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Climatic Adaptation of the Dome Body Based on Solar Radiation Received; Case Study: The Domes of Shah Mosque, Sheikh Lotfollah Mosque, Al-Nabi Mosque of Qazvin and Jameh Mosque of Urmia

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ABSTRACT

The dome has long been an essential element of Iranian mosque architecture. The majority of research has so far focused on the form and symbol of the dome rather than the effect of the dome form on climatic comfort. The climatic diversity of Iran's various regions necessitates identifying and implementing strategies for thermal comfort conditions inside the building. Based on a study of the domes of Shah Mosque, Sheikh Lotfollah Mosque, Al-Nabi Mosque of Qazvin, and Jameh Mosque of Urmia, this study aimed to examine solar radiation received and shading on the dome surfaces in hot and arid and cold climates, using solar radiation simulation in the Honeybee and Ladybug plugins with the Radiance Simulation Engine. The first step was to model the domes of the selected mosques in the Revit 2017 software. Then, the annual solar radiation received by each at 2:00 p.m., 4:00 p.m., and 6:00 p.m. on the hottest day of the year was determined using the Honeybee and Ladybug plugins. Analyses indicate that as the dome surface increases, the amount of heat absorbed by them increases in both solar radiation-exposed and shadowed areas. High-rise domes of considerable height can survive in hot and arid climates as they produce appropriate shading, while high-rise domes with great contact surfaces can survive in cold and arid climates as they receive a large amount of solar radiation. Constructing a dome on the tambour increases the amount of shading on the dome surfaces. Thus, in both hot-arid and cold climates of Iran, the dome's form, rise, and arch type can be said to have been designed based on thermal conditions and the amount of solar radiation absorbed throughout the year.

Keywords: Mosque Dome, Solar Radiation, Radiance, Honeybee-Ladybug, Climate.

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1. INTRODUCTION

Historians argue that the construction of a dome on the Chahartāq and the establishment of pendentive can be traced back to the Parthian period. The dome of Qal'eh Dokhtar in Firouzabad, Fars, which was built on a four-meter-wide wall, is the oldest surviving dome from the Sassanid period (Pope, 2016, pp. 47-50). Single-shell domes are older than other types, and they can be thought of as the forerunners of load-bearing domes and historical origins of dome formation. The first domes in Iran were oval or ovoid in shape, with various sections and a wide variety of shapes during the Islamic era. This has contributed to tracing the origins of the dome form, symbolization, and structural solutions (Memarian, 1988, p. 123).

However, the impact of climatic factors on dome formation should not be overlooked. How buildings, as one of the major energy consumers, are designed will significantly affect and change environment and resource consumption (Bazazan & Khosravani, 2016). As a critical component in a building, roof geometry significantly affects the building energy consumption and thermal comfort. The roof geometry of a building is a key determinant of its thermal performance (Fooladi, 2014, p. 85). The amount of solar radiation received on the surface of domed buildings depend on their dome shape and form. Heat absorption is higher in buildings with greater surfaces exposed to solar radiation (Shiri et al., 2018). For many years, traditional Iranian architecture has provided comfortable living conditions while using the least amount of energy. In the meantime, the mosque has been identified as the most widely used historical structure open to the public throughout the year. Using EnergyPlus software, this research attempted to analyze the amount of solar radiation received on single- and double-shell domes in both mountainous and hot and arid climates.

The domes of Jameh Mosque of Urmia, Sheikh Lotfollah Mosque, Al-Nabi Mosque of Qazvin, and Shah Mosque, all with high historical value and antiquity, were studied as single-shell and double-shell samples, respectively. Furthermore, these domes have different vaults and arches. First, the plans of these mosques were derived from library documents. The domes were then modeled on an accurate scale in the Revit 2017 software. Honeybee and Ladybug plugins were used to analyze the amount of solar radiation received on the dome surfaces after importing the modeled domes to the Rhinoceros 5 software. This study aims to address the following questions: “What are the effects of climate on the formation and construction of a dome?” and “What are the effects of the dome shape on the amount of solar radiation received”?

2. THEORETICAL FRAMEWORK

First, one must know the terminology of the elements being studied to determine the amount of solar radiation.

2.1. Single- and Double-shell Domes

A dome is a single- or double-shell cover, with the second shell (dome crown) being primarily of coating role. The single-shell dome is a type of vault that is formed by rotating around the central vertical axis (with the center of the dome apex) (Memarian, 2012, p. 367). Changing the dome shell thickness is one of the Iranian initiatives in the dome architecture. The dome shell thickness changes at a 22.5-degree angle (Šekargāh) (Memarian, 1988, p. 63). Fig. 1 depicts how single- and double-shell domes are modelled in the Revit 2017 software. The roof in a double-shell dome form is a vernacular element of Iranian architecture in hot and arid regions. However, double-shell domes have been used in the cold mountain climate. Double-shell domes were first built in the fifth century AH and became widely known in the eighth century AH (Memarian, 1988, p. 167). On a double-shell dome roof, external (Khood, in Persian) and internal (Ahiyane, in Persian) shells are completely separate, with a drum between them. When the two shells are close together, the drum in “Arbane” turns into a disc, which can be called tambour when it is far apart (Pirnia, 1991, p. 65).

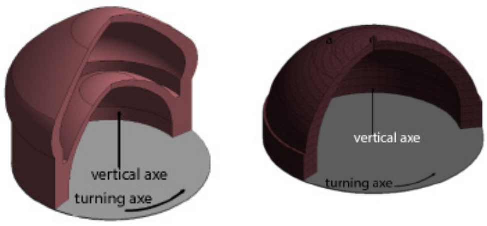


Fig. 1. PartRight: Modelling of a Single-shell Dome; Left: Modelling of a Double-shell Dome Rotating around the Central Vertical Axis

2.2. Features of Vernacular Architecture in Cold Regions

While the coldness and its longevity in cold areas vary, the principles observed to avoid heat loss in buildings are the same and essentially identical to those considered in hot and arid areas. The difference is that in cold regions, the heat comes from inside the building. The only difference between cold and hot-arid areas is the propensity and need to exploit the heat generated by solar radiation within buildings during winter (Kasmaei & Ahmadinejad, 2003, p. 92). Due to the extreme cold in these areas for most of the year, it is necessary to best use solar radiation, to take advantage of daily temperature fluctuations, to maintain heat, and to avoid cold winter winds in residential areas (Ghobadian, 2014, p. 99). This climate is common in Qazvin and Urmia. The maximum dry-bulb temperature (DBT) in Qazvin reaches 41 degrees Celsius throughout the year while amounting to -12.5 degrees Celsius on the coldest day. Fig. 2 depicts the annual outputs of the Honeybee and Ladybug plugins, with weather conditions (EPW) in Urmia and Qazvin. The maximum DBT reaches 34.7 degrees Celsius throughout the year while amounting to -13.70 degrees Celsius on the coldest day.

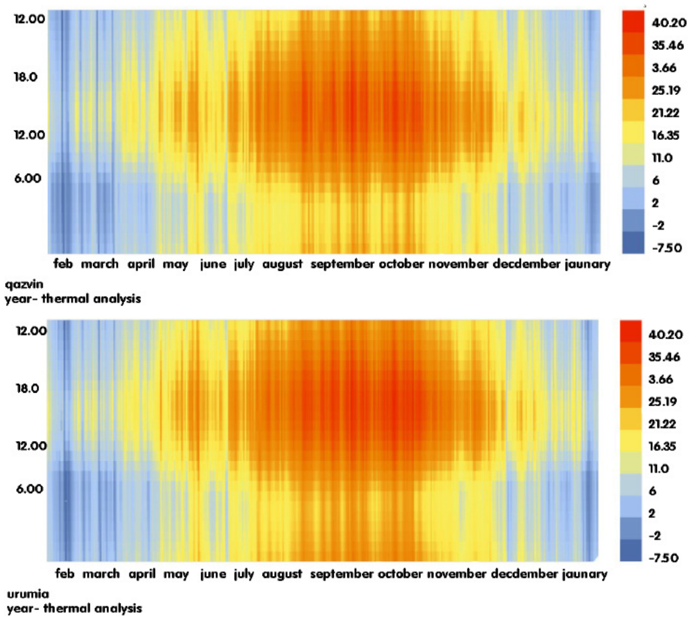


Fig. 2. Top, The Annual DBT Chart of Qazvin and Bottom, the Annual DBT Chart of Urmia

2.3. Features of Vernacular Architecture in Hot and Arid Regions (Central Plateau of Iran)

During the day, the sun warms the earth's surface up to 70°C. However, the earth's surface temperature drops steadily at night, reaching a minimum of 15 degrees Celsius (Kasmaei & Ahmadinejad, 2003, p. 84). The difference in air temperature during the day is significant due to the low humidity and distance from the sea. Traditional architecture has offered rational solutions to the climatic problems in this region as a result of thousands of years of experience (Ghobadian, 2014, p. 123). Residents of hot and arid regions have devised strategies to address the climatic problems in these areas, including the use of high-heat-capacity materials such as adobe and mud in the construction of buildings (Kasmaei & Ahmadinejad, 2003, p. 89). In this research, Isfahan City was chosen as the representative area with this climate based on certain parameters. Fig. 3 shows the graphical output of the analysis on Isfahan City in terms of the solar radiation received throughout the year. In Isfahan City, the hottest point during the year reaches 40.20 degrees Celsius, and its coldest point reaches -7.50 degrees Celsius.

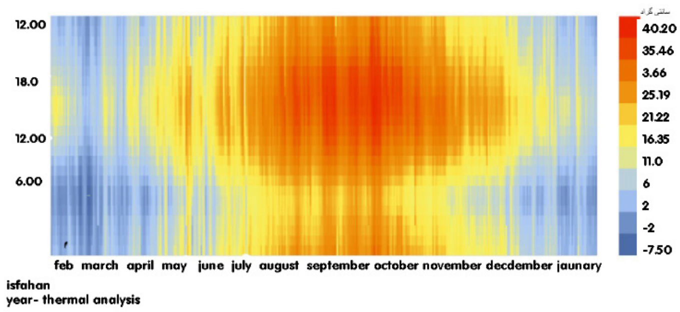


Fig. 3. Top, The Annual DBT Chart of Qazvin and Bottom, the Annual DBT Chart of Urmia

3. INTRODUCTION OF CASE STUDIES

The case studies were chosen based on climatic conditions, dome construction quality, and the historical significance of the building. The physical and structural characteristics of each dome were discussed in this regard.

3.1. Double-shell Domes

Iranian artists worked hard to create a unique space in appearance, color, and form for the dome of Shah Mosque (Michel, 2001, p. 150). Shah Mosque is located on the south side of Shah Square (Naghsh-e Jahan), and it was built by Shah Abbas's order in 1020 AH. The double-shell dome of this mosque is discontinuous. The internal shell is about 2.1 and 75 cm thick in the impost (Pakar, in Persian) and the crown, respectively, with an oval cross-section. The external shell has been built on a 7.20m-high drum, with a span of about 19.8 m and a height of about 2.6 m, equivalent to that of the external skin in the impost. The thickness becomes the size of a brick in the impost. Al-Nabi Mosque of Qazvin has a double-shell dome, with a span of about 16.5 m and an approximately 10 m-high external shell crown (Memarian, 1988, pp. 258-243). Fig. 1 illustrates the section drawings of the double-shell domes studied in this research. The physical characteristics and dimensions of Shah Mosque and Al-Nabi Mosque of Qazvin are listed in Table 1.

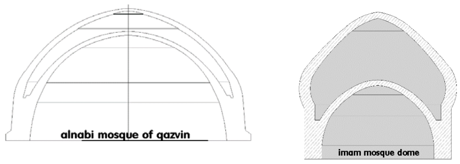


Fig. 4. The Section Drawings of the Double-shell Domes; Right: Al-Nabi Mosque of Qazvin Dome, Left: Shah Mosque Dome
(Memarian, 1988)

Table 1. Physical Characteristics and Dimensions of the Double-shell Domes of Shah Mosque and Al-Nabi Mosque of Qazvin (in Meters)

Double-shell Domes	Span	Height	Internal shell Thickness in the Crown	External Shell Thickness in the Crown	External Shell Thickness in the Impost	Distance between the Two Shells	Climate	Climate Information	Material
Shah Mosque	19.8	18.9	0.75	0.85	2.66	9.3	Hot and Arid	EPW Weather Files	Bricks, Tiles
Al-Nabi Mosque of Qazvin	16.5	10	0.35	0.35	1.8	2.1	Cold	EPW Weather Files	Bricks, Tiles

(Memarian, 1988)

3.2. Single-shell Dome

Single-shell domes must now be discussed. Sheikh Lotfollah Mosque was constructed on the southeastern part of Naqsh-e Jahan Square, Isfahan. The inscription on the vault's edge refers to 1025 AH as the construction date of this building (HajiGhasemi, 2015, p. 124). This lovely small mosque has resurrected the solid shape of a dome on a quadrangular room, which is a Sassanid architectural legacy (Pope, 2016, p. 217). This dome has an exquisite proportion. The use of various colored tiles gave a certain allure and beauty to it (Memarian, 1988, p. 127). Another double-shell domed building is the Jameh Mosque of Urmia, dating back to the second half of the seventh century AH, in the Ilkhanate period. The dome of the Jame Mosque of Urmia is approximately 15.8 m high, with a crown 18 m above the ground and an oval low-rise cross-section (Memarian, 2012, p. 310). Fig. 5 demonstrates the section drawings of the single-shell domes studied in this research. Moreover, Table 2 lists the physical characteristics and dimensions of Sheikh Lotfollah Mosque of Isfahan and Jameh Mosque of Urmia.

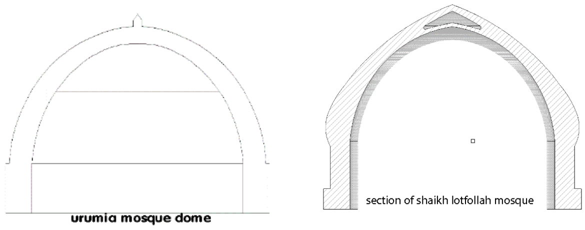


Fig. 5. Modeling of Single-shell Domes; Right: The Section of Sheikh Lotfollah Mosque of Isfahan; Left: The Section of Jameh Mosque of Urmia
(Memarian, 1988)

Table 2. Physical Characteristics and Dimensions of the Single-shell Domes of Sheikh Lotfollah Mosque and Jameh Mosque of Urmia (in Meters)

Single-shell Dome	Span	Height	Impost Thickness	Dome Ccrown Thickness	Haunch	Climate	Climate Information	Material
Shah Mosque	19.8	18.9	2.1	0.35	1.1	Hot and arid	EPW Weather Files	Bricks, Tiles
Al-Nabi Mosque of Qazvin	16.5	10	3.2	0.68	N/A	Cold and Mountainous	EPW Weather files	Traditional Bricks

(Memarian, 1988 with Emphasis by Authors)

4. LITERATURE REVIEW

This section aims to compile the most relevant research in this field based on concepts such as the effect of solar radiation, how solar radiation is absorbed on curved surfaces like domes and related standards. This body of research can be divided into two categories: software simulation and quasi-experimental studies.

4.1. Analysis of the Effect of Solar Radiation on Domed Surfaces

The effect of solar radiation on domed roofs, such as those of cisterns and markets, has been studied by many researchers. Researchers such as Fathy (1973), Mainstone (1983), Bowen (1981), Koita (1981), Bahadori (1978), and Shiri et al. (2019) have investigated the roofs of buildings in hot-arid regions. Tang, Meir, & Etzion (2003) have investigated the effect of solar radiation on domed roofs using experimental and simulation methods. Using the Honeybee and Ladybug plugins, Shiri et al. (2019) explored the effect of form on shading and heat absorption in the dome of Yazd cisterns. They determined the effect of solar radiation on the domed roof of cisterns in the hot and arid climate of Yazd. They demonstrated the best dome of the cistern for receiving solar radiation in a hot and arid climate. Khorasani and Bahadorinejad (2009) studied the roof of Fatima Masumeh Shrine in Qom. They modelled the shrine, calculated the amount of radiation energy and heat flux, and introduced the minimum energy loss for 50 to 60-degree angles. They also claimed that the use of tiles to cover the dome surfaces in traditional Iranian architecture decreases the amount of solar radiation absorption. In a study by Fooladi, Tahabaz, and Majedi (2016), the effects of solar radiation and indoor ventilation on a double-shell domed building in Kashan were simulated. The results showed that the daily temperature difference between the internal and external shells is about 5 degrees in summer and approximately 11.5 degrees Celsius in winter. In a study by Bahadori and Haghighat (1985), the results showed that the thermal layering of the air under the domed or the vaulted roof makes the heated air in the upper layer so close to the roof and makes living conditions in the building highly favorable. According to Khorasani and Bahadorinejad's (2009) research, the airflow from windcatchers also helps ventilate the interior and keep the cistern dome cool during hot seasons. Biwole, Woloshyn, and Pompeo (2008), in their research on double-shell roofs, revealed that these roofs with high reflectivity and proper ventilation could help passive cooling in the summer. Miranville (2003) designed and model a roof-mounted radiant barriers and simultaneously compared a number of heat transfer coefficients in the model and a sample of the model. Convection and heat transfer can be used as a passive cooling system in a double-shell radiation dome to save money on electricity and for air conditioning in the summer (Chang, 2008, p. 148). The smaller the air column gap in a double-shell dome, the less air circulation and less convection impact there is. Reduced roof loss improves the thermal comfort conditions by 8 to 10 degrees and increases air circulation in a spherical domed roof (Moshfegh & Ibrahimi, 2008). Using the Honeybee and Ladybug plugins, ….. analyzed the dome surfaces of several mosques in desert areas. They also used the Radiance engine to simulate the effect of solar radiation on the dome surfaces on the hottest day of the year. The results showed that the high-rise domes expose 58%, 51%, and 49% of their surfaces to solar radiation at 2:00 p.m., 4:00 p.m., and 6:00 p.m., respectively. On the other hand, low-rise domes expose 75%, 68%, and 46% of their surfaces to solar radiation at 2:00 p.m., 4:00 p.m., and 6:00 p.m., respectively.

5. TESTING AND RESEARCH METHOD

To measure the amount of solar radiation received on the exterior surfaces of buildings, first, it is required to apply a method with an ability to accurately simulate the solar radiation on the model surfaces. The time, location, and weather conditions of the area are required to simulate solar radiation on the exterior surfaces of buildings. The impact of shading on the exterior surfaces of buildings must also be shown. Thus, it is required to use a suitable tool for evaluating the amount of solar radiation received on building surfaces to analyze solar radiation and shading. Radiance, Daysim, and ArcGIS Ecotect are all useful tools for assessing solar radiation and shading on building surfaces (Brito, Gomes, Santos, & Tenedório, 2012; Freitas, Catita, Redweik, & Brito, 2015; Andersson, Wayne, Kammerud, & Peter, 1985). For small scales, RADIANCE software can provide solar radiation analysis with high accuracy. For analysis, the software employs the Perez Diffuse Radiation Model (Perez, Ineichen, Seals, Michalsky, & Stewart, 1990; Perez, Seals, Ineichen, Stewart, & Menicucci, 1987). The software is based on a projection algorithm written for solar radiation analysis in the Grasshopper software. The software demonstrates the effects of solar radiation on three-dimensional models with high accuracy. RADIANCE software is also recommended for analyzing complex curved geometries (Ward, 1994). The valid Radiance simulation engine has also been used in this research.

The current research was conducted based on the hypothesis stating the shape characteristics of double- and single-shell domes affect solar radiation received and shading in hot and arid, and cold climates. The thermal conditions of these structures were compared. Cities with the following characteristics have been chosen for each climate: 1) The selected domes must be old and historically significant, 2) Records and documents must be available and usable to display the dimensions of the domes and the building characteristics, and 3) In selected cities, there are Qajar and Pre-Qajar buildings with a single- or double-shell dome, registered in Iran's national cultural heritage list. In this study, it has been attempted to formulate the research framework by investigating single- and double-shell domes in hot and arid and cold climates. The domes of the Jameh Mosque of Urmia, Al-Nabi Mosque of Qazvin, Sheikh Lotfollah Mosque, and Shah Mosque were assumed as base roofs in this study to develop an energy-efficient model for single- and double-shell roofs in hot and arid as well as cold and mountainous climates. The domes of the Jameh Mosque of Urmia and Al-Nabi Mosque of Qazvin, as domes in cold climate and the domes of Shah Mosque and Sheikh Lotfollah Mosque, as domes in hot and arid climate, were chosen and modelled, as shown in Fig.6.

Fig. 6. Top/Right: Jameh Mosque of Urmia; Top/Left: Al-Nabi Mosque of Qazvin (Cold Climates); Bottom/ Right: Shah Mosque and Bottom/Left: Sheikh Lotfollah Mosque (Hot and Arid Climates)
(Memarian, 1988, p. 148; HajiGhasemi, 2015, p. 96; Memarian, 1988, p. 158; HajiGhasemi, 2015, p. 85)

Authentic Honeybee and Ladybug plugins were used under the Radiance engine to perform solar radiation analysis. First, the domes of selected mosques were set to zero levels in the Rhinoceros 5 software. The solar radiation estimation algorithm was then run using Honeybee and Ladybug plugins on the hottest day of the year, at three time intervals of 2:00, 4:00, and 6:00 p.m. to perform analyses based on the climatic conditions of each region, each city's epw weather file was obtained from the related weather station and then loaded into the software. It should be noted that the dome form was considered the main variable in all stages. Other basic parameters, e.g., dome thickness and materials, were assumed to be fixed.

6. ANALYSIS OF FINDINGS

To determine the heat received on the solar radiation-exposed, and shadowed areas of the domes of Sheikh Lotfollah Mosque, Shah Mosque, Al-Nabi Mosque of Qazvin, and Jameh Mosque of Urmia, Honeybee and Ladybug plugins were used under the Radiance. The results are illustrated graphically and numerically into two sections: analysis of single-shell dome and analysis of double-shell dome.

6.1. Analysis of Single-Shell Domed Mosques

This section deals with single-shell domes. Table 3 shows the graphical analysis of the impact of solar radiation received on single-shell dome surfaces at three intervals, namely 2:00 p.m., 4:00 p.m., and 6:00 p.m. from the top and 3D views. For the single-shell domes, the excel outputs of the analyses of heat received on the solar radiation-exposed and shadowed areas are shown in Table 4 and 5, respectively.

Table 3. Analysis of the Amount of Solar Radiation Received on the Dome Surfaces of Double-Shell Mosques at Intervals of 2:00 p.m., 4:00 p.m., and 6:00 p.m. in KWh/m²

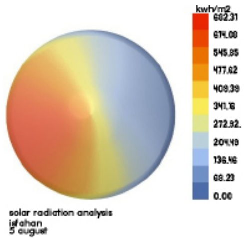
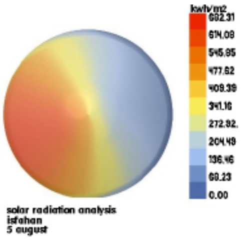
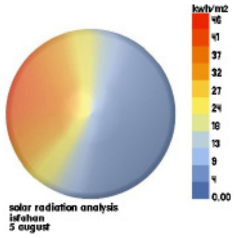
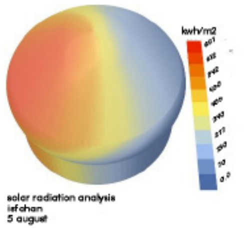
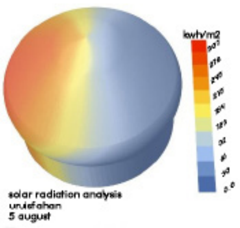
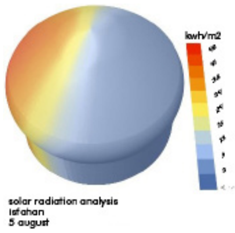
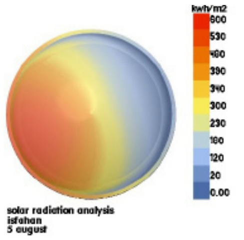
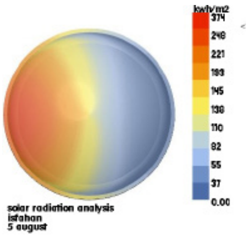
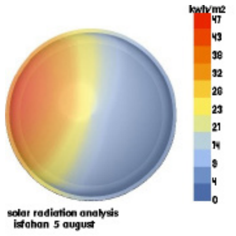
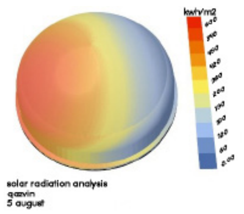
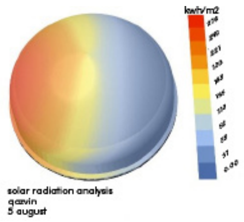
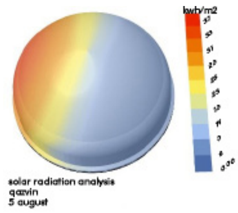
Double-shell Dome	Analyzed at 2:00 p.m.	Analyzed at 4:00 p.m.	Analyzed at 6:00 p.m.
Top-view Shah Mosque Dome			
3D view of Shah Mosque Dome			
Top-view Al-Nabi Mosque of Qazvin Dome			
			

Table 4. The Amount of Heat Absorbed on the Solar Radiation Exposed-area of the Domes of Double-shell Domed Mosques in kWh/m², the Area of the Dome Exposed to Solar Radiation = Heat-Absorbed Area

Mosque Dome	Dome Area		The Efficiency of Heat Received on Surfaces Exposed to Radiation at 2:00 p.m.						Total Heat Absorbed in kWh/m²
			682 kWh/m²	614 kWh/m²	545 kWh/m²	477 kWh/m²	409 kWh/m²	341 kWh/m²	
Shah Mosque	977 m²	Heat-absorbed Area	5844	2832	2514	1517	808	3306	16937
			600 kWh/m²	540 kWh/m²	480 kWh/m²	420 kWh/m²	360 kWh/m²	300 kWh/m²	
Al-Nabi Mosque of Qazvin	1430 m²		3234	3175	2822	3087	3528	2205	18051
Mosque Dome	**Dome Area**		**The Efficiency of Heat Received on Surfaces Exposed to Radiation at 4:00 p.m.**						**Total Heat Absorbed in kWh/m²**
			307 kWh/m²	276 kWh/m²	245 kWh/m²	215 kWh/m²	184 kWh/m²	153 kWh/m²	
Shah Mosque	977 m²	Heat-absorbed Area	2026	911	808	567	242	1010	5567
			176 kWh/m²	248 kWh/m²	221 kWh/m²	193 kWh/m²	165 kWh/m²	138 kWh/m²	
Al-Nabi Mosque of Qazvin	1430 m²		1217	1215	1082	851	808	676	5851

Mosque Dome	Dome Area		The Efficiency of Heat Received on Surfaces Exposed to Radiation at 6:00 p.m.						Total Heat Absorbed in kWh/m²
			47 kWh/m²	41 kWh/m²	37 kWh/m²	32 kWh/m²	27 kWh/m²	23 kWh/m²	
Shah Mosque	977 m²	Heat-absorbed Area	303	135	122	84	35	151	833
Al-Nabi Mosque of Qazvin	1430 m²		47 kWh/m²	43 kWh/m²	38 kWh/m²	33 kWh/m²	28 kWh/m²	23 kWh/m²	
Jameh Mosque of Urmia	1430 m²		207	210	186	145	137	112	999

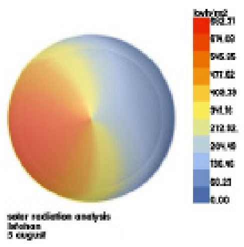
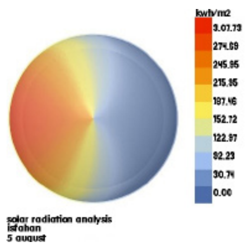
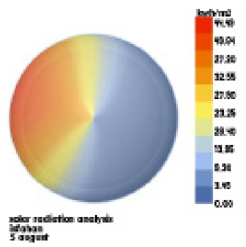
Table 5. Amount of Heat Absorbed on the Shadowed Area of the Domes of Double-Shell Domed Mosques in kWh/m², the Area of the Dome Surface under the Shadow = Heat- Absorbed area

Mosque Dome	Dome Area		The Efficiency of Heat Received on the Shadowed Area at 2:00 p.m.				Total Heat Absorbed in kWh/m²
			272 kWh/m²	204 kWh/m²	136 kWh/m²	68 kWh/m²	
Shah Mosque	977 m²	Heat-absorbed Area	718	673	1257	224	2873
			240 kWh/m²	180 kWh/m²	120 kWh/m²	60 kWh/m²	
Al-Nabi Mosque of Qazvin	1430 m²		470	176	470	29	1146
Mosque Dome	**Dome Area**		**The Efficiency of Heat Received on the Shadowed Area at 4:00 p.m.**				**Total Heat Absorbed in kWh/m²**
			122 kWh/m²	92 kWh/m²	61 kWh/m²	30 kWh/m²	
Shah Mosque	977 m²	Heat-absorbed Area	805	728	644	396	2574
			110 kWh/m²	82 kWh/m²	55 kWh/m²	27 kWh/m²	
Al-Nabi Mosque of Qazvin	1430 m²		592	482	377	164	1716
Mosque Dome	**Dome Area**		**The Efficiency of Heat Received on the Shadowed Area at 6:00 p.m.**				**Total Heat Absorbed in kWh/m²**
			18 kWh/m²	13 kWh/m²	9 kWh/m²	4 kWh/m²	
Shah Mosque	977 m²	Heat-absorbed Area	356	291	297	132	1077
Al-Nabi Mosque of Qazvin	1430 m²		19 kWh/m²	14 kWh/m²	9 kWh/m²	4 kWh/m²	
			186	157	105	58	508

6.2. Analysis of Double-shell Domed Mosques

This section addresses double-shell domes. Table 6 illustrates the graphical analysis of the impact of solar radiation received on double-shell dome surfaces at three intervals of 2:00, 4:00, and 6:00 p.m. from the top and 3D views. For the double-shell domes, the excel outputs of the analyses of heat received on the solar radiation-exposed and shadowed areas are shown in Table 4 and 5, respectively.

Table 6. Analysis of the Amount of Solar Radiation Received on the Dome Surfaces of Single-shell Domed Mosques, at Intervals of 2:00 p.m., 4:00 p.m., and 6:00 p.m. in KWh/m²

Dome	Analyzed at 2:00 p.m.	Analyzed at 4:00 p.m.	Analyzed at 6:00 p.m.
Top-view of Sheikh Lotfollah Mosque Dome			

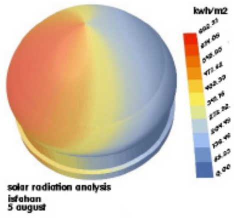
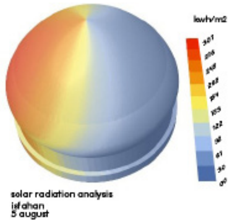
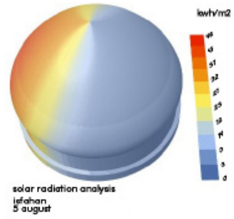
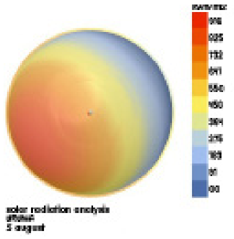
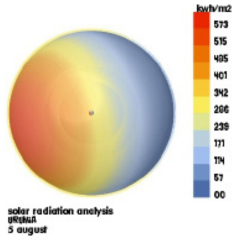
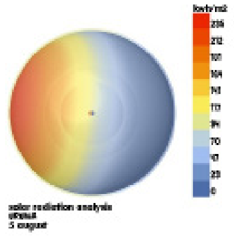
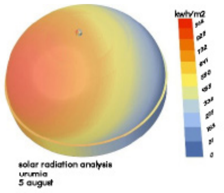
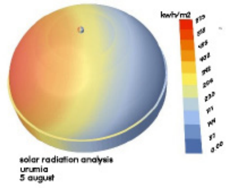
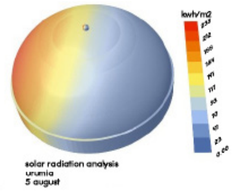
Dome	Analyzed at 2:00 p.m.	Analyzed at 4:00 p.m.	Analyzed at 6:00 p.m.
3D View of Sheikh Lotfollah Mosque Dome			
Top-view of Jameh Mosque of Urmia Dome			
			

Table 7. Amount of Heat Absorbed on the Solar Radiation-Exposed Area of Single-Shell Domes in Kwh/M², the Area of the Dome Surface Exposed to Solar Radiation = Heat Absorbed Area

Mosque Dome	Dome Area		The Efficiency of Heat Received on Surfaces Exposed to Radiation at 2:00 p.m.						Total Heat Absorbed in kWh/m²
			682 kWh/m²	614 kWh/m²	545 kWh/m²	477 kWh/m²	409 kWh/m²	341 kWh/m²	
Sheikh Lotfollah Mosque	1034 m²	Heat-absorbed Area	6793	2912	4730	3620	3103	7197	28357
			916 kWh/m²	825 kWh/m²	733 kWh/m²	641 kWh/m²	550 kWh/m²	485 kWh/m²	
Jameh Mosque of Urmia	1479 m²		13602	9188	8163	9518	4083	6801	51358
Mosque Dome	**Dome Area**		**The Efficiency of Heat Received on Surfaces Exposed to Radiation at 4:00 p.m.**						**Total Heat Absorbed in kWh/m²**
			307 kWh/m²	276 kWh/m²	245 kWh/m²	215 kWh/m²	184 kWh/m²	153 kWh/m²	
Sheikh Lotfollah Mosque	1034 m²	Heat-absorbed Area	2329	1047	1162	1019	1047	2177	8783
			537 kWh/m²	515 kWh/m²	458 kWh/m²	401 kWh/m²	343 kWh/m²	286 kWh/m²	
Jameh Mosque of Urmia	1479 m²		4254	3823	3400	4168	1528	2568	19723
Mosque Dome	**Dome Area**		**The Efficiency of Heat Received on Surfaces Exposed to Radiation at 6:00 p.m.**						**Total Heat Absorbed in kWh/m²**
			47 kWh/m²	41 kWh/m²	37 kWh/m²	32 kWh/m²	27 kWh/m²	23 kWh/m²	
Sheikh Lotfollah Mosque	1034 m²	Heat-absorbed Area	256	155	175	151	153	327	1320
			235 kWh/m²	212 kWh/m²	188 kWh/m²	164 kWh/m²	141 kWh/m²	117 kWh/m²	
Jameh Mosque of Urmia	1479 m²		1395	1101	1116	1217	418	694	5945

Table 8. Amount of Heat Absorbed on the Shadowed Area of the Domes of Single-Shell Domed Mosques in Kwh/M², the Area of the Dome Surface under the Shadow = Heat-Absorbed Area

Mosque Dome	Dome Area		The Efficiency of Heat Received on the Shadowed Area at 2:00 p.m.				Total Heat Absorbed in kWh/m²
			272 kWh/m²	204 kWh/m²	136 kWh/m²	68 kWh/m²	
Sheikh Lotfollah Mosque	1034 m²	Heat-absorbed Area	645	483	479	648	2257
Jameh Mosque of Urmia	1479 m²		366 kWh/m²	275 kWh/m²	183 kWh/m²	91 kWh/m²	
			1358	2041	1358	472	5232
Mosque Dome	**Dome Area**		**The Efficiency of Heat Received on the Shadowed Area at 4:00 p.m.**				**Total Heat Absorbed in kWh/m²**
			122 kWh/m²	92 kWh/m²	61 kWh/m²	30 kWh/m²	
Sheikh Lotfollah Mosque	1034 m²	Heat-absorbed Area	810	654	549	412	2427
Jameh Mosque of Urmia	1479 m²		229 kWh/m²	171 kWh/m²	114 kWh/m²	57 kWh/m²	
			2210	1904	1692	846	6654
Mosque Dome	**Dome Area**		**The Efficiency of Heat Received on the Shadowed Area at 6:00 p.m.**				**Total Heat Absorbed in kWh/m²**
			18 kWh/m²	13 kWh/m²	9 kWh/m²	4 kWh/m²	
Sheikh Lotfollah Mosque	1034 m²	Heat-absorbed Area	170	178	153	94	598
Jameh Mosque of Urmia	1479 m²		94 kWh/m²	70 kWh/m²	47 kWh/m²	23 kWh/m²	
			1326	1091	1046	68	4147

The amount of solar radiation received on mosque dome surfaces depends on the arch type, its rise, and area. Analyses using the Honeybee and Ladybug plugins determined that the area of the dome surfaces plays a significant role in the amount of solar radiation absorption. The maximum amount of solar radiation was received at 2 p.m. The dome of the Jame Mosque of Urmia with an area of 1479 m2 and a value of 51358 kWh/m², had the greatest amount of solar radiation absorbed, while the Shah Mosque dome, with an area of 977 m² and a value of 16937 kWh/m², had the least. The amount of heat absorbed is reduced as the radiation angle approaches sunset. At 2:00 p.m., the dome of the Jameh Mosque of Urmia had the greatest heat absorption on the shadowed area (5232 kWh/m²), while the Al-Nabi Mosque of Qazvin dome had the least amount with 1146 kWh/m². Fig. 7 depicts the total heat absorption on the solar radiation-exposed and shadowed areas at intervals of 2:00 p.m., 4:00 p.m., and 6:00 p.m., separately.

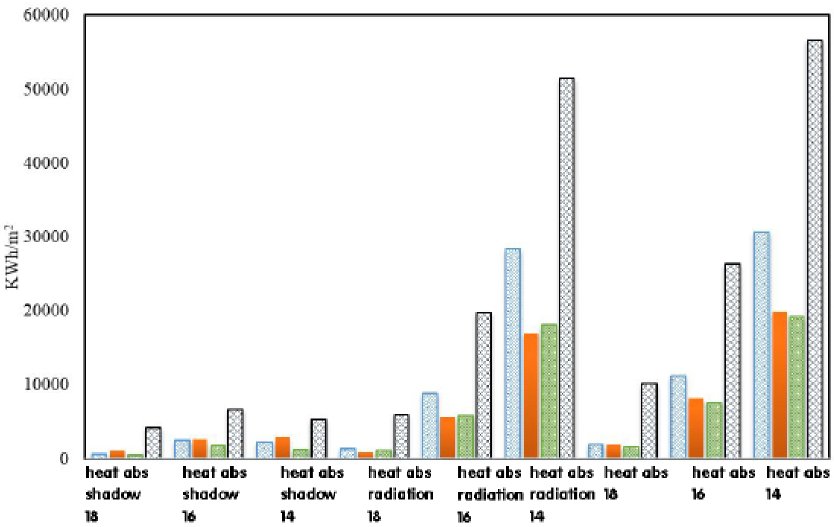


Fig. 7. Total Heat Absorbed on the Solar Radiation-exposed and Shadowed Areas on Domes at 2:00 p.m., 4:00 p.m., and 6:00 p.m. in kWh/m²

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7. CONCLUSION

Our ancestors' understanding and perception of the environmental and climatic conditions of each region in Iran led to the construction of structures with Islamic architecture to provide thermal comfort. Through the comprehensive study of architectural structures, one can obtained the knowledge of their forms and identify the backgrounds of their emergence. The majority of research on dome has been focused on the quality, theoretical foundations or architectural history of it, and there is a little less quantitative research on it. One of the quantitative studies on domes can be the study of climatic conditions in which domes were constructed. This paper attempted to understand the formal diversity of spire domes in Iranian architecture from a climatic standpoint. The heat absorbed on the solar radiation-exposed and shadowed areas of the domes of Shah Mosque and Sheikh Lotfollah Mosque in hot and arid climates, as well as Jameh Mosque of Urmia and Al-Nabi Mosque of Qazvin in cold climates, were analyzed and evaluated.

The findings revealed that the amount of solar heat received on the shadowed area of mosque domes is positively correlated with increased dome area. The larger the dome surface area, the more heat it absorbs. In addition to the area, the amount of heat received also changes as the rise and height of the mosque domes rise. In cold climates, the low-rise and low-height dome outperforms the high-rise dome during the day because it exposes more contact surfaces to solar radiation and provides less shading. Low-rise domes produce less shading than high-rise domes as fewer surfaces are exposed to solar radiation at sunrise and sunset. However, because of their arch form and shape, high-rise domes with considerable heights are better suited to hot and arid climates than low-rise domes for shading during the hottest part of the day.

Moreover, constructing a dome on the tambour significantly contributes to dome shading. The tambour body is well suited to hot and arid climates. This could indicate that tambour was used in hot and arid areas to reduce the amount of radiation received on the surfaces of mosque domes.

Furthermore, the 3D graphical results revealed that the southern fronts of domes in the cold climate have less shading due to their low height. This condition, however, does not apply to domes in the hot and arid climate, and it has always been associated with a long shadow behind the dome. According to the findings, there is a direct link between dome shape and climatic adaptation. If the dome deformation trajectory is followed from hot and arid to cold areas, it can be observed that the dome height and contact surface played a prominent role in the amount of solar radiation received.

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