

Daylight Performance of Single Pedentive Dome Mosque Design During Winter Solstice

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ABSTRACT

In this study, the analysis is to measure lighting performance of single pedentive dome type and pyramid roof type in mosque design built during the Ottoman Empire in Istanbul, Turkey and Mostar, Bosnia-Herzegovina. The selected case studies are the Firuzaga and Orhan Gazi Mosques as single pedentive dome styl and Neziraga Mosque as case study for the pyramid roof type. This analysis aims to have a research finding to show that Turkish style's pedentive dome mosque design provides efficient indoor daylighting in the Orhan Gazi Mosque in comparison with the Firuzaga Mosque and Neziraga. This assessment is simulated during winter solstice occurred when the sun is perimetering at its most southern position along the Tropic of Capricorn. This study applies simulation analysis using Autodesk software known as 3D Studio Max Design 2011 programme. The simulations were done by the program using weather data file to provide the weather information and climate changes of the study area. The analysis shows that both mosques have mostly an evenly distributed illuminance level with Scales 1 to 5. The Orhan Gazi Mosque has slightly higher illuminance levels compared to those of the Firuzaga Mosque and bothe of the pedentive dome mosques have butter illuminance level than the pyramid roof mosque. The study concludes that the pedentive dome mosque design has an effect on the mosque indoor daylighting. Having excellent illuminance level distributed at all the locations is one of the crucial reasons why the mosques with pedentive dome roof cover are built by Ottoman master builders.

Keywords: Illuminance Level, Pedentive Dome, Orhan Gazi Mosque, Firozaga Mosque

1. INTRODUCTION

The aim of this study is to identify the lighting performance in single pedentive dome mosque and compare it wth the pyramid roof mosque to give an explanation why this pedentive dome mosque is very popular design in the Balkan region especially during the Ottoman Empire. This research depends on getting the results of illuminance levels to measure the lighting performance inside the case study and then compare the results of the indoor illuminance levels of the Firuzaga, Orhan Gazi Mosque located in Istanbul and Neziraga Mosque located in Mostar, Bosnia-Herzegovina. This study applies lighting simulation analysis generated in computer software known as 3D Studio Max Design 2011. The Firuzaga and Orhan Gazi Mosque have

single's pedentive dome mosque design while Neziraga Mosque has a pyramid roof. Pedentive dome construction had made possible for a mosque design with vast interior and 'double space' in height; as a result, it is able to provide excellent daylighting inside the mosque as well as give reflect to its architectural grandeur. The dome design is an ingenious works of Ottoman master builders who reinvented the pedentive dome concept of Hagia Sophia's architecture. They translated the dome design which provides elaborated lighting performance from indirect sunlight in the mosque design (Necipoglu and Al-Asad, 1996).

The main idea of the pedentive dome style is to transmit the daylight into the mosque interior space through upper window openings at the projected domes besides intensifying a sense of sacredness inside the

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prayer hall (Hillenbrand, 1994). Pedentive dome is a construction of 'dome above dome' concept, dome design supported by four giant arches (Mango, 1976).

With simple plan design, the single pedentive dome design comprises a square plan and dome. Referring to its plan layout, this square form is highlighted by lines of the building wall with door and window openings. It marks a confined space used as a prayer hall. The other element is a dome highlighted by a dotted circle line which represents a void with double volume space surmounted under pedentive dome as the roof cover.

2. MATERIALS AND METHODS

The indoor lighting performance is evaluated using illuminance level as the measurable scale. This illuminance level is measured in lux or lumen per metre square (lumen/m^2), which means the amount of luminance (lumen) affected on a 1×1 m surface area. By referring to this measurement, this study can determine the indoor lighting performance inside the mosque (Runsheng *et al.*, 2009). Building design using daylight system is considered as having excellent passive lighting design. Daylight is lighting obtained from indirect sunlight source. It provides the best source which comfortably matches with human visual response. The projected dome above the dome concept allows sunlit penetration. The amount of daylight penetration into a building through sunlit area from windows and door openings provides dual functions not only of admitting natural light into the indoor area but also allowing the occupants to have visual contact with the outdoor environment (Chel *et al.*, 2009a; 2009b).

2.1. The Case of Study

Like in other parts of the Ottoman Empire, the Orhan Gazi and Firuzaga Mosque play as an important symbol of the Turkish architecture, which portrays the belief, culture and politics of the Muslim community in this region (Saoud, 2004). Location of the mosques is in Istanbul, Turkey at latitude $40^{\circ}48'36''\text{N}$ and longitude $29^{\circ}26'24''\text{E}$ (Gaisma, 2011). On 21 December 2010 when Winter solstice occurs, sunrise in Istanbul is at 7:25 am and sunset at 4:38pm with 9 h 13 min day time (Harnick *et al.*, 2005).

The location of the Orhan Gazi Mosque is at Gebze, an urban area of Istanbul City whereas the Firuzaga Mosque is located in the heart of Istanbul city. The Orhan Gazi Mosque (**Fig. 1**). According to investigation by Kuran, he argued that the Orhan Gazi Mosque was built in early 1400s AD by referring to the building material of coarse rubble stones without any brick construction in between and Byzantine construction elements such as its column

capitals and bases, which typify atypical design on that period. The mosque design has a dome and square wall construction with a minaret at the east wall adjacent to the building entrance on the north wall. The dome measurement based on the building plan and section has 6.15 m in radius and the square wall height is 9.55 m. The building height (dome with square wall) is 15.70 m. The dome is supported by four arches covered as a part of the building stone walls with 1.15 m in thickness. Squinches are places of a joint system between the dome and arch wall. There are 23 windows built at the building wall aligned in 4 tiers. A mihrab is a niche area located at the south wall.

The Firuzaga (**Fig. 2**) mosque is one of the famous mosques in Istanbul. The mosque is located at Divanyolu, the main street overshadowed by the long queue of trees. It was built by the head treasurer of Sultan Beyazit II, Firuz Aga in 1491. Unlike other mosques, Firuzaga Mosque has a minaret placed to the left side of the wall while minarets of most mosques (single dome type) had to be on the right side on the wall. Although, the exact reason behind the minaret being placed on the left is still unknown, there are a number of stories relating different reasons for this.

This mosque was built during the first few years after Sultan Mehmet II conquered Constantinople in 1491. The Firuzaga Mosque has a square plan design with 13.5 m by 13.5 m and about 14 m high. The mosque is built with Bursa style and has a dome with eight sides with 5.20 m radius. The mosque is located in the neighbourhood of Sultanahmet which was considered to be the heart of Constantinople or known as Istanbul today.

Neziraga mosque is the other selected building for the case study as illustrated in (**Fig. 3**). Its location is closed to Mostar Old Bridge. This mosque has a single pyramid roof form with one minaret. The mosque was built in 1550 but it was closed in 1930 and later torn down in 1950, left derelict not until it is reconstructed in 1999 under UNESCO rehabilitation plan and IRCICA's (Research Centre for Islamic History, Art and Culture) Mostar 2004 programme with cost of USD453,000.

The mosque name is taken from the name of a person, Neziraga who was a local novel family from a highly respected Vucjakovic family (Serageldin, 1989). It is located at elevated hill platform east of Neretva River at distance of 150 meter from the old bridge of Mostar. This mosque has a design of simple plan unit layout comprising basic square plan with pyramid roof type. This single pyramid roof covers the main prayer hall. The most discrete characteristic of this single plan design is that it has a dominant pyramid roof. This mosque has a square plan design with 10.2 m width and 10.2 m length. Its height is 7.77 m with its roof's height at 2.59m.

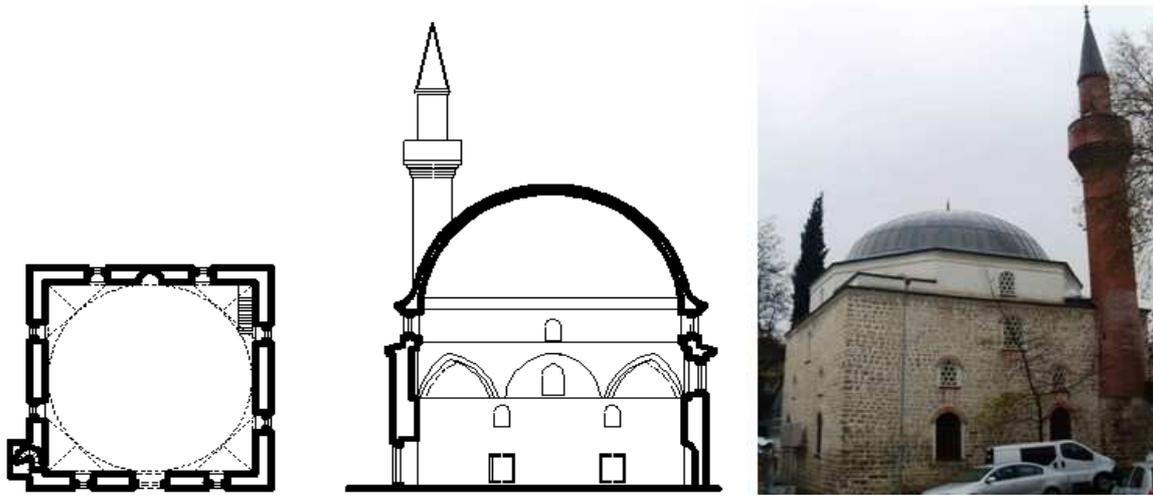


Fig. 1. Plan (left), section (middle) and photo (right) of the Orhan Gazi Mosque

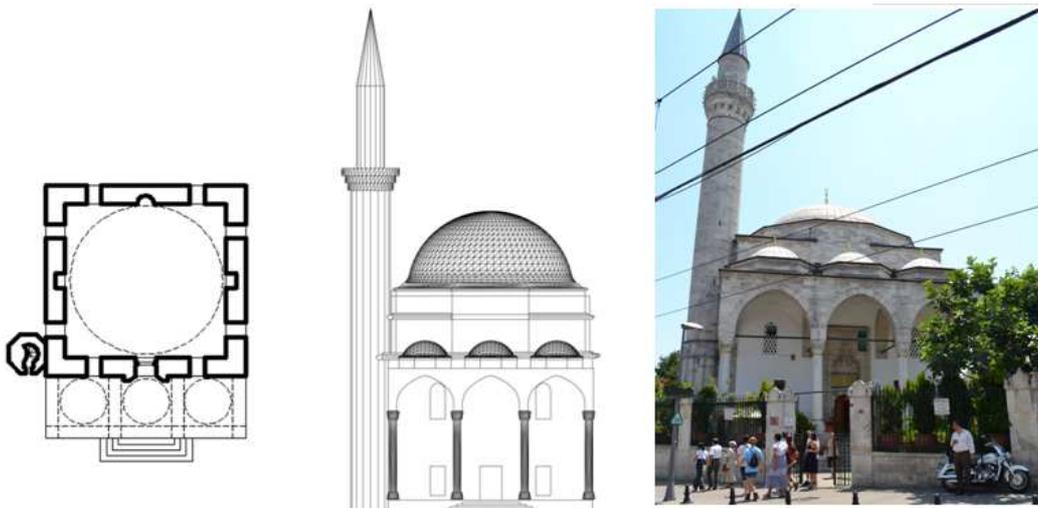


Fig. 2. Plan (left), elevation (middle) and photo (right) of the Firuzaga Mosque

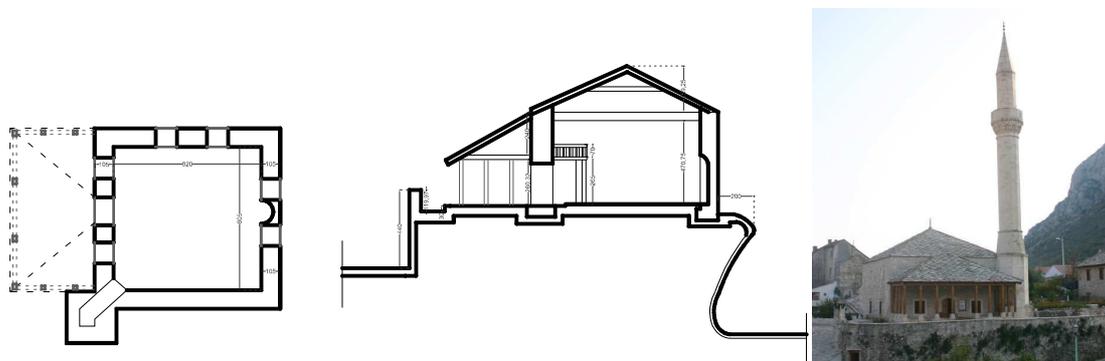


Fig. 3. Plan (left), section (middle) and photo (right) of the Nezirag Mosque

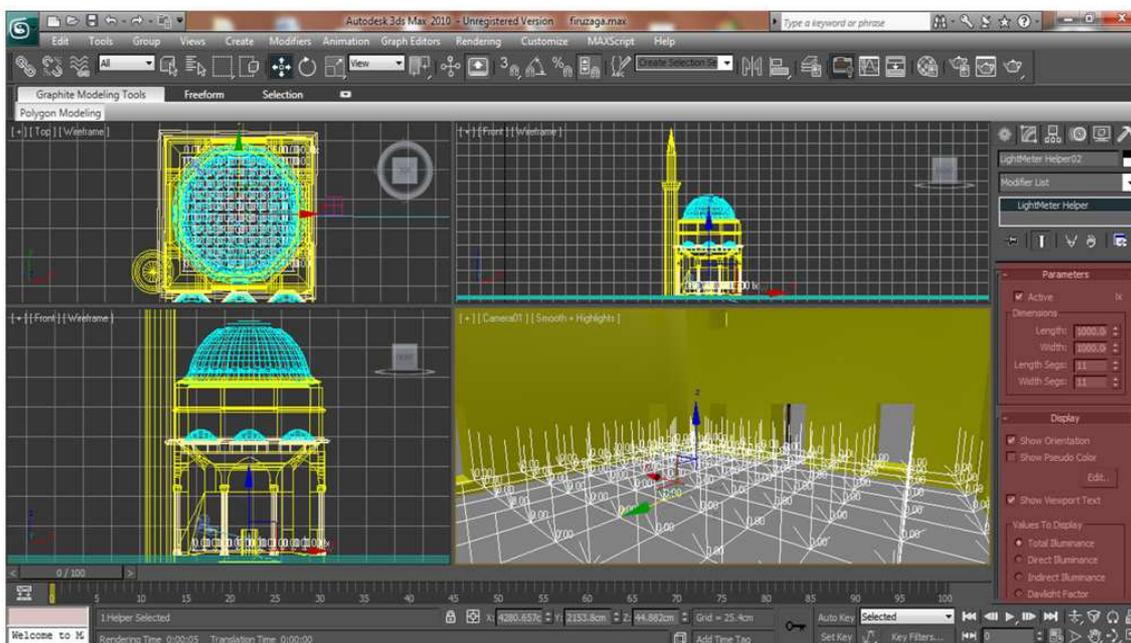


Fig. 4. Computer simulation using 3DS Max

2.2. Method of Simulation

The scope of this survey is to simulate the indoor lighting performance of the mosques and to do comparative analysis of the results among these mosques. This simulation (Fig. 4) was conducted on 21st June 2010 on the occurrence day of winter equinox when the sun path is at perimeter along the Tropic Cancer. This daylight simulation deployed a computer-based calculation of the amount of daylight inside the building using 3D Studio Max Design programme. Before simulation analysis was conducted, three dimension drawings of these two mosques were created using AutoCAD software based on one to one scale illustrating exact measurement of the building form with reference to the mosque's two dimensional AutoCAD plan and section.

After that, these three dimension drawings were imported to 3D Studio Max 2010. A daylight system was created in this programme and a camera view was set to the top view (perspective) before lighting analysis could be generated. A specific local daylight system was inserted in this programme using the available weather data file of Sarajevo and Istanbul. This weather file was downloaded from weather data files (*.EPW) (DE, 2010), which contained annual data for typical climatic conditions at this site. It would provide data with respect to the local climatic condition.

A light metre was created by setting points of incidence which showed the illuminance level. Each subdivision represented a point at which incident illuminance normal to the grid (0.5×0.5 m) would be measured (calculated). It provided overlaying a grid of illuminance results. This simulation was created after identifying a light meter at human body level 45 cm (when sitting on the ground while praying and listening to the Friday's sermon) above the ground floor plan of the mosque. The results were based on its reference to this light meter's setting with modification of the daylight system to the selected weather file (Landry and Breton, 2009). The simulation were done in selected points in the prayer hall in both of mosques, this simulation took 12 h from and it had been done every hour from 6:00 am until 18:00 pm on 21st June 2010. The 5 selected points were (P1= entrance door; P2 centre prayer hall; P3 = *mihrab*; P4 = right/east side prayer hall; and P5 = left/west side prayer hall) inside the building for each mosque (Fig. 5). The results for each selected points were collected and then converted to tables and line charts. These results allowed us to have comparative analysis of lighting performances among these three mosques. This analysis referred to measurable scales (Table 1) which recommend ranges of minimal illuminance levels as follows: (Schlyter, 2009; Krochmann, 1989).

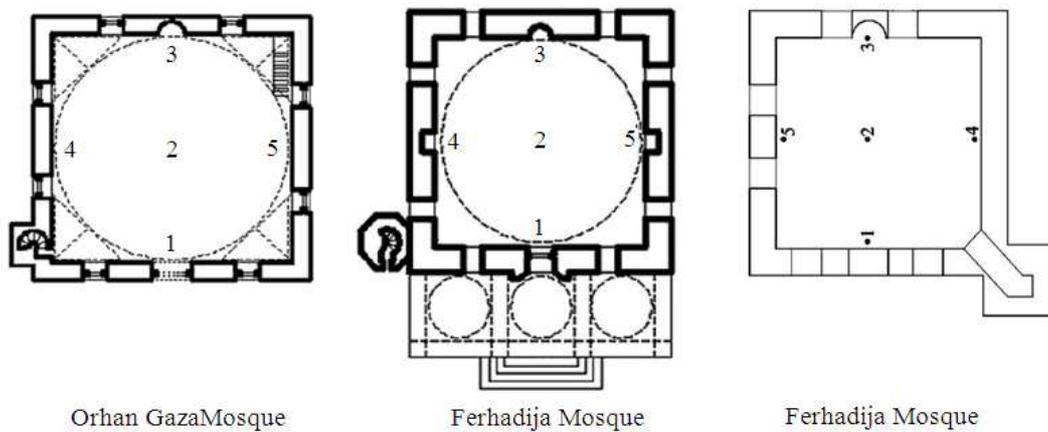
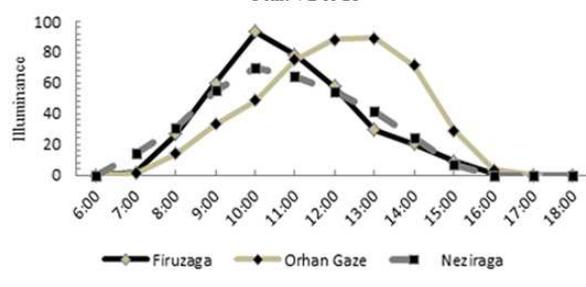
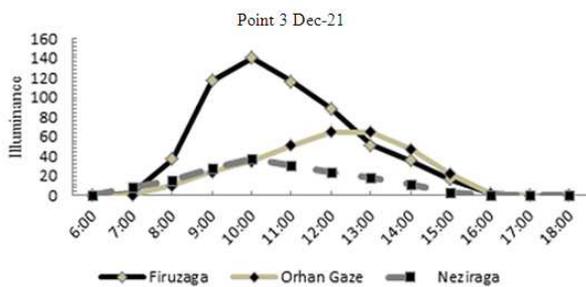
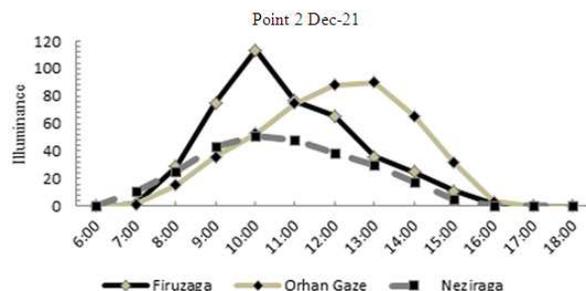
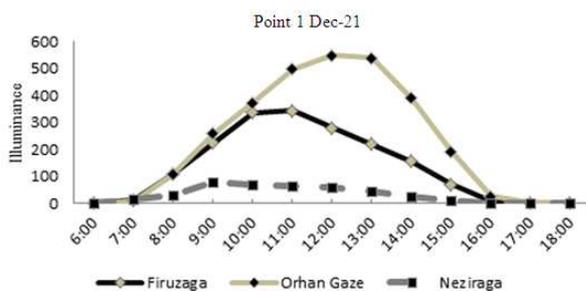


Fig. 5. Location Point 1, 2, 3, 4 and 5 of the simulation

Table 1. Measurable scales

Scale	Illuminance (lux)	Level
1	0-19	Total darkness to dark
2	20-49	Do not demand a high visibility of the task (public areas)
3	50-99	Do not demand a high visibility of the task (orientation during short stop)
4	100-199	Do not demand a high visibility of the task (rooms not in permanent use and hallway rightness)
5	200-499	Details easy to see at normal brightness for reading or office area
6	500- 999	Details difficult to see like intricate work for brightness
7	1000-1999	Tasklighting for highly demanding work-extremely fine details like microelectronic assembly
8	2000-10000	Tasklighting for highly demanding work-extremely fine details like special tasks in surgery (10000 lux is maximum brightness from sunlight to indoor area)
9	10001-100000	Outdoor area brightness (100000 lux is the maximum measurement)



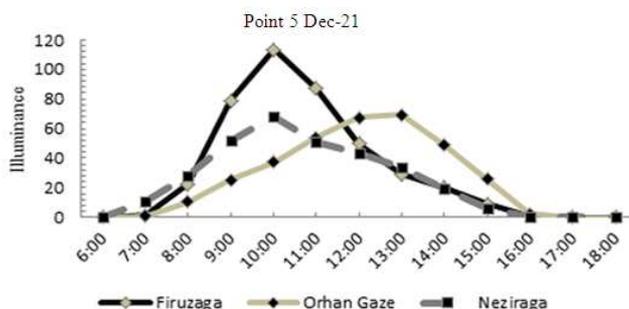


Fig. 6. Line charts of firuzaga, Orhan Gazi and Neziraga Mosques

Table 2. Indoor lighting performance of the Firuzaga Mosque

Firuzaga Mosque 21 -12													
	6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00
1	0	10.70	108.5	222.4	336.1	343.2	280.1	217.0	154.3	69.80	8.05	0	0
2	0	1.73	28.7	75.0	113.6	76.6	65.8	35.7	24.8	11.20	1.30	0	0
3	0	2.51	37.4	116.9	140.5	116.5	88.4	51.7	36.0	16.30	1.89	0	0
4	0	1.41	26.6	59.8	93.3	78.1	57.8	29.3	20.2	9.13	1.05	0	0
5	0	1.39	22.5	79.0	113.3	87.1	49.8	29.4	20.0	9.06	1.05	0	0

Table 3. Indoor lighting performance of the Orhan Gazi mosque

Orhan Gazi Mosque 21 -12													
	6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00
1	0	9.180	107.9	257.1	372.2	494.9	547.7	537.4	388.5	190.8	25.30	0	0
2	0	1.290	15.1	36.0	52.5	74.7	88.1	89.8	65.6	31.6	3.54	0	0
3	0	0.866	10.2	24.2	35.4	51.0	64.5	64.9	47.5	22.0	2.38	0	0
4	0	1.190	14.0	33.3	48.5	75.0	88.4	89.1	71.4	29.2	3.27	0	0
5	0	0.910	10.7	25.5	37.2	54.2	67.7	69.2	49.0	26.0	2.50	0	0

Table 4. Indoor lighting performance of the Orhan Gazi mosque

Orhan Gazi Mosque 21 -12													
	6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00
1	0	13.4	30.5	75.4	67.4	62.8	56.3	43.5	25.8	7.17	0	0	0
2	0	10.9	24.9	43.6	51.3	47.7	38.8	29.6	17.5	4.88	0	0	0
3	0	8.01	14.9	28.3	37.7	30.6	23.8	18.3	10.8	3.01	0	0	0
4	0	14.2	30.9	55.3	69.5	64.1	53.9	41.4	24.5	6.81	0	0	0
5	0	10.6	28.3	52.3	68.2	51	43.3	33.3	19.7	5.48	0	0	0

3. RESULTS

The results are illustrated in Table 2-4 and Fig. 6. This analysis comprises a comparative study between the Orhan Gazi, Firuzaga and Neziraga Mosque with reference to results of the simulation as follows:

4. DISCUSSION

The study is able to identify the sacred index of the illuminance level provided in pedentive dome mosque design. Pedentive dome design has good illuminance levels inside the mosque (in the winter time). The

result of the simulations records illuminance level below 20 lux equivalent to Scale 1 was at 7:00 am slightly before the sunrise and before the sunset in both of the mosques (totally dark). The findings from the results of analysis are as follows:

- Orhan Gazi Mosque has better results of illuminance levels at Point 1, 3 and 4 recorded throughout the simulations. Most illuminance levels were under (Scale 4 and 5) at Point 1 in the Orhan Gazi and Firuzaga Mosque
- **Table 2-4** show that results of simulation at Point 1 in both of Orhan Gazi and Firuzaga mosque have the highest illuminance levels compared to Point 2, 3, 4 and 5, while Neziraga mosque has lower illuminance level than the other two case studies. Point 1 in the Orhan Gazi Mosque records higher illuminance levels than Point 1 in the Firuzaga Mosque. In the Firuzaga Mosque, Point 3 has the second highest followed by Point 2 and 5 whereas Point 4 has the lowest ranking
- The results show that in the Orhan Gazi Mosque, point 1 has the highest illuminance level, followed by point 2, 4 and 5, while point 3 has the lowest illuminance level
- The results show that all points in the Neziraga Mosque have similar illuminance level, point 1 has the highest illuminance level followed by point 4, 5, 2 and 3.
- The research findings show that large door openings for entrance at the Firuzaga and Orhan Gazi Mosque become an important factor that provides high illuminance at Point 1
- The research outcomes also show that upper windows opening built around the dome perimeter provide daylight factor which transmits daylight at Point 2 location at central prayer hall in the Orhan Gazi mosque, even with less high than the Firuzaga Mosque. On the other hand the lack of the windows design in the Firuzaga makes the central of prayer hall with low illuminance level. This shows that the impact of the upper windows openings to pedentive dome design to the level of illuminance level at Point 2, while the pyramid roof in Neziraga Mosque does not provide good brightness

5. CONCLUSION

This study concludes that single pedentive dome design creates sunlit factor to give additional brightness

at central prayer hall inside the mosque. Besides due to sunlit factor by the sun perimetering at the Top of Cancer from southern atmosphere, adding the upper windows openings surrounding the dome in the Orhan Gazi Mosque provides additional daylight especially in the centre of the prayer hall at point 2 in both cases of the mosques. As a result, the extra high ratio to the plan dimensions helps to provide the good illuminance levels through the windows from the walls in the Firuzaga Mosque even without the upper windows openings. However applying the pedentive dome style in both case studies offers illuminance level distributed at all locations inside the mosque which gives a better illuminance level in all locations inside these mosques. Applying this pedentive roof form gives inspiration to the master builders to design a mosque with a perfect lighting performance with sacred sense of worshipping activities in the mosques and helps creating vast interior space plan layout without obstruction by walls and columns (Goodwin, 1993). These offers the master builders to explore daylighting design as a source of sacred expression a place of worship with a presence of divinity inside prayer hall.

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