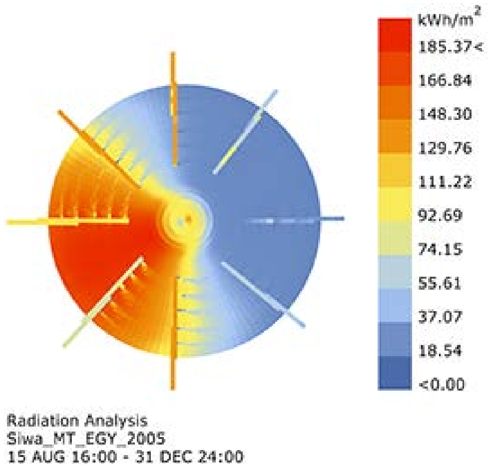
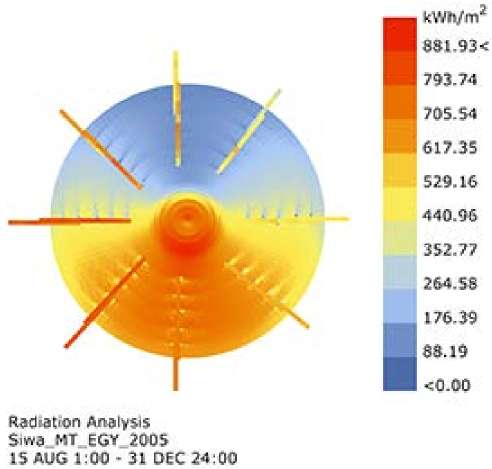
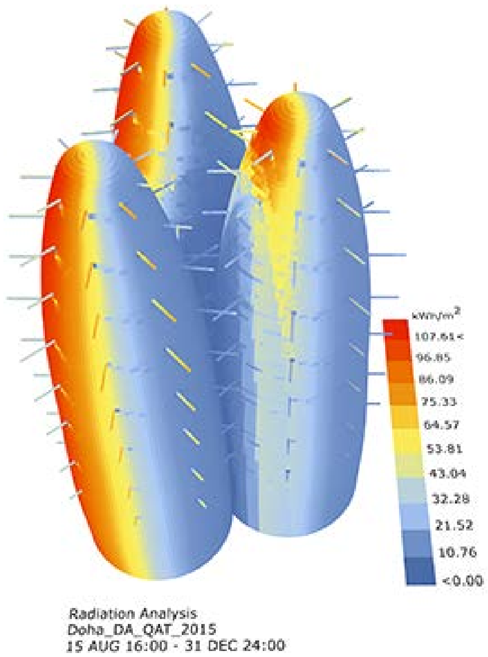
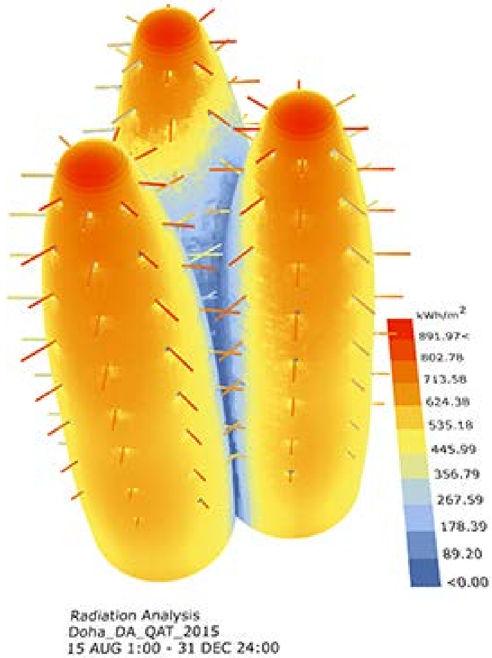
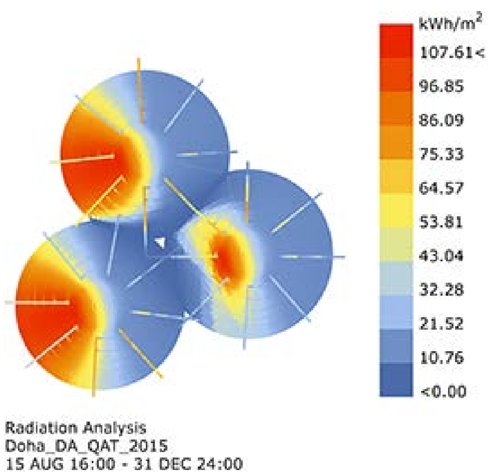
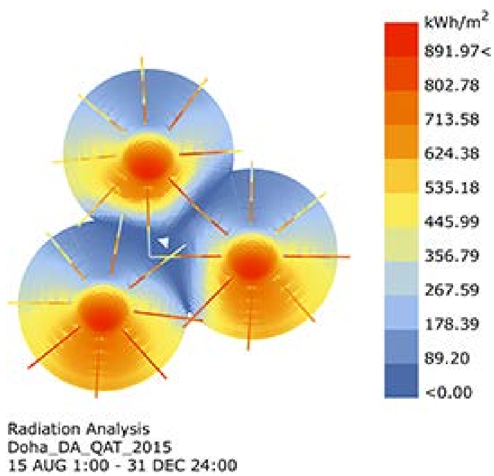
3.1. Graphical simulation results

Solar radiation on the surfaces of different types of pigeon towers in Central Asia was simulated on the hottest day of the year at 13 and 16. Table 3 presents the top view and three-dimensional representation of the pigeon towers of different shapes. The solar energy density in kWh/m^2 received by the upper surfaces of the pigeon towers was maximized at 13 given the perpendicular solar rays to these surfaces, while the lower surfaces received lower levels of solar energy. The oblique direction of solar rays at 16 decreased the intensity of sunlight compared to that at 13; nevertheless, the surfaces of the body of the pigeon towers received the maximum heat legend given the almost perpendicular solar rays to these surfaces. The analyses suggested the heat legend of the surfaces of single-form pigeon towers was maximized when exposed to sunlight and that low-heat legends were observed at the back of these pigeon towers. In addition, low-heat legends were observed on the surfaces of adjacent pigeon towers with identical forms and exposed to sunlight, as these forms lying in the vicinity of one another block the sunlight.

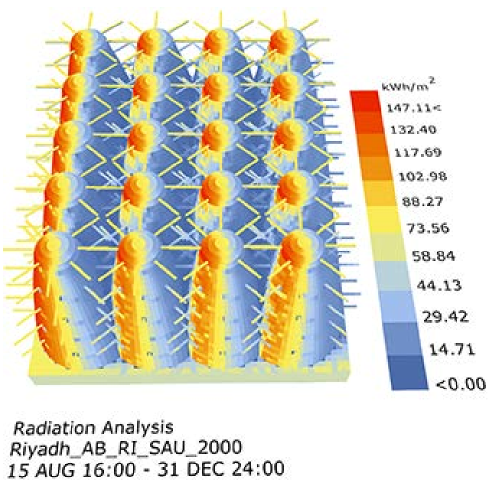
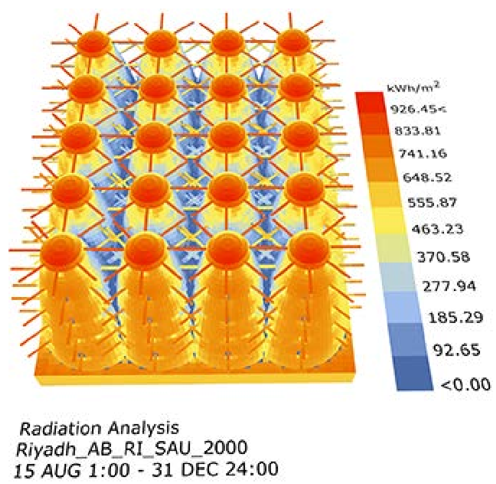
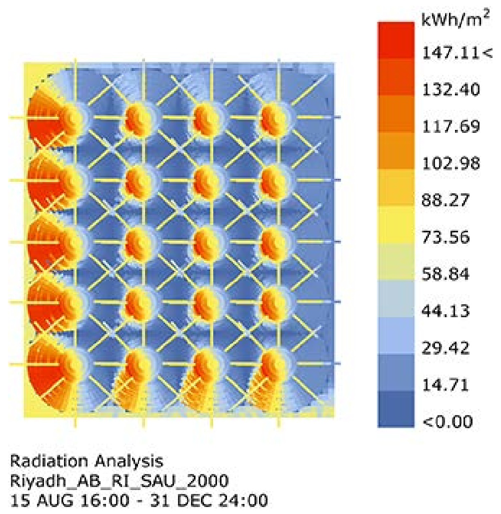
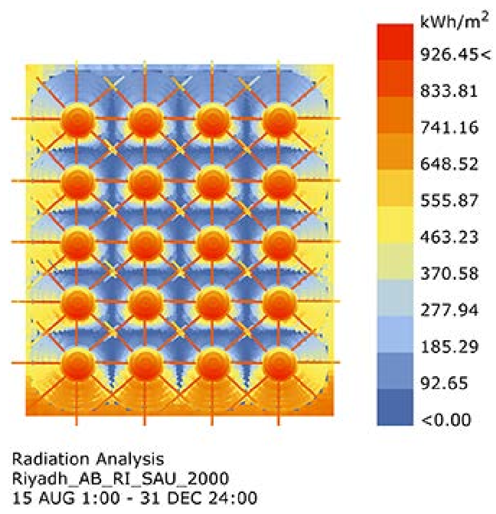
Table 3. Simulation of solar radiation on the surfaces of different types of pigeon towers

Sample	Radiation at 16:00	Radiation at 13:00
Egypt cylinder tower 3D view		

Continue of Table 3

<table>
<tr><th>Sample</th><th>Radiation at 16:00</th><th>Radiation at 13:00</th></tr>
<tr><td>Egypt cylinder tower top view</td><td>
</td><td>
</td></tr>
<tr><td>Multi-cylinder tower in Qatar 3D view</td><td>
</td><td>
</td></tr>
<tr><td>Multi-cylinder tower in Qatar top view</td><td>
</td><td>
</td></tr>
</table>

End of Table 3

Sample	Radiation at 16:00	Radiation at 13:00
Multi-cylinder tower in Saudi Arabia 3D view		
Multi-cylinder tower in Saudi Arabia top view		

3.2. Solar radiation on the surfaces of pigeon towers

Solar radiation on the total surface of pigeon towers in Central Asia was ultimately obtained on the hottest day of the year at 13 and 16, Figure 3 shows the diagram of the of total heat received in kWh/m^2 by the surfaces of the pigeon towers at 13 and 16. The pigeon towers with a higher surface area exposed to sunlight received more heat. The higher surface area of the replicated adjacent pigeon towers caused their heat absorption to exceed that of the other types. On the other hand, heat absorption was the lowest in the single-form pigeon towers with the lowest surface area. Heat absorption by the surfaces was the highest at 13 when the sunlight was intense. At 13, the large surface area of the multi-cylinder pigeon tower in Saudi Arabia caused its heat absorption to reach 496070 kWh/m^2 as the maximum compared to the heat absorption of the other samples. The minimum heat absorption of 18235 kWh/m^2 was observed at 13 in the single-cylinder pigeon towers in Iran. At 16, the highest (74742 kWh/m^2) and lowest (2668 kWh/m^2) heat absorption was respectively observed in the multi-cylinder pigeon tower in Saudi Arabia and the single-cylinder pigeon tower in Iran. The higher the surface area of the pigeon towers, the higher thus the heat they absorb when exposed to sunlight.

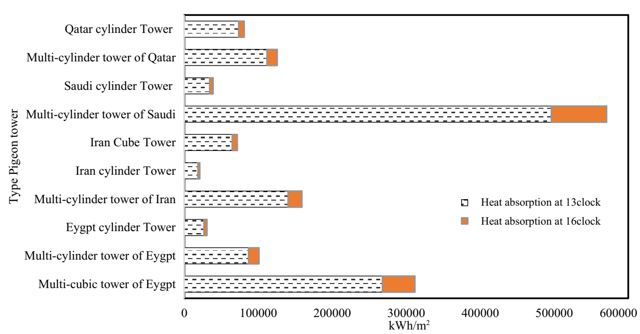


Figure 3. Total heat absorption by the surfaces of the pigeon towers

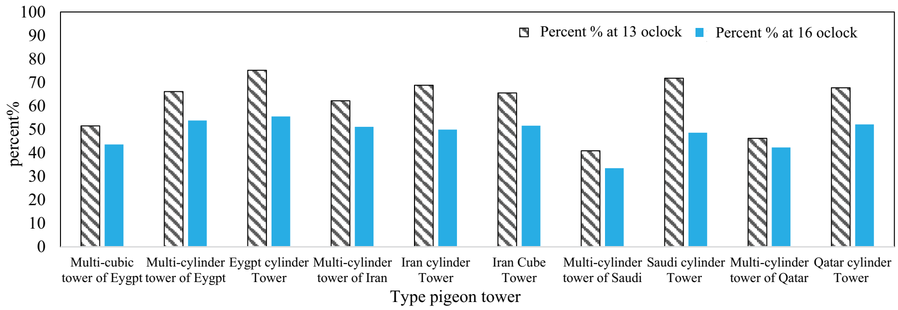


Figure 4. Total heat absorption in percentage by the surfaces of the pigeon towers

3.3. Heat received by the surfaces of pigeon towers in percentage

Although the heat received by the surfaces of pigeon towers depends on their surface area, the percentage of the surface they expose to heat is higher in the single form than in the replicated form, as solar radiation is shielded by the latter. The shape of pigeon towers therefore plays a key role in their solar heat absorption. Figure 4 shows the amount of heat received by the entire surface of the pigeon towers in Central Asia on the hottest day of the year at 13 and 16, suggesting that the single-form pigeon towers expose more of their surface to heat. Despite the smaller surface area of the single-form pigeon towers, their shape exposed a higher percentage of their surface to sunlight. In contrast, the replicated adjacent pigeon towers exposed a lower percentage of their surface to sunlight owing to their congestion. According to Figure 4 the exposed-to-heat surface was maximized at 75.2% in the single-cylinder pigeon towers in Egypt at 13 and minimized at 40.9% in the multi-cylinder pigeon towers in Saudi Arabia. In fact, congestion functioned as a barrier to sunlight in the latter. At 16, the highest and lowest surface areas of the pigeon tower exposed to sunlight were those of the single-cylinder towers in Egypt (55.5%) and the multi-cylinder towers in Saudi Arabia (33.5%). The replicated adjacent pigeon towers exposed a lower percentage of their surface to sunlight and formed more shadow, while a lower percentage of surface area received shadow in the single-form pigeon towers.

4. Analyzing shadow on the surfaces of the pigeon towers in Ecotect

Shadow on the surfaces of the pigeon towers was analyzed at 13 and 16 in Ecotect to validate the developed models. These simulations obviously showed the effect of shadow on the building surfaces. Almost the same parts of the surfaces of the pigeon towers were found to be exposed to sunlight in both Radiance and Ecotect. Parts of the pigeon towers exposed and not exposed to sunlight were respectively marked in yellow and blue. Almost no shadow was created in the Ecotect analysis of the single-form pigeon towers and they were found not to cast shadow on their surfaces. In contrast, adjacent buildings cast shadow on one another in the replicated adjacent pigeon towers, which caused a major portion of their surface to lie in shadow. Figure 5 shows an example of an Ecotect analysis of the multi-cylinder pigeon towers in Qatar at 16. These towers comprised three identical forms, and that at the back received lots of shadow on their surface.

Figure 6 shows the percentage of the sunlight and shadow received by the surfaces of the pigeon towers in Central Asia at 13 and 16 and analyzed in Radiance and Ecotect, respectively. The diagram in this figure illustrates the surface area of the pigeon towers exposed to sunlight and lying-in shadow. As previously discussed, a large proportion of the surfaces of the pigeon towers with

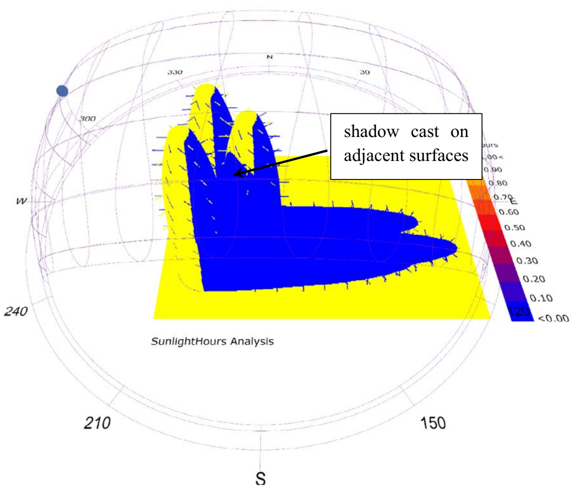


Figure 5. An Ecotect analysis of the shadow cast on the surfaces of the pigeon towers at 16

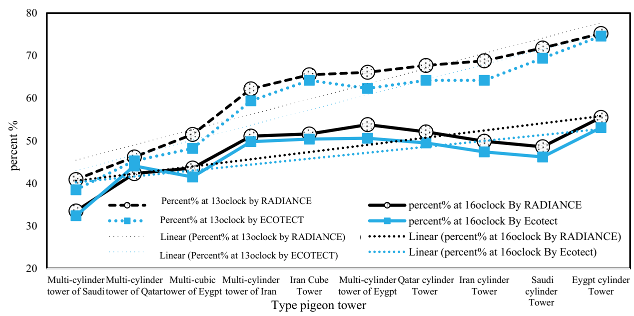


Figure 6. The percentage of the received sunlight by the surfaces of the pigeon towers in Central Asia and analyzed in Radiance and that of shadow analyzed in Ecotect

replicated adjacent forms lay in shadow and they were rarely exposed to sunlight, which explains the low percentage of these pigeon towers in the diagram.

In the absence of shade and barriers to sunlight, the single-form pigeon towers did not cast shadow on the adjacent surfaces. The majority of the surfaces of these pigeon towers were therefore exposed to sunlight and these forms provided less shade against the intense sunlight. According to the diagrams of both analyses, the multi-cylinder pigeon towers in Saudi Arabia exposed the least surface area to sunlight. On the other hand, the single-cylinder pigeon towers in Egypt exposed most of their surface to sunlight and their surface rarely lay in shadow. The results obtained for the effects of sunlight and shadow from the simulations conducted in Radiance and Ecotect were consistent.

Conclusions

This study was conducted to evaluate the effects of solar radiation and shadow cast on the surfaces of different types of pigeon tower in Central Asia (Iran, Qatar, Egypt and Saudi Arabia).

Given the hot climate of Central Asia, shading and decreasing solar radiation on the forms in these areas is crucial. The present study aimed at analyzing solar radiation and shadow on the surfaces of pigeon towers. The findings can be used to design roofs for houses and buildings in Central Asia in a way that solar radiation be decreased and shadow increased. The amount of heat received by the pigeon towers was found to be determined by their surface area, shape and density.

The solar energy received by the upper surfaces of the pigeon towers was maximized at 13:00 given perpendicular solar rays to these surfaces, while their body received lower levels of solar energy. The replicated adjacent pigeon towers exposed a lower proportion of their surface to sunlight, while the single-form pigeon towers exposed a higher percentage. The multi-form pigeon towers cast shadow over one another during the day, while no structure lay beside the single-form towers to case shadow on their surfaces. Pigeon towers that absorb less sunlight on their surfaces and cast more shadow on adjacent forms are therefore appropriate for hot and dry or humid climates with an intense sunlight. Replicated adjacent pigeon towers made of several identical tall forms in close vicinity of one another are therefore recommended for this climate in Central Asia.

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