J. King Saud Univ., Vol. 23, *Arch. & Planning* (2), pp. 31-40, Riyadh (2011/1432H.)

Shading Potential of Semi-spherical Roof Dome, with Special Reference to Gaza Strip

Ahmed S. Muhaisen
Associate Professor, Architecture Department,
The Islamic University of Gaza, Palestine, P.O. Box 108
amuhaisen@iugaza.edu

(Received 15/10/1430H.; accepted for publication 15/2/1431H.)

Keywords: Domed roof, Environmental design, Shading, Mosque building.

Abstract. This paper examines the shading potential of a semi-spherical roof dome in a temperate climate with special reference to Gaza Strip. It highlights the capability of the roof dome to reduce the amount of solar radiation incident on its surface, naturally, through its curvature shape, which is partially shaded at any time during the day. A case study of Al-Said Hashim Mosque in Gaza was studied as a typical religious building with semi-spherical roof domes. Also, the paper presents a computer model developed specifically to calculate the shaded area produced on a semi-spherical dome located in any place on the earth at any time during the year. Using the developed program, a parametrical study was carried out to investigate the effect of changing the time on the shading performance of the dome. The results showed a direct relationship between the time during the day and the shaded area produced on the dome's surface.

1. Introduction

A semi-spherical dome has been used as a type of roofs for buildings in different parts of the world, especially in the Middle East. It was usually used in the past as a structural system to achieve wide spans with minimum number of columns using available building materials such as stones and bricks. It is used in the hot dry regions to cover the internal rooms, especially in residential one-floor buildings. However, it is also common in other climatic regions particularly to cover large open halls in public buildings such as, mosques and churches. Besides the structural advantages of the semi-spherical domed roof, it is architecturally a distinguished and stable form that is traditionally used in governmental and religious buildings to express their majesty and strength.

In general, a building's roof should provide comfortable, safe and healthy conditions within the building through keeping out the wind and rain and preventing the penetration of excessive heat or cold (The Overseas Division of the Building Research Est., 1980). It is also required to be of good appearance and in the same time economical in its initial cost and maintenance. In hot climates, the effect of solar radiation received by the building's envelope, especially the roof, is considered the main reason for the thermal discomfort in the internal spaces. Usually, the roof surface receives the greatest proportion of solar radiation incident on the building's surfaces because of its slope angle with respect to that of the sun's altitude. Without shading, the roof surface absorbs solar radiation, raising that surface temperature above that of the ambient air and adding to the cooling loads required in the internal spaces below the roof due to the heat transfer from outside to inside. For most opaque surfaces, the amount of solar radiation that is absorbed as heat is dependent on the surface absorptivity. It is preferable, however, to intercept the solar radiation before it strikes the surface, in effect shielding the building from the sun (Muhaisen, 2006).

The inhabitants of the Middle East used the semi-spherical roof dome in their architecture for all the advantages mentioned above and also for its ability to generate shade on the roof, where providing shading is considered the basic strategy to achieve thermal comfort in buildings.

It should be mentioned that many studies have focused on domed roof with special consideration to its solar and thermal performance, but very little have examined its shading potential and highlighted that through studying a real roof dome. It is commonly believed that domed roof maintains lower temperatures and reflects more radiation than other type of roofs can do in summer. Fathy (1986) mentioned that the solar radiation incident on the dome is spread on a large surface area, which results in a reduction in the solar heat gain and heat transmission to the interior space. Pearlmulter (1993) concluded that there is more stability in the thermal performance (daytime temperatures) of vaulted roofs compared with corresponding flat roofs. An explanation to the advantageous thermal performance of domed roof was given by Bahadori (1978) who pointed out that domed roof dissipate more heat by convection as compared with flat roof assuming that both types receive the same amount of solar radiation. Also, Bahadori (1978) mentioned that the interior space under the domed roof is more comfortable because the hot air accumulate under the curved roof. However, Runsheng *et al.* (2003) demonstrated that domed roof receives 30% more solar radiation than flat roof in summer months, although domed roof receive less beam radiation than flat roof during the hours near midday (Runsheng *et al.*, 2003). They stated that, according to their findings, although domed roof receive more solar radiation, it is preferable in hot regions more than flat roof. The researchers referred that to the fact that the heated air gathers under the curved roof, so that more thermal comfort can be experienced by the occupants. Faghih and Bahadori (2009) found that covering domed roof by glazed tiles in Iran reduces the absorbed solar radiation considerably, which has the result of improving its thermal performance as compared with flat roof. Gomez-Munoz *et al.* (2003) reported that domed roof has the advantage of generating auto-shading, which results in reducing the solar radiation incident on the dome, especially when the sun is out of the zenith. Also, they demonstrated that the solar performance of domed roof is better near equatorial latitudes, and at noon time it is always better than flat roof (Gomez-Munoz *et al.*, 2003). Hadavand and Yaghoubi (2008) mentioned that the temperature varies along the vaulted roof during the day because of the self-shading of the roof, but for the flat roof, temperature distribution along the roof is nearly uniform. Tang *et al.* (2006) showed that vaulted roof buildings have lower indoor temperatures as compared to flat roof. The reason is curved roof structures dissipate more heat as compared to flat roof by convection and radiation at night due to enlarged surface area (Tang *et al.*, 2006). Chel and Tiwari (2009) found that the air temperature in rooms with domed roof is higher by 1-2°C than that in rooms with vaulted roof. This was referred to the large area of the domed roof, which is exposed to the sum as compared with that of the vaulted roof (Chel and Tiwari, 2009).

Al-Said Hashim Mosque in Gaza is presented in this study as a typical traditional building with domed roof. Observing the shade produced on the mosque's roof domes at different times helped to understand the shading performance of the dome and its relation with the sun's position in the sky. Accordingly, simple mathematical expressions were developed to calculate the shaded and sunlit areas produced on the dome's surface at any time during the day and anywhere on the earth. These expressions were computer programmed to avoid lengthy and tedious calculations, if it would be performed manually. This facilitated carrying out a parametrical study to examine the shading performance of the semi-spherical dome with different parameters.

2. Case Study (Al-Said Hashim Mosque)

2.1. Location

Al-Said Hashim Mosque is located in the old city of Gaza, on latitude 31° N, longitude 34° E and altitude 45 m, in Aldarag suburb. Gaza is the main city in Gaza Strip, which is called the Southern Province of Palestinian territories. It is considered the gate of Asia continent from Africa, because of its central location where the two continents, Asia and Africa, meet (Fig. 1). Gaza is one of the world's oldest cites, which was built by the Canaanites about 3000 BC (State Information Services, 1999).

2.2. Climate

The climate in Gaza Strip is temperate, with mild winters, and hot dry summers subject to drought (Wikipedia Foundation, 2007). Temperatures are generally high with a daily average of 24°C in summer (from May to August) and 15°C in winter (from November to February). However, the daily average maximum temperatures are 27°C in summer and 19°C in winter, whereas the daily average minimum temperatures are 21°C and 11°C in summer and winter respectively. The average number of yearly sunshine hours is 2863, and the sun shines in 300 days a year. The intensity of solar radiation is relatively high, reaching the maximum in summer with an average of 24.2 MJ/m^2 on horizontal surface, whereas, in winter it is about half of it with an average of 11.2 MJ/m^2. The average relative humidity ranges between 65% in winter and 73% in summer, with September and October the most humid, whereas January and February are the less humid. Rain falls only in winter with a yearly average of about 271.5 mm (Zanin, 2002).

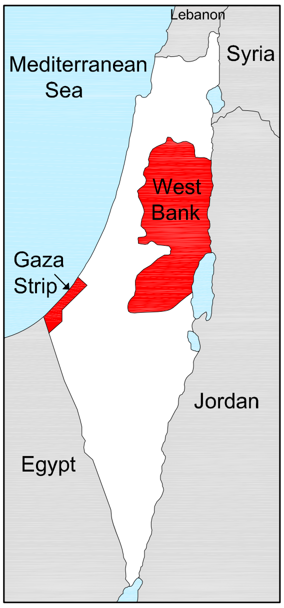


Fig 1. Gaza Strip map.

2.3. Description of the mosque

It is considered one of the oldest and most well done construction still exists (Fig. 2). It was built firstly by Mamelukes and renewed by Ottoman Sultan Abelhamid in 1850. During World War II some parts of it were damaged and destroyed, but after that the mosque was gradually repaired until it became as it was before (Islamicweb, 2002).

Fig. 2. Al-Said Hashim Mosque.

The design of the mosque's plan incorporates some architectural elements that characterize the mosque buildings and the Islamic traditional architecture (Fig. 3). These elements include open courtyard, roof domes, arches, arcades, thick walls and mosque tower. As most traditional mosque buildings, Al-Said Hashim Mosque has an open courtyard surrounded by four arcades and service rooms. The main praying hall is located on the Kiblah direction (the eastern side of the courtyard). The arcades and the service room are covered by semi-spherical roof domes, which are considered the main roof structural system. The praying hall is covered by a big semi-spherical dome that distinguishes the space below it, as the major space for praying, and identifies the Kiblah direction.

The mosque design includes some environmental design elements that are worth mentioning as follows.

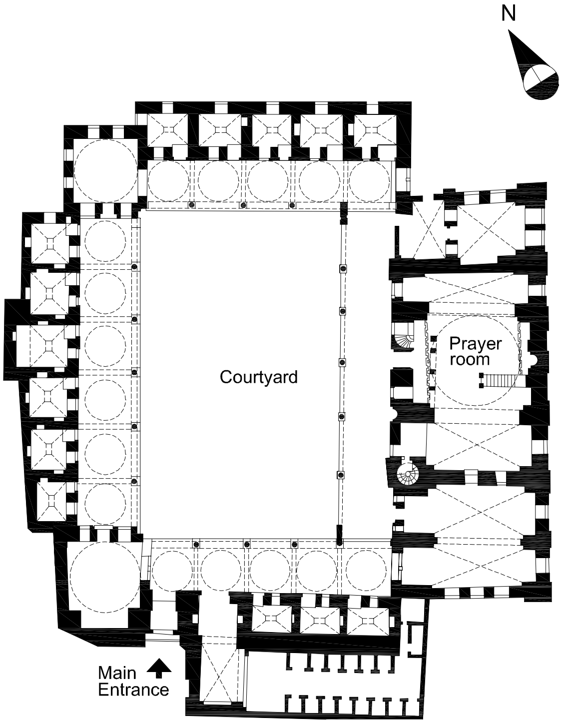


Fig. 3. Plan of Al-Said Hashim Mosque.

2.4. Semi-spherical roof domes

In climates such as that in Gaza Strip providing shading on the buildings surfaces in summer is considered the basic strategy to achieve comfort. During the summer period, the building's roof is considered the largest surface exposed to direct solar radiation, which significantly acts to increase the solar heat gain and elevate the internal temperature above that acceptable degree (comfortable temperature degree). The domed roof had been used by ancient builders as a roof structural system to obtain wide spans and in the same time to reduce the amount of solar radiation incident on the roof and consequently help to minimize the solar heat gain (Fig. 4). This is achieved through the shaded area produced naturally on the domes, which cover the internal spaces, as a result of its curvature surface.

Fig. 4. The Semi-spherical roof domes of Al-Said Hashim Mosque.

2.5. Courtyard

It is an open space surrounded by covered arcades and rooms through which they receive daylight and natural ventilation and have visual as well as physical communication (Fig. 5). It is used for praying, meeting and performing social activities by worshipers, especially in summer, when the weather permits. Courtyard space has been used in buildings in temperate regions as the main design elements to modify the climatic conditions and to provide a pleasant internal space that is open to outdoor. It is used to regulate the internal temperatures and generate a comfortable microclimate in the building.

Fig. 5. The courtyard of Al-Said Hashim Mosque.

It generates shade in summer on the internal walls and part of the ground during most of the day. This helps to reduce the undesirable effect of intense solar radiation and provides a pleasant internal area whereas, in winter, it allows solar access to internal spaces, contributing to a reduction in the need for heating. It is believed that the courtyard space is an efficient climate modifier if special consideration concerning its proportions, orientation, dimensions and finishes were considered in the design stage (Muhaisen, 2005).

3. Shading on the Semi-spherical Roof Dome

It is argued that at any time during the year and anywhere on the earth (except in the cases when the sunrays are vertical) part of the semi-spherical dome is shaded. The shaded part is always less than half of the surface area of the dome; it equals half of it only when the sunrays are horizontal, i.e. when the sun rises and appears in the horizon or when it sets.

Through examining the shape and area of shade produced on the dome at different times, it was found that they are mainly dependent on the sun altitude angle (α). Moreover, the sun's azimuth angle has no effect neither on the shape nor area of the shade produced on the dome. The sun's azimuth angle only determines the position of shade with relation to the four directions (Fig. 6). The shape of the shaded area in all cases is a segment of the semi-spherical dome but with different values of angle θ, depending on the sun altitude angle (α). Angle θ is that confined between the dome's base and an imaginary line linking the centre of the dome's base and the highest point (tangency point) on the curve outlining the shaded area on the dome's surface (Fig. 7-a). The tangency point is that where the sunray passing the center of the dome's base (in plan) hits the dome's surface (the highest point in the dome's shaded surface).

It is concluded that the ratio of angle θ to the complete angle (180°) is the same as that between the generated shaded area and the total surface area of the semi-spherical dome. For example, if the sun's altitude angle (α) is 40°, this means that θ is 50°, which is equivalent to about 28% of the complete angle. This also means that, 28% of the total surface area of the semi-spherical dome is shaded. The concluded relationship can be clearly shown in the case of sunrise or sunset, when half of the dome (50%) is shaded due to the horizontality of sunrays. At these times, θ is 90°, which is equivalent to half (50%) of the complete angle (180°) (Fig. 7-b).

By knowing the radius of the semi-spherical dome and time and location of the study, the total surface area can be given and consequently, the areas that are shaded and sunlit.

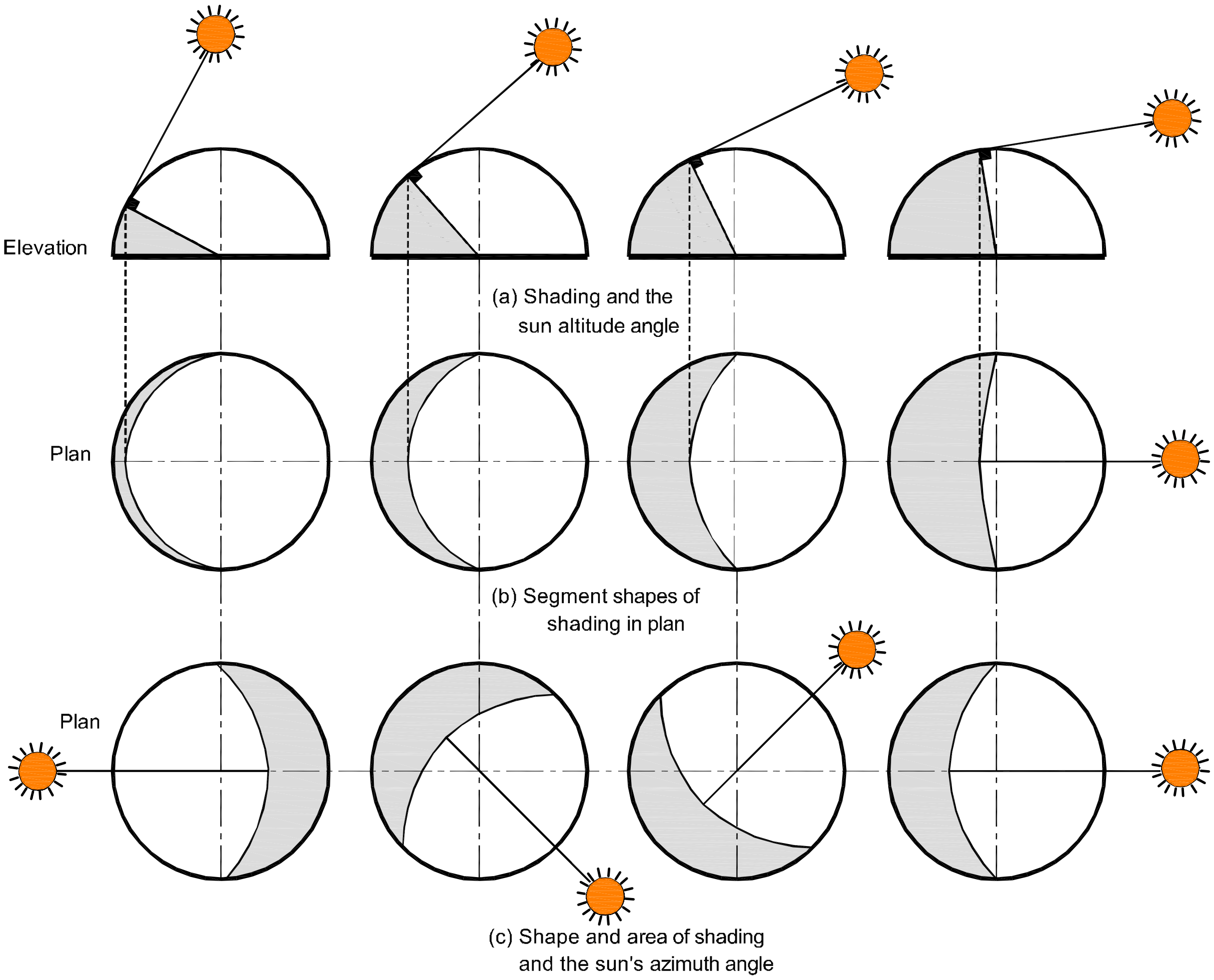
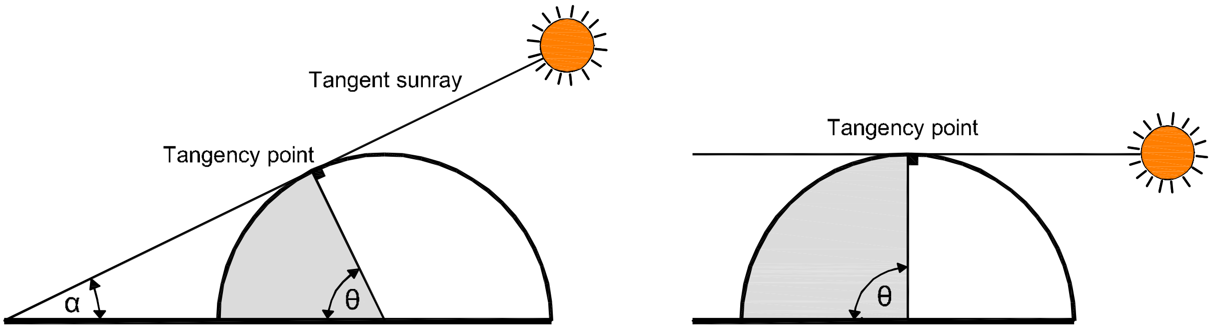


Fig. 6. Shading performance of the semi-spherical dome.



(a) At any time during the day

(b) At sunrise or sunset time

Fig. 7. The relationship between the sun's altitude and the shaded area.

This was validated and more explained through analyzing the shaded area generated on the main dome of Al-Said Hashim Mosque (Fig. 8). The figure shows a three-diminsisional analysis of the shade produced on the dome at 11:30 AM (local time), which is about 12:00 in solar time on 21st of December (the winter solstice day). This time was chosen because it is the time when the sun is at its lowest position, at this time, in the sky during the whole year. It is the most critical time during the year in terms of the dome’s shading performance, as at which the shaded area produced is the maximum area that would be generated during the year. The sun’s altitude angle at this time (α) is 35.5°, and consequently θ is 54.5°, which is equivalent to about 30% of the complete angle (180°). According to the developed relationship, the same percentage (30%) of the dome’s surface area is shaded, which is the case as clearly shown in the case study.

For more validation, the shade produced on Al-Said Hashim dome was simulated using Ecotect software at the same time and location (Fig. 9). Since Ecotect does not have the feature of computing the shaded area of the dome, the angles (α) and (θ) were measured on the side view of the shaded dome using AutoCAD software (Fig. 10). It was found that the measured angles were almost the same as those obtained from the real case study of Al-Said Hasim dome, which indicates that, the shaded area of the two cases are also equal. This validates the developed mathematical expressions and confirms the dependence of the dome’s shading performance, mainly, on the sun’s altitude angle.

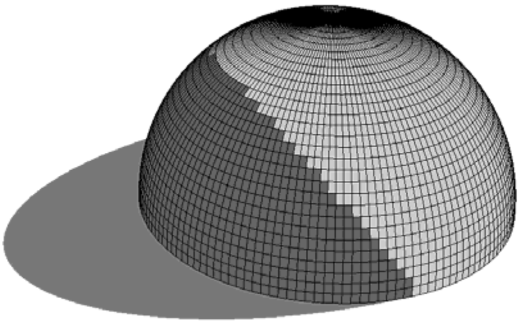


Fig. 9. **Shading simulation of Al-Said Hashim main dome using Ecotect software.**

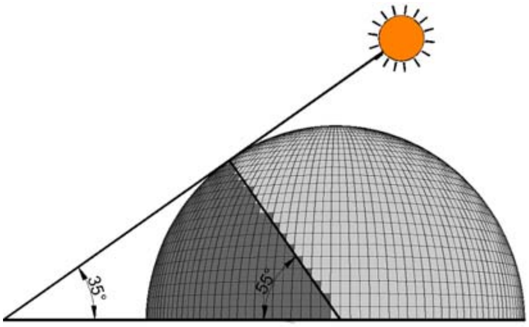


Fig. 10. **The measured sun’s altitude and θ angles on the shaded dome produced by Ecotect software.**

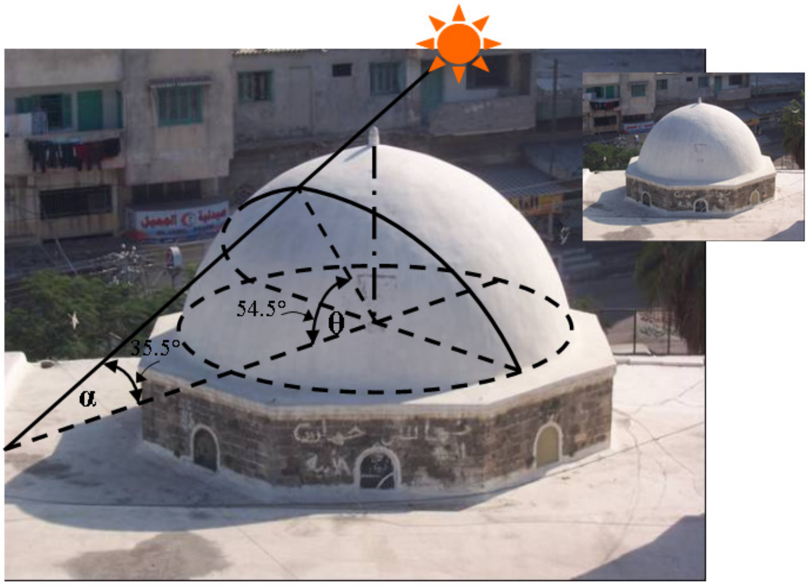


Fig. 8. Shading analysis of Al-Said Hashim main semi-spherical roof dome.

4. Computer Program

As mentioned previously, the shaded area produced on the dome is a function of θ, which depends on the sun's altitude angle. Angle θ can be given by the following equation:

$$\theta = 90 - \alpha \qquad (1)$$

where **α** is the sun's altitude angle.

The sun's altitude angle can be calculated numerically, as mentioned by Iqbal (1983), by the following equations:

$$\sin\alpha = \sin\delta \sin\phi + \cos\delta \cos\phi \cos\omega \qquad (2)$$

where

ω is the hour angle, noon zero and morning positive.
ϕ is the geographic latitude, in degrees, north positive.
δ is the declination, the angular position of the sun at solar noon with respect to the plane of the equator, north positive, in degrees.

The following empirical equation is used to calculate the angle of declination.

$$\delta = 23.45^\circ \sin\left(360\,\frac{(284 + a)}{365}\right) \qquad (3)$$

where a, is the day number in the year.

The shaded area of the dome's surface (**S**) can be determined accordingly as follows:

$$S = \left(\frac{\theta}{180}\right) \times D \qquad (4)$$

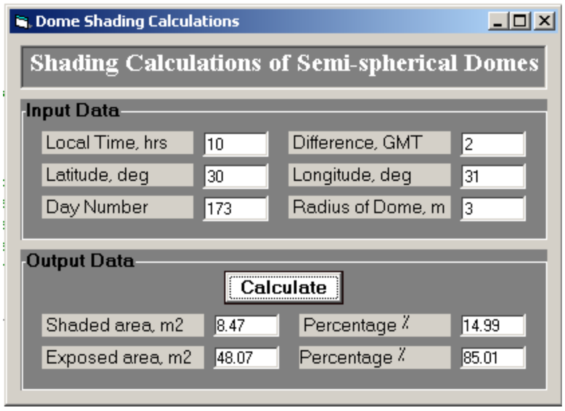
where **D** is the total surface area of the semi-spherical dome, which can be given by:

$$D = 2\pi r^2 \qquad (5)$$

The sunlit area of the dome's surface (**E**) is the rest of its total surface area, which can be calculated by:

$$E = D - S \qquad (6)$$

These simple mathematical expressions were applied on a computer model, using Visual Basic programming language, to avoid lengthy manual computations (Fig. 11). The input data required to perform the calculations are: the time and location determinants of the study and radius of the semi-spherical dome in question. The time is specified by the local time and its difference, in hours, from Greenwich Mean Time, depending on the time zone of the location. The day number states the day in the year in which the study is carried out. The location is identified by its latitude and longitude, which are available for every location on earth. The size of the dome is determined by the radius of its base. The output of the program are the shaded and sunlit areas produced on the dome, which are presented in meters square and as a percentage of the dome's total surface area.



Local Time, hrs 10
Difference, GMT 2
Latitude, deg 30
Longitude, deg 31
Day Number 173
Radius of Dome, m 3
Shaded area, m2 8.47
Percentage % 14.99
Exposed area, m2 48.07
Percentage % 85.01

Fig. 11. The developed program's interface.

5. Parametrical Study

A parametrical study was carried out using the developed model to investigate the shading performance of a semi-spherical dome in summer and winter in Gaza. The study was undertaken on the summer and winter solstices, i.e. 21 June and 21 December respectively, with the aim of finding out the effect of changing the time during the mentioned days on the shaded area in summer and sunlit area in winter generated on the surface of the dome. For this purpose, the shaded and sunlit areas were calculated in one hour intervals and plotted on an excel graph (Fig. 12). The graph clearly shows that in summer, the shaded area produced on the dome's surface decreases gradually as the time approaches midday where the minimum percentage of shaded area is generated (5%). Then the shaded area symmetrically keeps increasing in the same rate with the sun approaches to set in the west.

Apparently, this trend is referred to the symmetrical sun's motion about noontime. It is known that, as the time increases, the sun position in the sky (sun's altitude angle) becomes higher and consequently the sunrays hit larger area of the dome's surface. The graph shows that about 5% of the dome's surface area is shaded at midday (12:00 noon time) which is considered the most critical time during the year to generate shade, because at which the sun's altitude angle reaches the maximum.

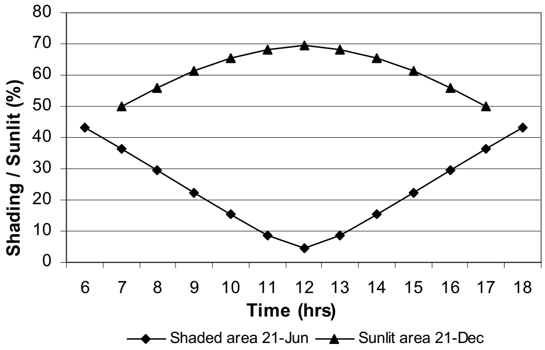


Fig. 12. **The time effect on the shaded and sunlit areas produced on summer and winter solstices.**

In winter, it is desirable to have as much areas exposed to the sun as possible to contribute to warm up the internal rooms. Clearly, the sunlit area increases as the time approaches noontime, then it symmetrically starts decreasing as the sun moves towards west. The maximum sunlit area (70%), produced at 12:00 noontime, is considered significant especially at this critical time when the sun is at its lowest position in the sky (with minimum altitude angle). The graph shows that at the sunrise and sunset times about 50% of the dome's surface area is sunlit. This is the minimum percentage of sunlit area that can occur due to the horizontality of the sunrays at these times.

Another study was undertaken to examine the performance of the dome in different latitudes at different times on the summer solstice. Figure 13 shows that as the latitude becomes higher or lower than 23.5°, the performance of the domed roof, in terms of producing self-shading, becomes better. The least percentage of shaded area on the dome is generated at latitude 23.5° regardless of the time during the day. However, with having the sun's altitude lower due to the sun's movement during the day, the effect of changing the latitude becomes smaller.

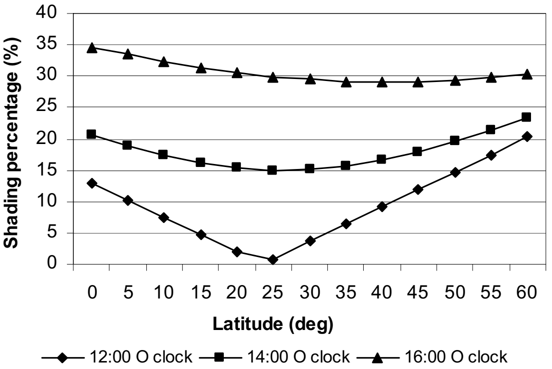


Fig. 13. **Effect of changing the latitude and time on the dome's shading performance.**

6. Conclusion

Semi-spherical domed roof is a traditional type of roofs that has been used in hot and temperate climates to produce shade and minimize the effect of the intense solar radiation incident on the roof. Al-Said Hashim Mosque was studied as a typical religious building covered by semi-spherical roof domes. Through observing the shading performance of the domes, it was found that the shaded and sunlit areas generated on the dome are dependent basically on the sun's altitude angle. Also, it was concluded that the ratio of angle θ to the complete angle (180°) is the same as that between the generated shaded area and the total surface area of the semi-spherical dome. Accordingly, mathematical expressions were developed to calculate the shaded and sunlit areas produced at anytime and anywhere on the earth. Having the expressions applied on a computer model helped to avoid the lengthy manual computations and facilitated carrying out a parametrical study into the effect of changing the time and latitude on the produced shading conditions.

The study showed clearly that the shading performance of the dome has a joint function with the time during the day. The generated shaded area decreases as the sun's altitude angle increases, whereas, the opposite occurs as the time moves away from noontime towards that of the sunset. The domed roof works better in terms of producing shading in summer at latitudes higher than 23.5°. The same trend was also noticed at latitudes lower than 23.5°. This is referred to the fact that the sun's rays are directly overhead along the Tropic of Cancer (the latitude line at 23.5° north) on June 21.

References

Bahadori, N. M. "Passive Cooling System in Iranian Architecture." *Scientific American*, Vol. 238, No. (2), (1978), 144-154.

Chel, A. and Tiwari, N. G. "Thermal Performance and Embodied Energy Analysis of a Passive House: Case Study of Vault Roof Mud-house in India." *Applied Energy*, Vol. 86, (2009), 1956-1969.

Faghih, K. A. and Bahadori, N. M. "Solar Radiation on Domed Roofs." *Energy and Buildings*, Vol. 41, (2009), 1238-1245.

Fathy, H. *Natural Energy and Vernacular Architecture*. Chicago, London: University of Chicago Press, (1986), 50 p.

Gomez-Munoz, M. V.; Porta-Gandara, A. M. and Heard, C. "Solar Performance of Hemispherical Vault Roofs." *Building and Environment*, Vol. 38, (2003), 1431-1438.

Hadavand, M. and Yaghoubi, M. "Thermal Behavior of Curved Roof Buildings Exposed to Solar Radiation and Wind Flow for Various Orientations." *Applied Energy*, Vol. 85, (2008), 663-79.

Iqbal, M. *An Introduction to Solar Radiation*. Toronto; London: Academic Press, (1983).

Islamicweb. "Gaza Mosques." (2002), retrieved January 10, 2007, from http://www.islamweb.net/ver2/archive/readArt.php?lang=A&id=17460

Muhaisen, S. A. "Solar Performance of Courtyard Buildings with Different Forms and Various Climatic Regions, Using a New Computer Model." *PhD Thesis, The University of Nottingham*, UK, (2005).

Muhaisen, S. A. "Shading Simulation of the Courtyard Form in Different Climatic Regions." *Building and Environment*, Vol. 41, No. (12), (2006), 1731-1741

Pearlmutter, D. "Roof Geometry as a Determinant of Thermal Behavior: A Comparative Study of Vaulted and Flat Surface in a Hot-arid Zone." *Architectural Science Review*, Vol. 36, No. (2), (1993), 75-86.

Runsheng, T.; Meir, I. A. and Etzion, Y. "An Analysis of Absorbed Radiation by Domed and Vaulted Roofs as Compared with Flat Roofs." *Energy and Building*, Vol. 35, (2003), 539-548.

State Information Services. "Tourism in Gaza Provinces." (1999), retrieved January 10, 2007, from http://www.pnic.gov.ps/arabic/tourism/tourism3.html

Tang, R.; Mein, I. A. and Wu, T. "Thermal Performance of Non-air-conditioned Buildings with Vaulted Roofs in Comparison with Flat Roofs." *Building and Environment*, Vol. 41, (2006), 268-76.

The Overseas Division of the Building Research Establishment. "Buildings in Hot Climates." *BRE NEWS*, Garston, (1980).

Wikipedia Foundation. "Gaza Strip." Retrieved January 10, 2007, from http://en.wikipedia.org/wiki/Gaza_Strip

Zanin, E. "Renewable Energy Resources in Palestine" [electronic version]. (2002), obtained from the Authority of Energy and Natural Resources in January 2007.

دراسة لوضع الظلال على أسقف المباني ذات القباب النصف كروية في قطاع غزة

أحمد سلامه محيسن

أستاذ مشارك، قسم العمارة، كلية الهندسة، الجامعة الإسلامية بغزة، فلسطين
amuhaisen@iugaza.edu

(قدم للنشر في ١٥/١٠/١٤٣٠هـ؛ وقبل للنشر في ١٥/٢/١٤٣١هـ)

ملخص البحث. تبحث هذه الورقة في قدرة الأسقف المقببة بشكل نصف كروي على توفير ظلال على أسقف المباني في المناطق المعتدلة مع التركيز بشكل خاص على قطاع غزة. أشارت الدراسة إلى قدرة هذا النوع من الأسقف على تقليل كمية الإشعاع الشمسي الساقط على السقف نتيجة لسطح القبة المنحني والذي يوفر ظلالاً بشكل طبيعي على سطحها الخارجي في أي وقت خلال النهار، ومن ثم توفير بيئة حرارية مريحة داخل المبنى. وللتأكيد على ذلك تم دراسة وتحليل مسجد السيد هاشم في مدينة غزة كنموذج للمباني الدينية والتقليدية المسقوفة بقباب نصف كروية. وبناءً على هذه الدراسة تم استنتاج بعض العلاقات والمعادلات الحسابية التي تربط بين موقع الشمس في السماء ومساحة المنطقة المظللة الناتجة على سطح القبة. ولتسهيل استخدام هذه المعادلات تم برمجتها وإخراجها على شكل برنامج كمبيوتر بسيط يمكن استخدامه لحساب مساحة كل من السطح المظلل والمعرض للشمس من القبة في أي وقت خلال السنة وفي أي موقع على الأرض. يذكر بأن تطوير هذا البرنامج ساعد الباحث على إجراء دراسة حول أثر اختلاف الوقت خلال النهار، بالإضافة لاختلاف خط العرض على مساحة الأسطح المظللة والمشمسة من القبة. وقد أظهرت الدراسة بشكل واضح أن هناك علاقة مباشرة بين الوقت ونسبة السطح المظلل أو المشمس من القبة، والتي تم التعبير عنها من خلال منحنيات توضيحية.