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Thermal Behavior of Domed Roofs, Case Study: Historical Dome-Shaped Roofs of Isfahan*

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ABSTRACT: As a covering method of buildings` roof, domed roofs have mostly been applied in Iranian vernacular architecture and also in the Middle East region according to adobe material abundance comparing with timber. Furthermore, dome remains in the first place in architectural designs due to large area coverage and favorable thermal performance; so that it has been widely utilized in mosques, shrines, churches, bazaars and schools construction. On this account, the current research studies the role of shape in roofs energy loss, specifically throughout a day or year to achieve an optimized form. The paper compares of different domed roofs in hot and dry climatic zones of Iran, speciallyIsfahan city. The research method is based upon modeling and simulation as an alternative to field-based research. To achieve this goal, ten different types of domes are selected, modelled and simulated in energy soft-wares, such as Autodesk Ecotect 2010 and Energy plus 7, while categorizing arches based on inscribed arc angle in three types. The paper is to find a way to recognize the most efficient form of buildings domed roof which can be designed and applied in further contemporary construction and buildings. The result shows that the more roof area, the more building energy consumption is. This means that the dome with lower rise appears in more appropriate thermal performance since it has the least surface area; so type 1, dome with an inscribed arc less than 180 degrees has not only less surface area, but also least energy loss resultant.

Keywords: Roof Shape, Domes Arch, Thermal Performance, Energy Simulation, Hot and Dry Climate.

INTRODUCTION

Presently, energy demand, as a vital economic requirement, plays an important role in increasing energy price, considering nonrenewable resources limitation and costs. Accordingly, parallel to efforts made to tackle the energy upgrading costs, improving energy efficiency and conservation in buildings are considered as main solution to the problem.

In addition to applying thermal insulation in buildings, it is extremely significant to implement energy-efficient strategies and approaches to decrease energy transfer rate in construction sector. Directly

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influenced by climatic condition, building elements specifically, roofs play an important role in heat transfer rate in a structure and as buildings covering compose in a large area of buildings envelope.The following paper studies roofs shape thermal behavior based on building heating load by emphasizing the domed shaped covering; Furthermore it explains why domed and vaulted models had been extensively used in traditional and vernacular buildings in hot and dry regions specifically in previous Iran architecture samples.

Discovering the role of domed shape roofs in energy loss at night time in hot and dry climate is an attempt to find the most efficient form of buildings which might be suitable for contemporary architecture of developing countries especially in Iran. The case study of this paper is selected from Isfahan historical mosques` domes since those are the most outstanding masterpieces of Iran. Furthermore, paper uses a computerized simulation methodology as an alternative to field-based research. By modeling and analyzing different geometrically classified domed covering types, consequently the final result will be discussed.

DOMES AND DOMED SHAPED ROOFS IN TRADITIONAL ARCHITECTURE

Domed roofs have traditionally been used throughout the world to cover large area and spans. In Iranian architecture, they have played another significant role of reducing the total heat gain from the roof and providing a passive cooling effect for the building they served (Haghighat & Bahadori, 2011, pp. 1254). Domes play very important role in building stability (Mahdavinejad et al., 2012, pp. 133-147) therefore are very important in architectural design (Mahdavinejad & Moradchelleh, 2011, pp. 677-682) especially when we want to interact traditional architecture and contemporary architecture of Iran (Mahdavinejad et al., 2012, pp. 176-183). Usage of indigenous architectural patterns and modeling traditional achievements (Mahdavinejad & Moradchelleh, 2012, pp. 2930-2935) are suitable ways to fulfill a helpful strategy (Mahdavinejad & Moradchelleh, 2012, pp. 1068-107) for contemporary architecture (Mahdavinejad & Moradchelleh, 2011, pp. 554-560) which roots in traditional architecture of hot and dry climate. In addition to Aesthetical characteristics, the presence of domed roof covered by glazed tiles and ventilation possibility through exterior skylight provide the buildings with more efficient thermal performance; so that, it was occasionally considered as the only solution to optimally design in traditional architecture and dealing with extremities of the climate. Accordingly, long ago, there have been myths about ideal performance of dome shape roofs so that currently, many believe that it carries less energy loss in comparison to other architectural forms; whether correct, the claim has not experimentally been proven.

METHODOLOGY AND RESEARCH PROCESS

Research Goals: Considering energy as an economic indicator, many industrial and developed countries apply energy friendly methods to compensate financial and economic issues related to. Furthermore, energy efficient design in building and its elements specifically roof design plays an effective role to lever the rate of energy use in construction sector. Moreover due to roofs large area covering in urban scale, buildings with low energy elements are effective in energy consumption reduction in an urban area. This paper intends to numerically achieve optimized form in domed shaped roofs while comparing them with traditional constructions, in terms of geometry and to evaluates thermal performance of aforementioned types.

Research Questions: 1- What is the role of roof shape in energy loss at night? 2- Is there any relation between the arch of dome and energy loss characteristics?

Research Method: Research approach is simulation and modeling (Groat & Wang, 2002, pp. 275-300) and applied techniques are numerical-comparative ones according to case study selection.

This paper adopts computerized simulation methodology as an alternative to field-based research. Computerized simulation provides a virtual environment to survey the thermal behavior of building elements in details. The results won't have any time and numerical limitations and it is possible to construct any building. In this research, energy plus software ver. 7 was used for simulation which is an independent simulation engine. The results are represented numerically and graphically. To have simulation methodology, firstly, the models are simulated in Ecotect software as graphic medium and then the model geometry (saved as an.idf file) is transferred to energy plus software to be calculated. The simulation weather date is based on Isfahan city, in Iran.

Buildings Form and Energy Loss: In the way of exploring sustainable solutions for energy efficiency construction, dow building solutions plays the leading and exploring role in energy consumption. Combined with global experience and local knowledge, there is a large scope of solutions to reduce the rate of energy loss in construction industry. To Increase the efficiency of heating and cooling equipment, the insulation increase for the building envelop and imposing building standards all are considered as contemporary solutions toward minimizing energy loss; (Soltandoost, 2011, p. 348) however, there is less tendency to use pure architectural forms which lead to sustainability. Furthermore, by adopting passive solutions toward energy saving, unlike the active ones, the architecture takes the most significant role in providing designs meeting the energy conserving necessities. In this case, the first step inclines toward building volume and form. It means that if it is essential to use natural means to reduce energy loss, then buildings type and envelope will be the first challenge to deal with (Soltandoost, 2011, p. 350). So that, the integration of the method and applying appropriate building design techniques can contribute to green echo-friendly buildings and societies (Mahdavinejad et al., 2012, pp. 175-181). Accordingly, however there is a large scope of studied energy efficient solution to decrease building energy demand, while less research has been done on optimum form. The following essay initially studies on building forms and energy loss reduction while reporting the simulation results with an emphasis on optimum domed roof shape.

RESEARCH BACKGROUND

As previously mentioned, widespread application of domed roof in traditional vernacular buildings appeals many research workers to the issue to discover the most influencingl parameters. Many researchers have analyzed and studied dome on different aspects, specifically thermal behavior. Tang et al studied on thermal behavior of curved roofs through numerical calculation methodology in hot and dry weather condition. They concluded that heat flux and the daily heat flow through curved roofs are almost unaffected by roof radius, thickness and thermal properties, but are significantly influenced by the half rim angle of both DRs (Domed Roofs) and VRs (Vaulted Roofs) and the ambient temperature. The results also confirm that curved roofs are not suitable for areas with higher air temperatures and intense sky diffuse radiation typical of hot humid zones (Tang et al., 2003, pp. 282-284). Faghih and Bahadori (2011) did numerical simulation on a simplified model of domed roof in paper entitled “Thermal Performance Evaluation of Domed Roofs”. They proved that thermal performance of the domed roof building under investigation is better than the building with flat roof on warm days although for no wind flow condition, flat roof building performs better than the domed one (Faghih & Bahadori, 2011, p. 1262). Also, in 2012, Faghih and Bahadori again discuss about domes thermal behavior. They show that the geometry of domes causes the wind velocity to increase, resulting in an increase in convection heat transfer coefficient. And as the surface area of domed roofs is greater than flat one, heat transfer rate is increased. The paper also compares several domed roofs in terms of direct and diffuse solar radiation comparing them with a flat and conical shape. The results show that domed roofs receive more solar radiation than the flat roofs of equal based area. Based on the unit areas of dome itself, the flat roofs received more solar radiation and the domes with higher aspect ratio received more solar radiation than the ones with lower aspect ratio when considered to be located in same city (Faghih & Bahadori, 2012, pp. 1238, 1245).

Moreover, by considering combined convection and solar radiation over the roofs, *Hadavand* et al studied thermal performance of vaulted roofs and comparing their heat transfer with flat roofs. They explained that heat transfer to the building with respect to time is at a given ceiling design temperature, is determinedly various wind flows and vault shapes. When the results were compared with corresponding flat roof, it was found that daily average heat flux for all vaulted roofs except the one with rim angle 180° is less than flat roof and it reduces further by increasing wind speed (Hadavand et al., 2007, p.265).

SIMULATION PROCESS

Mechanism of Case Studies Selection

It is very important to clarify that in hot and dry regions of Iran, architects mostly used domed roofs to provide large space coverage, in line with masonry material abundance compared to lack of timber, particularly in dominant mosque constructions. Therefore, 10 survived samples of Esfahan mosques` dome were selected in study on. Case studies provided us with the estimating energy load through 3 types of dome modelling and simulation thermally compared. To simplify the modeling, domes are 10 categorized in 3 groups, based on their rise height and the sector which is circumscribed under the dome. Therefore, the groups are:

Roof Types

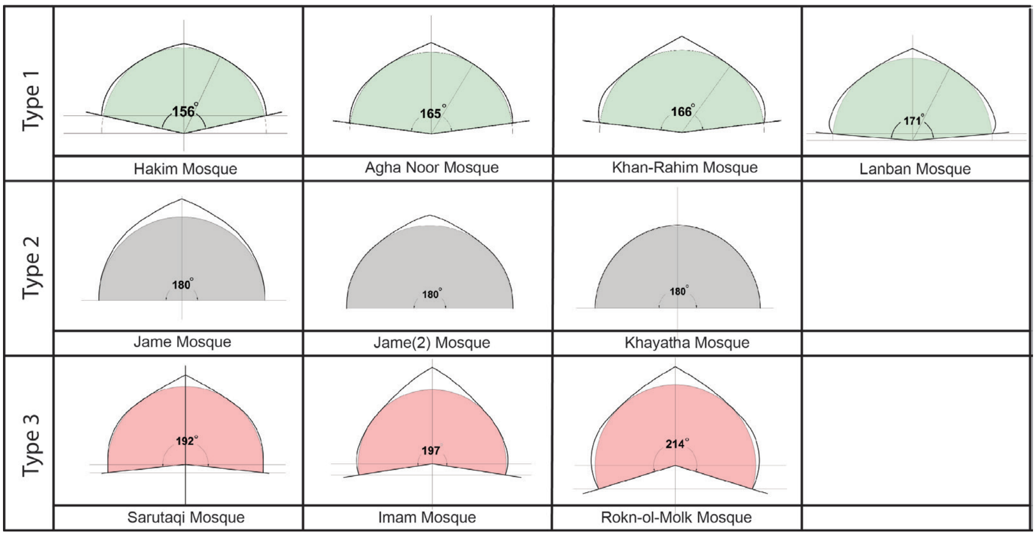
Type 1, with an inscribed arc less than 180 degrees.

Type 2, with a 180 degrees inscribed arc.

Type 3, with an inscribed arc more than 180 degrees.

Table 1 represents three graphical types categorized and modelled according to roof inscribed arc angle.

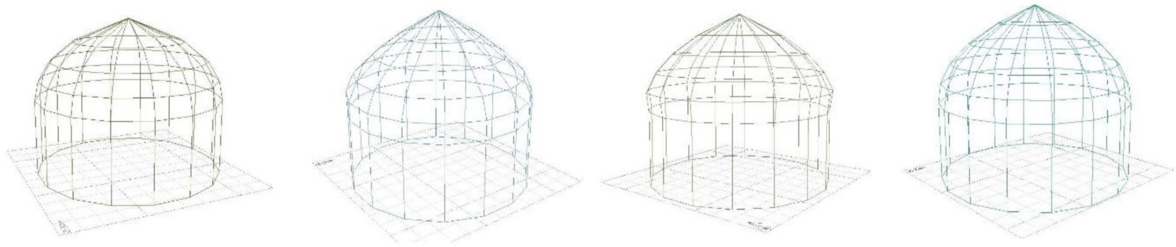
Table 1. Esfahan Domes Classification in 3 Types



Identifying the Polygons

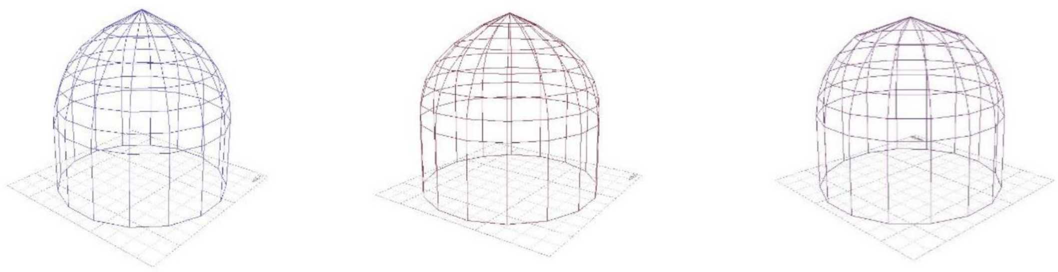
Three characteristic samples of each domed group are illustrated in table 1. These samples are: Hakim Mosque, Khan Rahim, Lanban and Agha-Noor with an inscribed arc less than 180 degrees (Type1), Jame' Mosque, Jame' (2) Mosque and Khayatha mosque with a 180 degrees inscribed arc (type 2) and Imam Mosque, Rokn-ol-molk and Sarutaghi mosques with an inscribed arc greater than 180 degrees (type 3). To numerically calculate and analyze, the circle at the base of the dome is replaced with a hex decagon. The dome is placed on a cylinder which is 10 meters in diameter and 4 meters in height. The rise height is divided into 1 meter segments; hence, the outer layer consists of similar trapezoids. With this meshing method, the surface area of each dome can be numerically calculated and finally the simulation results for the domes will be compared with a flat surface. Thus, thermal performance of samples is evaluated by the numerical simulation method using commercially available software. The following is a description of the parameters used for modeling.

As there is no graphical modeling device in Energy Plus; firstly, each type is separately simulated in Autodesk Ecotect (Version 2010) and then imported to Energy Plus software (Version 7) with.idf format to be calculated thermally. The ultimate result is illustrated on winter solstice (21th December) in a final graph to be easily compared. Figure 1 represents 3 types graphical modeling in Ecotect. Figure 1, 2 and 3 respectively represents three graphical types modelled in Ecotect energy software.



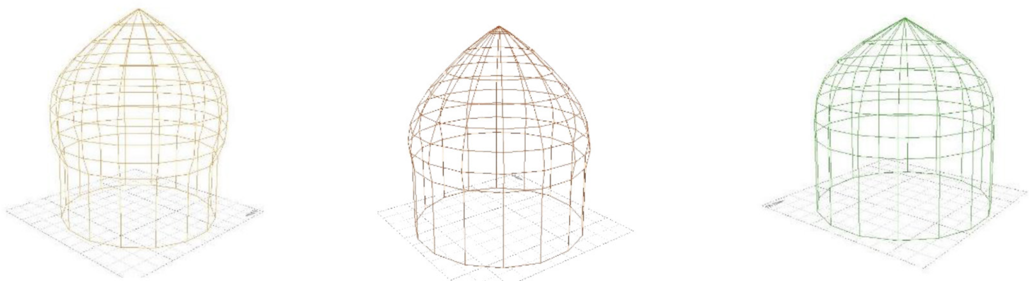
Hakim Mosque **Khan Rahim Mosque** **Lanban Mosque,** **Agha-Noor Mosque**

Fig. 1. Domed Roofs 3D and Mesh Modeling in Ecotect Software (Version 2010), Type 1: Hakim, Khan Rahim, Lanban and Agha-Noor Mosques.



Jame Mosque **Jame (2) Mosque** **Khayat-ha Mosque**

Fig. 2. Domed Roofs 3D and Mesh Modeling in Ecotect Software (Version 2010), Type 1: Jame Mosque, Jame (2) Mosque, Khayat-Ha Mosque.



Rokn-ol-molk Mosque **Imam Mosque** **Sarutaghi Mosque**

Fig. 3. Domed Roofs 3D and Mesh Modeling in Ecotect Software (Version 2010), Type 3: Rokn-Ol-Molk, Imam and Sarutaghi Mosques.

Simulation Data in Ecotect and Energy Plus softwares:

Location: Isfahan, Iran.

(Latitude: 32° 38′ 0″ N, Longitude: 51° 39′ 0″ E)

Wall and roof Material: Brick masonry:

(Thickness of 30 cm,U-Value: 1.770 w/m²k, Time lag: 4hrs)

Day / time: 21 December (Winter Solstice).

Zone Comfort Temperature: 21 °

Table 2. Total Area and Total Volume Quantities in Type 1

Roof Type	Total area/ m2	Total volume/m3	area/ volume (Shape Factor)
Hakim	329.75	491.209	0.67
Khan-Rahim	347.846	537.16	0.647
Lanban	353.449	548.596	0.644
Agha-Noor	339.856	516.373	0.65

Table 3. Total Area and Total Volume Quantities in Type 2

Roof Type	Total area/ m2	Total volume/m3	area/ volume (Shape Factor)
Jame Mosque	366.496	581.389	0.630
Jame(2) Mosque	358.995	563.463	0.637
Khayat-ha mosque	352.748	548.382	0.643

Table 4. Total Area and Volume Quantities in Type 3

Roof Type	Total area/ m2	Total volume/m3	area/ volume (Shape Factor)
Rokn-ol-molk	472.477	853.514	0.55
Imam Mosque	394.794	651.807	0.60
Sarutaghi	376.865	610.032	0.61

DISCUSSION

To achieve the goal, all three roof type are modelled and calculated in software emphasizing on the rate of heating load in cold months of year specifically in cold night (which needs more energy consumption to achieve the human comfort zone in comparison to the rate in daylight). Moreover, the numerical modeling is indicative of the thermal performance of domed roof buildings while comparing them. Considering the same ordinary material which is applied to all models (brick masonry), the thermal transmittance coefficient will be the same providing the possibility to calculate the area and volume influence.

All models are individually simulated in energy software. The paper firstly discusses on daily heating load with an emphasis on energy demand at nights and subsequently, it considers the annual cold period graphs to compare all types of thermal behavior while calculating the quantity of heating load by kwh. Therefore, the paper tries to to find a relation between numerical simulation and roofs geometry.

Table 5. The Comparison of Heating Load Quantities in Type1 Roofs

Heating Load	Hakim	Khan Rahim	Lanban	Agha-Noor
Heating load (Night) (Kwh)	25.45	28.66	28.19	27.41
Heating load (Day) (Kwh)	30.60	34.75	34.06	32.34
Total Heating load (Kwh)	56.05	63.41	62.25	59.75

Table 6. The Comparison of Heating Load Quantities in Roofs Type 2

Heating Load	Jame Mosque	Jame (2) Mosque	Khayatha mosque
Heating load (Night) (Kwh)	31.49	29.93	29.48
Heating load (Day) (Kwh)	35.75	34.88	33.87
Total Heating load (Kwh)	67.25	64.81	63.35

Table 7. The Comparison of Heating Load Quantities in Roofs Type 3

Heating Load	Rokn-ol-molk Mosque	Imam Mosque	Sarutaghi Mosque
Heating load (Night) (Kwh)	46.79	35.72	32.44
Heating load (Day) (Kwh)	52.44	39.82	37.32
Total Heating load (Kwh)	99.24	75.55	69.76

As it can be seen in tables 5, 6 and 7 and by comparing them, the least total rate of heating load refers to type 1 domes which are 56.05, 59.75, 62.25 and 63.41 kwh respectively referring to Hakim, Agha-Noor, Lanban and khan-Rahim mosques while this type has the least rise geometrically. Thus, in the order given type 2 and type 3 subsequently bear the least annual heating load. While the domes type 3 have the most rise height rate and external surface area. As a sample, in Rokn-ol-molk mosque, inscribed arc angle is about 215 degrees that provides the most rise height and surface area. Therefore, the more dome height is, the more external area is which lead heat transfer to increase through conduction and finally it results in more building thermal load.

Table 8. The Comparison of Annual Heating Load Quantities in Roofs Type 1

Heating Load	Hakim	Khan Rahim	Lanban	Agha-Noor
Annual Heating load (Kwh)	6253.23	6943.9	6908.68	6717.7

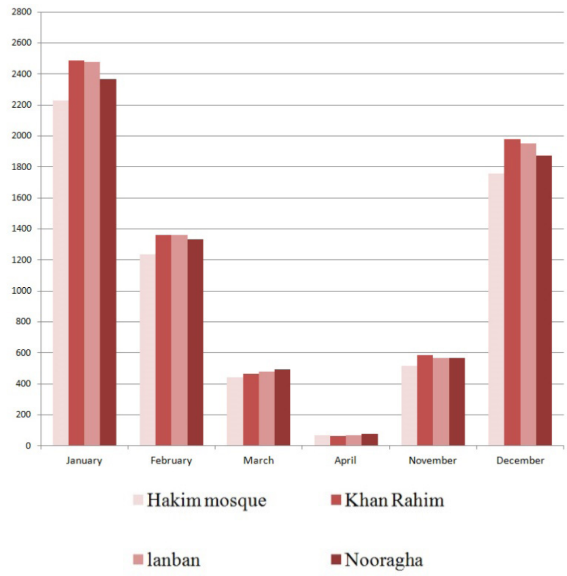


Fig. 4. Final Comparison of Heating Load In Roofs Type 1

Comparing individually all domes with each other the more external area provides more annual energy consumption except in case of Khan-Rahim and Lanban dome in type one. As represented in table 8, however in type1, external area of Lanban mosque is more than Khan-Rahim mosque which are 353.45 m^2 and 347.85m^2, the heating load of Khan-Rahim mosque is less (although the difference is not considerable). Fig. 4 shows the graphical comparison of annual heating load in domes type 1.

In January, February, December and November, in an increasing order mosques respectively behave more appropriate: Hakim mosque dome (area: 329.75m^2), Agha-Noor mosque (area: 339.856 m^2), Khan-Rahim (area: 347.84 m^2) and finally Lanban mosque (area: 353.449 m^2).Although in March and April there is a negligible difference (as less energy is needed to heat the model), table 8 verifies the mentioned order.

Table 9. The Comparison of Annual Heating Load Quantities in Roofs Type 2

Heating Load	Jame Mosque	Jame(2) Mosque	Khayat-ha Mosque
Annual Heating load (Kwh)	7778.50	7372.92	7271.47

As represented in Fig. 5, in January, February, December, November, April and March in an increasing order mosques type 2 respectively behave more appropriate: Khayat-ha mosque dome (area: 352.748m²), Jame (2) (area: 358.995 m²) and finally Jame mosque (area: 366.496m²). The table 9 verifies the mentioned order.

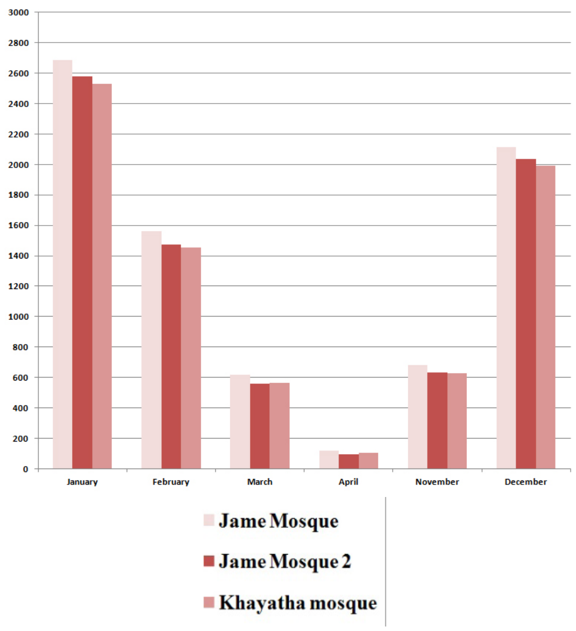


Fig. 5. Final Comparison of Heating Load in Roofs Type 2

Table 10. The Comparison of Annual Heating Load Quantities in Roofs Type 3

Heating Load	Rokn-ol-molk Mosque	Imam Mosque	Sarutaghi Mosque
Annual Heating load (Kwh)	11475.89	8803.44	8005.02

As it is represented in Fig. 6, all domes of type 3 are in a same order in all cold months. Respectively, mosques type 3 have the following order: Sarutaghi mosque (area: 376.85m²) has the least heating load, Imam Mosque (area: 394.79 m²) and finally Rokn-ol-molk dome (area: 472.47m²) respectively bear more heating load in cold weather. The table 10 verifies the mentioned order.

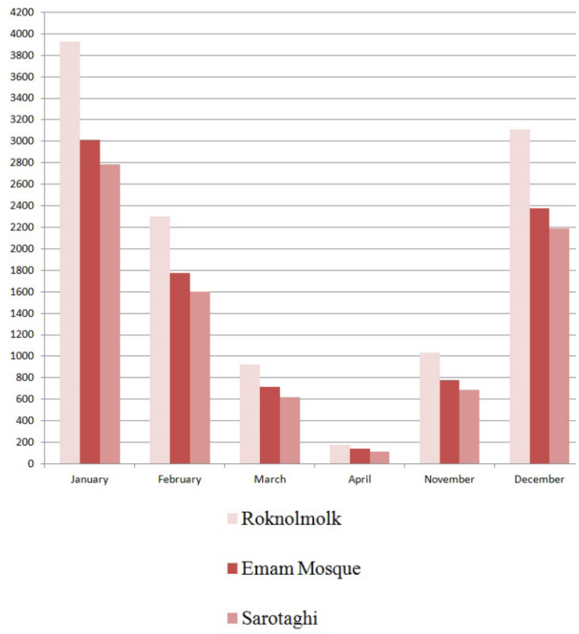


Fig. 6. Final Comparison of Heating Load in Roofs Type 3

CONCLUSION

Comparing all 10 models together Fig. 7, the result shows that the more external area is, the rate of heating load and consequently the rate of heat transfer flux will be more. So that, Rokn-ol-molk Mosque in type three with the most side area,which is about 472.5 m², behaves as the least efficient shape of the roof in a daily and annual period. It seems that as the inscribed arch get larger than 180 degrees, energy load significantly increases in calculation. Rokn-ol-molk mosque with inscribed arch 240 degrees performs the highest rise in dome shape. This effectively increases dome area. It can be concluded that type one roof (Hakim Mosque) has better thermal performance due to a significant reduced area and volume. Nevertheless, the paper proposes following assumptions to achieve accurate assessment of influencing parameters in further investigations:

1. According to various range of arcs` type in domes, the angles of polygons should be separately calculated. This also needs numerical computing and mathematical equations.
2. It is recommended that the stack effect (vertical

ventilation) is evaluated by using the same energy simulation equation method.

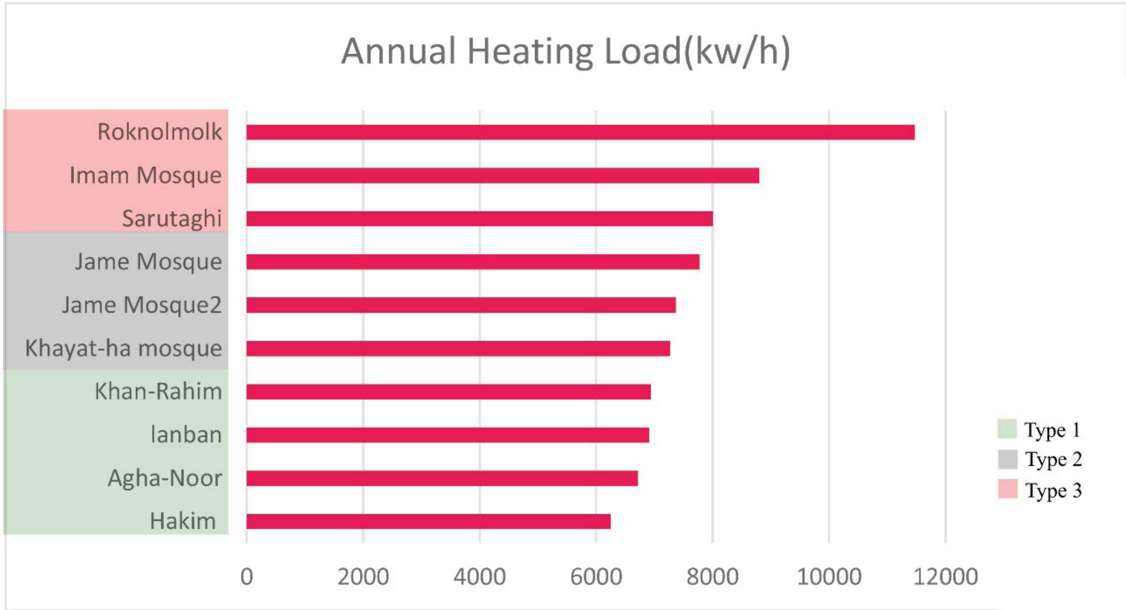


Fig. 7. Final Comparison of Annual Heating Load in All Roofs

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