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Thermal study of domed roofs in a traditional bazaar (the case of old Ganj-Alikhan bazaar in Kerman, Iran)



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ABSTRACT

The impact of dome shaped roofs of various buildings on thermal comfort has been investigated by many researchers across the world. However, thus far, the advantage (or disadvantage) of multiple-domed roofs, which are most common in ancient bazaars of Iran, has not been evaluated. The subject of this article is to study the effect of shadows of multi-domed roofs on the receiving solar radiation on their surface temperature variation during a summer day. For studying, a numerical program for 3D geometry and quasi-steady state heat transfer is developed. The code is used to calculate and compare receiving solar radiation and temperature distribution on the dome roof as well as for flat roof in a hot summer day. Besides, effect of domes' orientation (north-south & east-west) and the ratio of height to radius of dome on the shadow area are determined during the day time. To validate the code, temperature distribution on the roof of numerical solution is compared with thermo-graphical pictures taken experimentally from Kerman's historical bazaar (for the same condition). The results show that despite the positive effect of using multiple-domed roofs on producing shadows, total heat transfer from roof is more in comparison with flat roofs. However, most part of the transferred heat is able to be convected out through the top opening of the dome.

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Introduction

In the past centuries, domed roofs have been widely used in mosques, cisterns and bazaars mostly due to lack of wood in central regions of Iran. Such roofs, in addition to structural and architectural considerations, played an important role in buildings ventilation for the warm and arid regions. In 1978, Bahadori (1978) introduced the role of domed roofs in building ventilation and keeping water in public cisterns cooler in warm seasons in Iran. Also, Najafi and Yaghoubi (2015) have investigated a relatively modern cistern benefiting from six separated windcathers that have been used in one of the hot and dry cities in Iran under different conditions. They realized that using cisterns can be efficient for keeping water cool during hot summer days. Receiving solar energy by a flat roof or a domed roof causes an increase of roof temperature in comparison with outside temperature. When wind blows on such roof, an amount of heat will be transferred outside and the rest will be transferred to the inside air. Over domed roofs, the speed of wind is higher and therefore convective heat transfer coefficient is higher and a larger part of heat will be taken back to the outside of building. By making an opening on top of a dome, a negative

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pressure will be produced by wind blow and an airflow will occur from inside of building toward this hole which can deliver an amount of the transferred heat from the ceiling of the dome. This makes the lower surface of the dome cooler and will reduce the exchange of radiation and convection between ceilings and the inside surfaces and air of the building (Najafi and Yaghoubi, 2015). Natural airflow inside the building, as shown in Fig. 1, can help the residents to have thermal comfort in hot summer days (Haghighi et al., 2015; Rahmatmand et al., 2014). Faghih and Bahadori (2009) experimentally determined the pressure coefficients over the roof for a 1/10 scale model of a real domical roof in the central desert region of Iran by the aid of a wind tunnel. Their model included a number of windows at the collar of the dome and a hole on its apex. Their tests were got under three conditions of windows and the hole being open or closed. They found that the maximum value of pressure coefficient is at the lowest point on the dome facing the wind for all the conditions. Also the minimum of pressure coefficient is at the apex only when the windows are all closed. In the further investigation (Faghih and Bahadori, 2010) they employed a numerical method to simulate the turbulent flow on the model. The numerical results for the pressure coefficients were in good agreement with the experimental results. In another investigation (Faghih and Bahadori, 2011), Faghih and Bahadori studied about domed roofs thermal performance by introducing a detailed thermal model in order to determine how they can be helpful in reducing the maximum

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Fig. 1. Air stream in an ancient bazaar with domed roofs and boundaries notation.

air temperature of inside buildings during warm days. Their results showed that the domical roof is better than the building with flat roof except for the no-wind condition. In order to improve the human comfort, they also mentioned the positive effects of using glazed tiles and openings for domical roofs.

Serpoushan and Yaghoubi (2002), have determined the amount of solar radiation on a flat roof, half-cylinder roofs, hemisphere roof and a real dome in Shiraz for one year. Their results show that solar radiation per unit area on a flat roof is more than other roofs. For half-cylinder roofs and hemisphere roofs it is approximately equivalent and on the domed roofs it is less than all of them. Runsheng et al., (2003) have computed the received solar radiation on cylinder roofs and compared with flat roofs. They have reported that the amount of received radiation on cylinder roofs is more than their equivalent flat roofs and their ratio does not change with geographical and weather conditions. Their study also show that the north-south cylinder roof has less radiation in summer and more radiation in winter in comparison with the east-west cylinder roof. In another study, Gómez-Muñoz et al. (2003) reported that the received radiation in Mexico on a hemisphere roof per unit area of its surface is 35% less than its equivalent flat roof which is similar to the results reported by (Serpoushan and Yaghoubi, 2002).

Kanagaraj and Mahalingam (2011) proposed a comprehensive design process (called Integrated Energy-Efficient Building Design Process) that provides a framework based on systems theory that facilitates the integration of various facets of the energy-efficient alternatives selection process. Their proposed framework seeks to aid designers in performing holistic building design. During a case study to design an office building, they found that sloped, vaulted and domical roofs were preferred against flat roofs in hot climates.

Haghighi Poshtiri et al. (2016) investigated application of a solar silica gel-water adsorption chiller in a one floor building with domed roof and a cooling channel under two different climatic conditions. They found that a minimum wind velocity of 0.8 m/s is needed to achieve a suitable air change rate. They also stated that the system's cooling production is less in humid climates.

Usage of domical roofs could be beneficial even in cold regions. Ouria et al. (2016) Analyzed shaded area of the Blue-mosque of Tabriz in Iran to assert its cold climate accordance. They found that the Blue-mosque compensates a portion of loosed area (flat area covered by shadows) by the extra surfaces of domes during winter. Also they found that its architecture formation provides a position to decrease at least 9.43 (l/h) gasoil during heating process of the building.

An important and interesting parameter about domed roofs is their effect on each other when they are organized sequentially and consecutively. This pattern had been used in several bazaars in Iran as shown in Figs. 2 and 4. Fig. 5 shows locations of cities with bazaars in Iran as well as the province of interest of this study. According to the Koppen-Geiger climatic classification for the middle-east, Kerman city is located in a hot arid climate (http://koeppen-geiger.vu-wien.ac.at/ pdf/kottek_et_al_2006_A4.pdf). Direct solar radiation is blocked for parts of a dome that are covered by the shadow of adjacent domes. In this research, three real and consecutive domed roofs (considering their geographical orientation and position) related to Kerman's Ganj-Alikhan bazaar (Fig. 3) is simulated. A numerical program with a 3D geometry and guasi-steady state condition is developed to model and compare the receiving solar radiation and temperature distribution on the domed surface and flat roof in a hot summer day. Computation will be made to investigate thermal condition of the domed roofs shown in Figs. 4 and 5. Texture of these domes is illustrated in Fig. 6.

Status and climate of Kerman

The state of Kerman with an area about 180,434 km² lies between 25.92° and 32° north latitude and 53.43° and 59.43° east longitude. This state containing 11% of total Iran's area covers a vast region of southeast section of central plateau of Iran. Unlike its location, it has not signs of a complete desert climate. Based on Fig. 5 the climate is arid and warm. This is due to the presence of wide mountains areas. Height of Kerman plain varies from 1650 m to 2100 m from sea level. The monthly normal climate of Kerman city is given in Table 1.

An overview of the traditional Ganj-Alikhan complex in Kerman

The Ganj-Alikhan complex (Fig. 7) used to be the center of Kerman in few decades ago. This complex was structured by Ganj-Alikhan who was the governor of Kerman (1596 to 1624) during reign of Shah-Abbas over Iran. Area of this complex is about 11,000 m² and it contains several buildings as: the square (built in 1596), the bazaar

a) Gheisarie bazaar (Lar)

(built in 1596), the bathroom (built in 1611), the mint, the school (built in 1598), the inn (built in 1612) and the cistern (built in 1612).

The square and its circumstance

In the past, main squares of cities in Iran were used to easily gather people for important announcements and rites. The square of Ganj-Alikhan complex is surrounded by the bazaar from three sides and by the inn (school) from one side as shown in Fig. 7. Its length and width are about 100 and 54 m.

The city public bathroom

The city public bathroom in Ganj-Alikhan complex is one of the most famous and earliest bathrooms in Iran. The tiling and modeling on the ceilings and walls have made it unique as shown in Fig. 8. Its area is about 1300 m².

Governing equations

Solar energy

In order to specify the amount of total irradiance received on the domes' surface, the outer layer is divided into several small areas and each part is assumed as inclined flat surface. Summation of total irradiance received on all segments will specify the summation of radiation received on the domes' surface. Fig. 10 shows the geometries for specifying solar radiation direction and angles for a typical inclined flat segment surface (Duffie and Beckman, 1980).

In this figure Θ_i is the incidence angle that is determined by the following relation.

$$\cos \Theta i = \cos \alpha \, \sin \beta \, \cos \left(\psi_{\rm s} - \psi_{\rm p} \right) + \, \sin \alpha \, \cos \psi_{\rm p} \tag{1}$$

The declination angle (δ), solar-time angle (ω), sun's azimuth angle (ψ_s) and zenith angle ($\Theta_z = 90 - \alpha$) are determined by relations (2–5).

$$\delta = 23.45 \, \sin\left(360 \frac{284 + N}{365}\right) \tag{2}$$

$$\omega = (t - 12) * 15$$

Fig. 3. Ganj-Alikhan bazaar (Kerman).



critical situations.

The inn

supervisions.

In the cistern of Ganj-Alikhan complex as shown in Fig. 9, a long corridor and many steps should be passed to reach the reservoir of

An inn is a place which is used for temporary habitation, loading,

In this article, studies will be made on thermal condition of a single

dome (Figs. 4 and 5) of Ganj-Alikhan bazaar (Fig. 3), located in the

main row of Ganj-Alikhan complex (Fig. 7).

unloading etc. Reasons for building such places were: economic and commercial reasons, security of people and commodities and political

water. Reasons for building cisterns in Iran were low precipitation and absence of rivers. These buildings helped people to save water for

The cistern





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(3)



Fig. 4. Ganj-Alikhan bazaar in city of Kerman, a) Aerial photo from the Ganj-Alikhan bazaar and the intended domes (google map) b) Schematic of Ganj-Alikhan bazaar and position of the thermographic view orientation.

$$\cos (\psi_s) = \frac{\sin \delta - \cos \Theta_z \sin \phi}{\sin \Theta_z \cos \phi}$$

$$(4)$$

$$\cos \Theta_z = \sin \delta \sin \phi + \cos \delta \cos \phi \cos \omega$$

$$(5)$$

where *N* is number of the day, *t* is solar-time and ϕ is latitude of the considering location.

Daneshyar (1978)) has offered a correlation that predicts radiation of sun with enough precision for almost 34 cities of Iran. According to this model, the beam radiation of sun without considering the effect of clouds, is determined by the following relation.

$$I_{b,(\Theta_z)} = 950(1 - \exp[-0.075(90 - \Theta_z)]), \quad \frac{W}{m^2}$$
(6)

Including the effect of clouds, the term (1-*CF*) will be multiplied to Eq. (6). The diffusive term of irradiance and total irradiance received on a horizontal surface are determined by the following relations.

$$I_{d,(\Theta_z,CF)} = 1.432 + 2.107(90 - \Theta_z) + 121.3CF \frac{W}{m^2}$$
(7)

$$I_{h,(\Theta_z)} = (1 - CF)I_{b,(\Theta_z)} \cos \Theta_z + I_{d,(\Theta_z, CF)}$$
(8)

For a tilted wall, the diffusive part of irradiance will be calculated by:

$$I_{d,\beta} = \frac{1+\cos\beta}{2} * I_d \tag{9}$$



Fig. 5. The cities with bazaar and status and climate of Kerman province.



Fig. 6. Texture of domes in Ganj-Alikhan bazaar.

The magnitude of reflected radiation from ground can be found by:

$$I_{ref,\beta} = I_{hor} * \rho_g * \frac{1 - \cos\beta}{2}$$

$$\tag{10}$$

Where ρ_g is the ground's coefficient of reflection and is usually assumed 0.2. Therefore total irradiance on an inclined surface is:

$$I_{glo,\beta} = I_{dir} \cos \Theta_i + I_{dif} \frac{1 + \cos \beta}{2} + I_{glo,hor} * \rho_g \frac{1 - \cos \beta}{2}$$
(11)

Geometry of vaulted roofs

The approximate curve that is considered for domes of bazaar is an ellipsoid with a circular base. This kind of geometry as shown in Fig. 11 is usually expressed "spheroid" with the following relation.

$$z = C \sqrt{1 - \left(\frac{r^2}{R^2}\right)} \tag{12}$$

Here *C* is the height of the dome, *R* is the radius of base and *r* is the radius of the sections which are parallel to the ground. The parameters *x*, *y* & *z* are the Cartesian coordinates of the differential elements.

Each cell in the computational domain is named by three individual indexes (i,j,n). Where *n* is used for numbering the layers and i & j are used for numbering the cells in each layer as shown in Fig. 11.

In order to generate mesh on the outer layer of the dome, two independent angles (u & v) are used. One for making several belts around the dome and the other for dividing these belts into equal sections. Using these variables, the coordinates of nodes on the surface of dome can be generated by relations (13), (14) and (15). In these relations *u* changes from 0 to $\pi/2$ and *v* changes from 0 to 2π . The magnitudes of increments ($\Delta v & \Delta u$) are altered by the amount of grid numbers.

$$x = R \cos u \cos v \tag{13}$$
$$y = R \cos u \sin v \tag{14}$$

$$z = C \sin u \tag{15}$$

The number of belts, number of sections in a belt and number of layers had been chosen 200 & 200 & 10 respectively. Independency of solution from the mesh and creating shadows with high resolution were reasons for these numbers. Maximum amount of aspect ratio for these 400,000 nodes found to be 4.

Table 1
Weather condition in Kerman [from Meteorological Organization of Iran].

Description	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.
Max average temp. (°C)	23	31.2	23.6	37.8	35.5	31.7	30.2	23.3	10.7	11.9	14.3	17.2
Min Average Temp. (°C)	6.8	13.1	13	18.9	16.2	10.5	9.8	6.4	-3.2	- 5.5	-2	2.6
Absolute max temp. (°C)	29.4	35.9	36.4	41	40.2	33.2	32.5	28	17.4	18.4	19	23.6
Absolute min temp. (°C)	0	6.8	9	13	8	5.6	6.4	-0.4	-11.6	-14	-8.4	-2.2
Average temp. (°C)	14.9	22.2	18.3	28.4	25.9	21.1	20	14.9	3.8	3.2	7.1	9.9
Monthly precipitation (mm)	34.1	3.1	_	_	_	_	_	1.6	17.8	8.7	51.9	17.1
Max precipitation in a day (mm)	11.5	2.8	-	-	-	-	_	1.6	5.8	5.5	15	5.4
Relative humidity at 6:30 (%)	60	41	28	26	28	30	30	58	87	68	80	68
Relative humidity at 12:30 (%)	23	15	11	10	10	11	10	25	52	29	40	31
Maximum wind speed (m/s)	18	17	9	12	14	9	11	12	11	15	15	18



Fig. 7. The Ganj-Alikhan complex in Kerman.

Coordinates of first sublayer are named like (x', y', z'). If one consider the center of the ellipsoid as the center of Cartesian coordinates and assume constant thickness "*l*" for all cells in the direction of a line that connects the center to the outer layer points (x, y, z), then:

$$l = \sqrt{(x'-x)^2 + (y'-y)^2 + (z'-z)^2}$$
(16)

By using equations x'/x = y'/y = z'/z and Eq. (16), the nodes of first sublayer will be obtained. In the same way nodes of subsequent sublayers will be specified.

Shadow calculation

Consider \vec{V} as vector of sun and \vec{N} as normal unit vector of each dome's surface cell shown in Fig. 12. The dot product of \vec{V} and \vec{N} must be positive for creating shadow on a cell surface (\vec{V} . \vec{N} >0).

Consider formation of shadow on a dome due to neighbor of domes, such as Fig. 13. These domes are taken to have the same orientation of Figs. 3, 4, for the main Ganj-Alikhan bazaar direction. Having the vector of sun and the coordinates of neighbor domes (x1, y1, z1), several lines can be



Fig. 8. The city public bathroom in Ganj-Alikhan complex.



Fig. 9. The cistern of Ganj-Alikhan complex.

produced by following relation:

$$\frac{z-z1}{\overrightarrow{V} \cdot k} = \frac{y-y1}{\overrightarrow{V} \cdot j} = \frac{x-x1}{\overrightarrow{V} \cdot i}$$
(17)

Solving the system of Equations (17) and (12), shadow area for any specific time over each dome due to neighboring dome will be determined.

Method of solution

Some parameters are needed for computing solar radiation on each dome surface. These are: cells position, cells normal vector, orientation of bazaar (domes), area of cells, latitude of the place, solar time, number of the day, cloud factor of sky, emissivity of the surface and coefficient of refraction of solar radiation from ambient (sky and ground).

Knowing cells position and normal vectors and orientation of the bazaar is important for determining shadow on each dome. Varying the orientation causes significant impact on the shadows especially near sunrise and sunset. By having number of the day, latitude of the place and solar-time, the vector of sun is defined. To apply the exact orientation of bazaar, the suns vector is rotated instead of changing the place of domes, and this scheme is applied for other orientations.

Three possible cases may generate for a cell on the dome surface:



Fig. 10. Geometry of solar radiation on an inclined surface.



Fig. 11. Variation of computational indexes in spatial coordinates.

- 1) For first case, the dot product of suns vector and surface cells normal vector may become negative and indeed the nearby domes don't create shadow on that cell. In this case solar energy received on the cells surface is computed by Eq. (11).
- 2) In the second case, the dot product of suns vector and surface cells normal vector becomes positive. For this situation the following relation is used.

$$I_{glo,\beta} = I_{dif} \frac{1 + \cos\beta}{2} + I_{glo,hor} * \rho_g \frac{1 - \cos\beta}{2}$$
(18)

3) In the third case, the nearby domes create shadow on the cell. Like the previous case, the Eq. (18) will be applied.

To calculate thermal energy conducted across the roof thickness to inside area, several factors such as heat transfer between the domes surface and ambient air by convection and also radiation exchange between the domes surface and sky & ground should be included. For these parameters, convection coefficient is determined with the aid of empirical relations. However, the elements of heat transfer are:

- Total irradiance of sun (direct, diffusive and reflective) on the domes surface
- Heat transfer between the domes surface and ambient air by convection
- Radiation heat transfer between the domes surface and sky & ground
- · Convection heat transfer between the inner surface of dome and inside air
- · Convection heat transfer between the sidewall of the top hole and inside air passing through it
- Conduction heat transfer between any two adjacent elements in the dome

Radiation exchange between domes is neglected. Convective heat transfer coefficient is defined by (Yazdanian and Klems, 1994):

$$h_0 = \sqrt{h_n^2 + \left[2.38V_w^{0.89}\right]^2}, W/_{m^2K}$$
(19)

In this relation V_w is the velocity of free stream near the wall in m/s (Faghih and Bahadori, 2007). Usually the boundary layer profile of air velocity near the ground is approximated by the following relation [19].

$$\frac{V_h}{V_H} = \left[\frac{h}{H}\right]^a \tag{20}$$

Where *h* is the elevation of the point with unknown velocity and $V_H \& H$ are the velocity and height of the reference point. Values of 400 m and 0.28 had been recommended for H & a respectively (Penwarden and Wise, 1975).



Fig. 12. Shadow creation on a dome and samples for normal and sun vectors.



Fig. 13. Sun rays and shadow formation due to neighbor dome.

Since the surfaces are curved, Eq. (20) should be modified to approximate wind velocity near surface of the dome. Therefore according to the high values of Reynolds number (higher than 10⁵), potential flow relations is used to specify the velocity distribution on the dome (Hess, 2012), as follows:

$$V_{w} = \sqrt{(u_{\theta}^{2} + u_{T}^{2})}$$
(21)

$$u_{\theta} = -U_{\theta} \sin \theta \tag{22}$$

$$u_{\rm T} = U_{\rm T} \cos \Theta \tag{23}$$

$$U_{\theta} = U_{inf}G(f) \tag{24}$$

$$U_T = U_{infG(f)} \sin\left(\frac{\pi}{2} - \beta\right) \tag{25}$$

$$G(f) = \frac{2\left(1 - f^2\right)^{3/2}}{\left(2 - f^2\right)\sqrt{1 - f^2} - f\cos^{-1}f}$$
(26)

In the above relations U_{inf} is the free stream velocity from (20), Θ is the angle between direction of the free stream and points that had been generated on the surface and f is the fineness ratio that is defined as the length of the body along its axis of symmetry divided by the diameter of the largest circular cross section.

In Eq. (20), h_n is the natural convection coefficient. There are two formulation available for upward and downward heat transfer coefficient (ASHRAE, 1997),

$$h_{n} = 9.482 \frac{\sqrt[3]{|\Delta T|}}{7.238 - |\cos\beta|}, W/_{m^{2}K}$$

$$h_{n} = 1.810 \frac{\sqrt[3]{|\Delta T|}}{1.382 + |\cos\beta|}, W/_{m^{2}K}$$
(27)
(28)

Table 2Measured data at July, 7, 2015 from 6 AM to 6 PM of solar-time.

Solar-time	Out. temp. (°C)	Ind. temp. (°C)	Total horizontal irradiance (W/m ²)	Wind vel. (km/h) & direction
6	23.8	24.8	107	18 NE
7	25.5	26	321	18 N
8	28.1	27.9	524	19 N
9	29.6	29.2	704	19 N
10	32.1	30.2	845	18 NE
11	33.2	31	981	18 NE
12	35.2	32	1027	20 NE
13	35.5	32.2	993	24 NE
14	35.8	33	857	25 NE
15	35.8	33.5	719	25 NE
16	36.2	33.6	535	25 NE
17	35.4	33.5	304	25 NE
18	34.5	33.2	97	20 NE

Where ΔT is the temperature difference between the ambient air and each point on the surface. Radiation heat transfer between surface of the dome and sky can be computed by:

$$Q_{rad,s} = \varepsilon \sigma \left(T_s^4 - T_w^4 \right) \left(\frac{1 + \cos\beta}{2} \right)$$



Fig. 14. Comparison of thermal structures of dome surface from numerical computation and experimental measurements for different hours during daylight date July 7, 2015 (Ganj-Alikhan bazaar in Kerman).

(29)



Fig. 15. Comparison of temperature distribution on a line is specified in Fig. 14 at 15:00 date July 7, 2015 (Ganj-Alikhan bazaar in Kerman).

$$T_{s} = \varepsilon_{s}^{0.25}(T_{ao} + 273.15), K$$
(30)
$$\varepsilon_{s} = 0.74 + 0.006T_{dn}$$
(31)

In addition, radiation heat transfer between the outer surface of the building and the ground is:

$$Q_{rad,g} = \varepsilon \sigma \left(T_g^4 - T_w^4 \right) \left(\frac{1 - \cos\beta}{2} \right) \tag{32}$$

In this equation T_g is the temperature of ground which is considered equal to ambient temperature.

After applying the required relations at each specified region in the discretized energy equation, temperature equations can be obtained. For intermediate elements the following equation is used.

$$T_{n}(i,j) = \frac{k_{n-1}T_{n-1}(i,j) + k_{n+1}T_{n+1}(i,j) + k'_{n}T_{n}(i-1,j) + k''_{n}T_{n}(i+1,j) + k_{n}^{(3)}T_{n}(i,j-1) + k_{n}^{(4)}T_{n}(i,j+1)}{k_{n-1} + k_{n+1} + k'_{n} + k_{n}^{(4)} + k_{n}^{(3)} + k_{n}^{(4)}}$$
(33)

Where n is the index of layers, i is for the specified position of belts and j is a number that identifies position in belts. Coefficients that are shown by k are the conduction coefficients that are multiplied and divided by relevant areas and center to center distances. Differences between these coefficients comes from changes in distance between adjacent elements, areas of faces of an element and shape of elements. Indeed, Eq. (33) is



Fig. 16. Percent of shadow on a dome with different orientations during daylight of July 7, 2015 (Ganj-Alikhan bazaar in Kerman).



Fig. 17. Percent of shadow on a dome with different ratios of C/R during daylight of July 7, 2015 (Ganj-Alikhan bazaar in Kerman).

used for cells that are positioned below of the dome (region 4 in Fig. 1), without considering any heat transfer between these cells and walls of the bazaar.

Energy equation for the cells exposed to ambient air (and ground & sky) needs more attention. For this kind of cells the central difference method cannot be used for discretization of energy equation in the direction toward ambient air since only the external surface of the cell is in contact with the surrounding. Therefore the cells surface temperature is estimated by interpolating between temperatures of ambient air and adjacent cell in direction of domes thickness. This estimation is used by considering a linear variation for temperature. For instance the following equation is used for the outer surface cells of the dome (region 2 in Fig. 1).

$$T_{1}(j,k) = \frac{a_{1}k_{2}T_{2}(j,k) + a_{2}hT_{out} + Q + a_{2}h'T_{s} + a_{2}h''T_{g} + k_{1}'T_{1}(j-1,k) + k_{1}''T_{1}(j+1,k) + k_{1}^{(3)}T_{1}(j,k-1) + k_{1}^{(4)}T_{1}(j,k+1)}{a_{1}k_{2} + a_{2}h' + a_{2}h' + a_{2}h'' + k_{1}' + k_{1}^{(3)} + k_{1}^{(4)}}$$
(34)

Where $a_1 \& a_2$ are coefficients that are used for obtaining the surface temperature by interpolation. Eqs. (29) to (32) are used for specifying the coefficients h' & h'' and Eqs. (20) & (22)–(28) are used to determine coefficient h in the above equations. Similar to the conduction coefficients, these convective and radiative coefficients are multiplies of several parameters that can be obtained from the equations quoted. Note that in each iteration, the magnitudes of h, h' & h'' is altered due to changes in temperatures.

Measurements

The dome considered belongs to a traditional bazaar of Kerman (Ganj-Alikhan, Figs. 3–4). Its exact GPS coordinates is (30°17'26.44"N

 $\&~57^\circ4'42.89''E)$ and its orientation have a difference about 70° from the north axis (Fig. 4b).

For thermal measurement, Testo922 thermometer, Kipp&Zonen pyranometer, Testo417 anemometer and Testo881 thermograph are



Fig. 18. Variation of mean convection coefficient (\overline{h}) and wind velocity during daylight of July 7, 2015 (Ganj-Alikhan bazaar in Kerman).

used. The thermograph device provides accuracy within ± 2 °C. All data are measured at July/7/2015 from 6 AM to 6 PM of solar-time and presented in Table 2.

Numerical solution procedure

As explained in Section 4, except intermediate elements that undergo a similar condition, different forms of energy equation is used for boundary cells according to their position. Cells on boundaries 1 & 3 of Fig. 1 are in contact with inside and ambient air respectively. Cells on boundary 2 besides having contact with ambient air, have radiation heat transfer with sky and ground. Cells on boundary 4 exchange heat with nearby elements in five directions and it is assumed that they have not any heat transfer with walls of the bazaar.

For roof material in Fig. 6, conduction coefficient is assumed k = 2 W/mK (clay). For the inner surface of the dome, due to the presence of a hole in the middle of dome and creation of considerable airflow over the ceiling, a convection coefficient of 7 W/m²K is considered and radiation heat transfer is assumed to be negligible (http://koeppen-geiger.vu-wien.ac.at/pdf/kottek_et_al_2006_A4.pdf). Convection coefficient for the surface of the hole is calculated by using Eq. (19). Air velocity in this area is derived from Bernoulli relation considering the height of the ceiling and the magnitude of wind velocity on top of the dome. Same conditions are assumed for the flat roof, except that the inner convection coefficient is considered 4 W/m²K due to slower air flow motion.

Ambient and inside air temperatures (exactly above and below the investigating dome) and wind velocity and direction are used as inputs for the problem in each hour. By using finite volume method (Versteeg and Malalasekera, 2007) the system of energy equations are solved explicitly with an initial guess for all nodes temperature. The equations are solved in a general loop to the extent that the intended error rate is achieved.

Two examinations are applied to ensure the convergent of temperatures during trial and error iteration. First, the amount of transferred heat among the layers are compared; which is the heat enters from outside into the first layer of the dome, from the first layer to the second and..., and from the last layer to the air in the inside space. The proximity of amounts of transferred heat between layers is a good sign of the precision and convergence of solution. More specific parameters were the amounts of temperature of the cells in each step are compared with previous iteration and the mean amount of inequalities for all cells are monitored as the residual.

Results of solar simulation

To analyze thermal condition, solar radiation over the dome surface, rate of heat transfer from the roof, shadow area on the roof, convection coefficient on the roof and the impact of dome aspect ratio in receiving solar radiation, Eqs. (19)-(34) are solved explicitly in a quasi-steady state condition.

Three adjacent domes are considered in the traditional bazaar of Kerman (Ganj-Alikhan). Their exact location and orientation are shown in Fig. 4. Dimensions related to the domes are as: 3.5 m outer diameter, 0.45 m thickness, 1.6 m height, 0.5 m hole diameter, 3.5 m distance between two adjacent domes from center to center. Outdoor and indoor data are the values measured for July, 7, 2015 and reported in Table 2.

Fig. 14 shows temperature distribution on the dome for different hours of the day (solar-time). The left side pictures are from thermograph, Testo 881, and the right side pictures are results of solving radiation equations. Notice that all pictures have been taken from a specific position (geographically), shown in Fig. 4b.

Fig. 14 illustrates that temperature patterns from numerical solution are close to those from thermographical pictures. However, in order to investigate more carefully, temperature distribution on a belt on outside surface of the dome shown in Fig. 14 at 15:00 which is 1 m distant from the dome base are plotted in Fig. 15. This illustration displays temperature distribution on the belt for both numerical and thermographical measurement. Simulation results are consistent with the experimental measurements (<2 °C error). Also the validity of the quasi-steady state hypothesis based on the similarity of temperature changes on the belt between numerical and experimental results is confirmed. Note that L in Fig. 15 is total length of the intended line projected on the horizontal axis.

Fig. 16 shows the ratio of outside surface of the dome shadow to its total outside surface during the day. In the beginning hours of the day (6,7, 8 AM) and late afternoon, the effect of the adjacent domes on the occurrence of the shadow is more pronounce. For instance, changing orientation from north-south to the real conditions, causes the ratio of shadow area of dome to its total area to increase about 20% at 6 AM. Also dome shadows have not any effect on each other around noon. Similarly domes that are in a complete north-south or east-west orientation, would have a symmetric diagram with respect to 12 O'clock. Note that Figs. 16, 17 and 18 are drawn without considering the upper hole of the domes.

Fig. 17 presents the changes of shadow section of the dome which is due to changes of the ratio of height to radius of the dome (C/R) during the day. It can be seen that the higher this ratio is, the percentage of surface of the dome that is in shadow, raises simultaneously. About 90% of the surface of the dome with C/R = 4 is under shadow at 6 AM. However, higher shadows for C/R > 1 in Fig. 17 can be another concern for the high effect of adjacent domes. As C/R, the percentage of shadows decreases and becomes similar to flat roof and effect of adjacent domes vanishes. Since domes are not in a complete north-south or east-west orientation, diagrams in Figs. 17 and 20 are not symmetric with respect to 12 O'clock due to presence of neighboring domes.

Results of thermal balance

Fig. 18 shows changes of average convection heat transfer coefficient over outside surface of the dome and equivalent flat roof during the day. This figure indicates that due to higher speed of the airflow on the curve surfaces and due to higher temperature of the dome surface (in comparison with the flat roof), convection coefficient on the domed roof is more than the flat one. By increasing the air velocity from 18 km/h at 6 AM to 24 km/h at 14 PM, convection coefficient on the dome increased from 12.5 W/m² K at 6 AM to 16.5 W/m² K at 14 PM.

Fig. 19 displays variation of heat transfer into the domed roof for the real direction, north-south & east-west directions and also flat roof with equal base area. According to this illustration, for all hours total thermal heat going through flat roof is less than the domed roofs. At 6 AM the heat entering the domed roof is nearly 1.7 times the heat entering the flat roof with the same base area. For times close to noon hours of the day, the difference becomes less. Another point is the equal value of entering heat into the domed roofs for different orientations. However, the amount of the total daily transfer of heat into the domes with north-south orientation is slightly more than other orientations. It should be noted that natural convection below the dome roof due to top hole which remove heat due to stack effect is not considered. This effect reduces thermal load of dome roof considerably and might have greater effect in comparison to the production of shadow by neighboring domes.

Fig. 20 shows the changes of total solar radiation reached on the dome surface due to the changes of C/R. In this figure, the area of the dome base are the same and considered equal to the main dome base. It can be seen that similar to variation of Fig. 17, the radiation reached to the surface of the domes relates directly to C/R ratio. This means that due to the increase of dome height, a ratio of total outside surface exposed to the shadow raises. However, because of the enlargement of the dome surface, indeed solar radiation received on the surface swith



Fig. 19. Variation of total hourly heat transfer from dome to inside air for different dome orientation during daylight of July 7, 2015 (Ganj-Alikhan bazaar in Kerman).

C/R = 4 can reach 4 times more than the domes with C/R = 0.25. It can be concluded that total amount of solar radiation reached on a flat roof is always less than the domed roofs with the same base area.

Conclusion

In this study, by measuring outside and inside air temperatures, solar radiation reached on the dome's surface and speed and direction of the wind for a traditional bazaar in Iran (Ganj-Alikhan bazaar in Kerman), it is tried to thermally simulate three consecutive domes from the main row of bazaar. By considering three consecutive domes (shown in Fig. 4) and calculating heat transfer to the middle dome and an equal based flat roof (with completely same environmental conditions), the effect of continuous domed roofs has been studied. The results showed:

- 1- Although the shape of the dome had a positive effect for creating shadows and the presence of the adjacent domes increases the amount of shadow on the main dome, the net heat entered to the domed roof is still more than the flat roof.
- 2- Changing orientation from north-south to the real conditions, causes the ratio of the shadowed area of the dome to its total area to increase about 20% at 6 AM. However, the heat entering from the domed roof for certain hours, is nearly 1.7 times the heat entering from the flat roof with the same base area.
- 3- Increasing the dome height, ratio of the total outside surface exposed to the shadow raises. However because of enlargement of the dome surface, solar radiation received on the surface generally increases.
- 4- Considering early hours in the morning, although about 90% of the surface of the dome with C/R = 4 is under shadow at 6 AM, solar



Fig. 20. Variation of total solar radiation reached on the dome surface for various C/R during daylight of July/7/2015 (Ganj-Alikhan bazaar in Kerman).

radiation received on its surface can reach 4 times more than the dome with C/R = 0.25.

- 5- One of the factors which influences the efficiency of domed roofs is the speed of airflow on it. If the speed of airflow is low, convection coefficient for the outside surface of the dome cannot increase enough. By increasing the air velocity from 18 km/h at 6 AM to 24 km/h at 14 PM, convection coefficient increased from 12.5 W/m² K at 6 AM to 16.5 W/m² K at 14 PM.
- 6- Overall, considering the results of this investigation, increasing the amount of shadow by building traditional bazaars in Iran with multiple domes in a row could not be the main reason of thermal comfort obtained in these vernacular buildings. Other features of such vaulted roofs like the production of stack effect due to the presence of top hole, might have greater effect in comparison to producing shadow by neighboring domes.

Nomenclature

С	Height	of dome
-		

- (H),h Convection coefficient, (elevation)
- I Irradiance
- i,j,n Position index
- K Conduction coefficient
- L Thickness of dome
- N Number of day
- R Radius of dome
- T Temperature
- T Solar-time
- u Velocity
- U, V_0 Reference velocity
- *V_w* Velocity near surface
- x,y,z Cartesian coordinates
- B Slope angle
- Δ Declination angle
- E Emissivity of surface
- $\varepsilon_{\rm s}$ Emissivity of sky
- Θ_i Incidence angle
- θ_z Zenith angle
- σ Stefan-Boltzmann constant
- φ Latitude angle
- ψ Azimuth angle
- ω Hour angle

Subscripts

- T Tangential
- a Ambient
- b Beam
- d Diffuse
- dp Dew-point
- g Ground
- h Horizontal
- s Surface
- Θ Circumferential

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