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Correspondant: ammarcad@gmail.com

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Investigation of air velocity effect on thermal comfort in mosques-hot-dry climate

Ammar MEBARKI et Yasmina BOUCHAHM

Laboratoire ABE, Université Constantine 3, Algerie, BP 72, 25010, Constantine

Abstract

In hot climate areas, the proper understanding of thermal comfort parameters leads to help building designers in providing a suitable and refreshing environment for occupants. The rational model such as ASHRAE 55/2013, ISO: 7730 defines comfort boundaries based on the experimental results, which are conducted in climatic chambers. Research works have been rarely conducted in buildings with high density of occupants like mosques. In order to study the thermal comfort and the effect of air velocity in mosques in hot dry climate, a rational and adaptive comfort study by applying ASHRAE 55, ISO: 7730/10551 is carried out in El-Oued city, Algeria. The results show that the applicability of ISO7730 is suitable for a natural air velocity $v_{air} \in [0.35, 0.8]\text{m/s}$, where the comfortable operative temperature is 30.7 °C. However, this outcome doesn't exceed 26.8 °C for air velocity v_{air}< 0.35 m/s.

Keywords: Adaptive Comfort; El-Oued City; Chimney effect; Air speed.

1. Introduction

The examination of thermal comfort can help to reduce the use of cooling and heating systems through specifying the factors affecting the thermal comfort in buildings [1, 2], this last is defined by ANSI/ASHRAE-55[1] as [3]: *That state of mind which indicates satisfaction with the thermal environment*. Bluyssen presents a short history about comfort indoor environment [4]. Many works such as Dear *et al.* [5], Humphreys [6], Ogbonna *et al.* [7] and Modeste *et al.* [8] confirmed that air movement is one of the main parameters that affect the thermal comfort.

Kumar *et al.* found that in naturally ventilated buildings for temperatures between 22-26 °C the thermal comfort is ensured even if the air velocity is less than 0.25 m/s, however in hot climate areas the thermal comfort can be ensured when the air velocity varies between 0.2-0.5 m/s [9].

There are two international models used to examine the thermal comfort conditions in buildings which are: Predicted Mean Vote (PMV) rational model [10] and the Actual Mean Vote (AMV) adaptive model [11].

Previous researches concentrated on finding a rational model to evaluate the thermal comfort such as ASHRAE 55/2013, which was conducted in climatic chambers, have not covered the case of buildings like mosques including a high density of occupants that have limited ranges of movement.

As the majority of Islamic world is situated in hot climate areas, mosques in general require high energy consumption for cooling during the summer period. Obviously, the air-conditioning systems are the main consumers of energy in these buildings [12].

2. Goal of the paper

In hot climate areas, occupants in domestic buildings and offices can adapt their activity and clothing substantially in response to any thermal stress in their environment, whereas it is limited for occupants in mosques [13]. A proper setting of indoor thermal comfort inside such type of buildings can provide a suitable environment for occupants and does not disturb the achievement of the prayers.

[1] https://en.wikipedia.org/wiki/ASHRAE_55

As an example of the importance of ventilation in hot dry climate the mosque of Tiksept in El-Oued, Algeria is equipped with a dome distinguished by an electrical opening system that opens during hot weather to provide natural air movement at appropriate times. This study aims to investigate the effect of air velocity on thermal comfort inside the prayer hall in hot dry climate, by using the comparison between PMV and AMV indexes obtained from environmental measurements and questionnaire.

3. Context

3.1. City Analysis

The city of El-Oued in Algeria, known as "*The City of Thousand Domes*" is located between latitudes 31°-34° north and longitudes 6°-8° east, at an elevation of 20 m below the average level of the sea. The city climate is a typical dry desert with highest air temperatures being recorded in July and August with an average maximum of 40 °C. Summer period begins from the end of March until the end of October with a mean air temperature of 34.5 °C. The air is generally dry with an average relative humidity of 26 % recorded in June and July, the precipitation is low [14].

3.2. Description of Mosque Building

The mosque is the most important religious building in Islam; both used as a space for prayer besides a community centre and contribute to the generation of Islamic way of life [15, 16]. According to Sergeld [17], Othman *et al.* [18] and Al-Ajmi [13], The mosque in general, can have square or rectangular walled prayer hall with a high ceiling roof and it usually contains domes and minarets. The 'Qibla', is the wall oriented towards Kaaba in Makkah (KSA), it contains a Minbar and a Mihrab, see figure 1. The Variation in architectural designs, construction systems, and the materials used are influenced by local climate and culture. Islamic prayer (Salat) is the repetition of a unit named 'Rak'ah' consisting of a series of actions and well prescribed words at five times a day (Fajr – the dawn prayer, Dhuhr, Noon prayer, Asr – the afternoon prayer, Maghrib – the sunset prayer and the Isha'a – night prayer), in addition of others (such as Friday noon prayer).

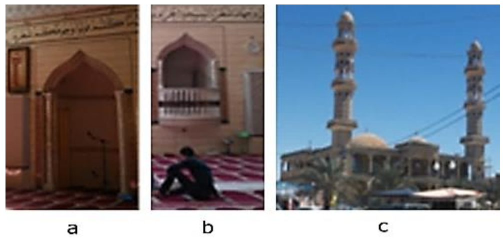
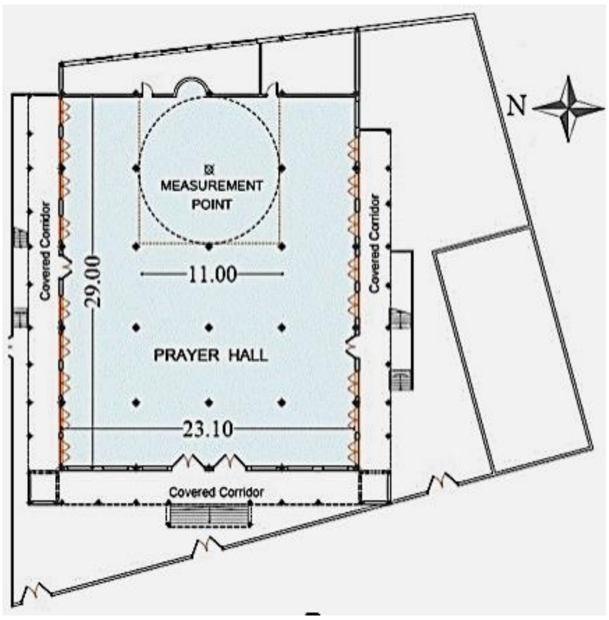


Figure 1. Features of the mosque:
(a) Mihrab, (b) Minbar, (c) Minarets and dome

3.3. Presentation of the case Study (Tiksept mosque)

Tiksept district mosque is a typical mosque in term of preserving the architectural identity of mosques in the region, especially the shape of prayer hall and dome emplacement as well as the shaded side corridors, which represent a prototype of historic mosques in the same area according to the information found in the search of Chehbi [19].

Tiksept mosque has a movable dome which opens during hot weather at night, the prayer hall size is about 670 m^2 with a height of 8.5 m under the top ceiling and it's accessible through 4 doors. The mosque has also two tall minarets located at the back corners and its construction system consists of a mixture of concrete structure and brick walls.



(a)

(b)

Figure 2. Tiksept mosque, (a) Floor plan and measurement point (b) Picture of the internal prayer hall.

3.3.1. Movable dome

The dome is an architectural component used to cover building, its usual occurrence in mosques has made it asymbol of Islamic architecture [20]. Tavakol *et al.* [21] and Cheng *et al.* [22] noticed that the acceleration of air flow over the domes roofs increases convective heat transfer compared to flat roofs, they can enhance natural ventilation and cooling. There are several technical innovations in the construction of domes, notably the system of movable dome which is replicated in Tiksept mosque (Figure 3).

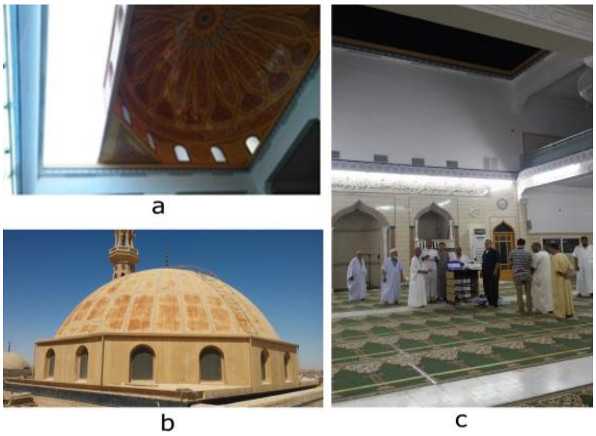


Figure 3. the movable dome (a) Exterior picture, (b) The dome opening during the day, (c) opening at night.

3.3.2. External Covered Corridors

The arched corridors have been associated to mosque architecture since ancient times, in addition to their aesthetic dimension, they have an important climatic role [20], where their shading devices are helpful to prevent excessive solar heat gain [23, 24].

The external covered corridors in Tiksept mosque provide shades on the eastern, southern, and western sides (Figure 4).

Figure 4. Presentation of the side corridor.

4. Methodology

4.1. Scenarios

Thermal environment and comfort survey were realized in 2015/2016 according to 8 scenarios during hot periods in desert climate in Algeria (Table 1). In order to achieve the study purposes two data collection methods were used: the former method is a questionnaire (subjective measurement) while the second one consists in using a physical measurement of certain parameters influencing the thermal comfort inside buildings. Each scenario is in accordance with ASHRAE 55/2013, ISO 7730 [25], and ISO 10551 [26], as well as the ASHRAE Standard 62.1-2013 guidelines in naturally ventilated building. The size of openings that connect directly with the outdoors should represent at least 4 % of the occupied floor area, which is a crucial factor that affects the natural ventilation [27]. It can be set by changing the openings of the construction or adjusting the gross size of the openings [24].

Table 1
Internal and external conditions associated to various scenarios.

Scenarios	Date	Time	Outdoor Ta (°C)	Wind V (m/s)	Outdoor H (%)	Air entrances	Opening Dome	Occupants	Questionnaires
1	21 July 2015	04:30	32.0	0.50	12		25 %	120	55
2	21 July 2015	13:10	42.6	0.95	11		00 %	138	52
3	21 July 2015	21:40	39.0	0.95	12	Shaded	100 %	368	71
4	30 March 2016	05:30	21.7	0.50	18	windows	10 %	184	11
5	30 March 2016	13:10	35.3	0.80	10	$28m^2$	10 %	322	55
6	30 March 2016	16:30	37.1	0.25	10		50 %	330	33
7	30 March 2016	19:10	31.7	0.30	10		25 %	414	73
8	30 March 2016	20:30	29.4	0.65	11	S. w 42 m^2	25 %	390	68

4.2. Field measurement of the environmental parameters

The physical measurements include: air temperatures, relative humidity, air velocity, average radiant temperature, and operative temperature. Measurements have to be taken at a height of 1.1 m from the ground level according to ASHRAE Standard 55 [28] and the work of Calis *et al.* [29]. Measures have been taken three times when the prayers were performed (at the beginning, during, at the end).

The parameters obtained from measurements are used to calculate the operative temperature and PMV, PPD[2] indexes according to Fanger's model[3]. The operative temperature T_o is deduced as follows [8]:

$$T_o = A \times T_a + (1 - A) \times T_r \quad \text{(Natural convection)} \qquad (01)$$

where:

T_a = Air temperature
T_r = Radiant temperature

$$A = \begin{cases} 0.5 & \text{for} \quad 0 < v_{air} < 0.2\ m/s \\ 0.6 & \text{for} \quad 0.2 < v_{air} < 0.6\ m/s \\ 0.7 & \text{for} \quad 0.6 < v_{air} < 1\ m/s \end{cases}$$

and:

$$T_r = \left[\left(T_g + 273\right)^4 + \frac{0.25\times10^8}{\varepsilon_g} \times \left(\frac{|T_g \times T_a|}{D}\right)^{0.25} \times \left(T_g - T_a\right)\right]^{0.25} - 273 \qquad (02)$$

where:

D = Diameter of globe thermometer
t_g = Temperature of globe thermometer
t_a = Air temperature
ε_g = 0.95
v_a = Air speed

The model ISO-7730 [25] determines the PMV index within a space as follows:

$$\mathrm{PMV} = (0.303e^{-0.036M} + 0.028) \times \{(M - W) - 3.05 \times 10^{-3} \times [5733 - 6.99(M - W) - P_a] - 0.42 \times [(M - W) - 58.15] - 1.7 \times 10^{-5}M\,(5867 - P_a) - 0.0014M(34 - t_a) - 3.96 \times 10^{-8}fcl \times \left[(t_{cl} + 273)^4 - \left(\overline{t_r} + 273\right)^4\right] - fclh_c(t_{cl} - t_a)\} \qquad (03)$$

$$t_{cl} = 35.7 - 0.028(M - W) - I_{cl}\{3.96 \times 10^{-8} \times fcl \times [(t_{cl} + 273)^4 - \left(\overline{t_r} + 273\right)^4] + fcl \times h_c(t_{cl} - t_a)\} \qquad (04)$$

———

[2] The percentage of persons who feel dissatisfaction from thermal conditions

[3] P.O. Fanger, Thermal Comfort: Analysis and applications in environmental engineering, McGraw Hill Book Company, 1970

$$hh_c \begin{cases} 2.38(t_{cl}-t_a)^{0.25} & \text{for } 2.38\times|t_{cl}-t_a|^{0.25} > 12.1\sqrt{V_{ar}} \\ 12.1\sqrt{V_{ar}} & \text{for } 2.38\times|t_{cl}-t_a|^{0.25} > 12.1\sqrt{V_{ar}} \end{cases}$$

$$fcl \begin{cases} 1.00+1.290\times I_{cl} & \text{for} \quad I_{cl}\leq 0.078\ \frac{m^2k}{w} \\ 1.05+0.645\times I_{cl} & \text{for} \quad I_{cl}\geq 0.078\ \frac{m^2K}{w} \end{cases}$$

The PPD index is calculated from PMV through the following equation [25]:

$$PPD=100-95\times\exp(-0.03353\times PMV^4-0.2179\times PMV^2) \quad (5)$$

It can be observed from equations (1) to (4) that the calculation of PMV is an iterative process. In this study, the calculations are carried out by writing a computer code in BASIC language. The appropriate range for thermal comfort is -0.5 < PMV < 0.5 in which 90 % of people have comfort feeling. More details on calculations of thermal comfort are found in ISO-7730 (2005) [26].

4.2.1. Equipments

In this paper indoor relative humidity, air temperature and black globe temperature are measured respectively by a Thermo-anemometer "model PCE-WB 20SD", while internal air speed is measured by "model PCE-423". The various values of outdoor temperatures are measured by a weather station "model PCE-FWS 20" (Table 2).

Table 2
Measurement equipment characteristics

Equipment	Function	Range	Resolution	Accuracy
Weather station PCE-FWS 20.	Ambient T°	- 40 ... +65 °C	0.1°	± 0.6 °C
	Air humidity	1... 99 %	1 %	
	Wind speed	0... 50 m/s	-	-
Thermo-anemometer PCE-WB 20SD	Globe T° (TG)	0 ... +80 °C	0.1°	± 0.8 °C
	Air T°	0 ... +50 °C	0.1°	± 3 %
	Humidity	5 ... 95 %	0.1 %	
Air speed. PCE-423.	Air speed	0.1 ... 25.0	0.01	± 5 %

4.2.2. Clothing description and activities

In order to standardize monitoring and questionnaire, a metabolic activity (met) and clothes (clo) information according to EN ISO 7730 [25] have been used.

Metabolic activity: depends on the provided activities according to ASHRAE Standard 55 [25] and the work of Calis *et al.* [29]. The prayer metabolic activity is limited to light activity movements for 15 minutes per prayer such as standing, kneeling, prostrating, and sitting. Metabolic rate value used for a worshiper in this work is estimated to be 1.2 met.

Clothes: the field study showed that worshipers often dress lightly in spring and summer as illustrated in figure 5 with underwear (0.04 clo), cotton t-shirt (0.09 clo), cotton trousers (0.2 clo), and light dress with short sleeves (0.24 clo) for a total clothing insulation of 0.57 clo.

Figure 5. Occupants and questionnaires

4.3. Subjective measurement questionnaires

The standard model ISO10551 [26] aims to supplement the objective measurements and receiving reliable data on real aspect of thermal comfort/discomfort [30]. AMV index is the result of answering the question: "*how do you feel at this precise moment*?" The answers for this question should vary from a judgment scale -3 (very cold) to +3 (very hot) with 0 as a neutral value. APD index is obtained by another question: “*Are you at ease in this thermal environment*?” The subjects can answer by "yes" or "no" and it contributes to the creation of a predicted percentage of negative judgments. Figure 5 shows a group of occupants holding questionnaires, before the distribution of questionnaires a period of 15 min is taken to allow the subjects to achieve a steady state of the thermal balance with their environment [31, 32].

A total of 418 questionnaires are distributed and different scenarios are used to collect subjective data. Some questions are filled up regarding the occupants such as personal data (age, weight, size …etc). The subjects consist of 100 % males, the age of the prayers is ranged from 12 to 84 years with a mean of 34.36 years, the mean height is about 169 cm and the mean weight is 75.7 kg as listed on the table 3.

Table 3
Personal factors

Age				**Height**			
Min	Max	Mean	STD	Min	Max	Mean	STD
12	84	34.36	18.8	134.0	190.0	169.0	12.5
Weight				**Clothing**			
Min	Max	Mean	STD	Mean			
50	108	75.7	19	0.57			

5. Results

The results of the research are shown in table 4 which contains measurements of the various physical factors of air temperature values as well as the results of the Predicted Mean Vote (PMV) and Actual Mean Vote (AMV).

Table 4
Rational and subjective measurement results

S	**Ta (°C)**		**Tg (°C)**		**V*air* (m/s)**	**H (%)**		**To (°C)**	**P M V**		**A M V**	
	Mean	STD	Mean	STD	Min-Max	Mean	STD		Mean	PPD	Mean	PPD
1	32.2	0.34	32.2	0.1	0.41-0.48	23.3	1	32.2	-	-	0.77	17.5
2	35.5	0.2	34.8	0.36	0.07-0.19	29.2	2.35	35.3	-	-	1.33	41.8
3	36.8	0.17	36.4	0.1	0.64-0.80	19.1	0.3	36.1	-	-	0.84	19.9
4	24.2	0.26	24.2	0.36	0.18-0.33	17.1	1	24.2	0.03	5.0	0.27	6.5
5	26.9	0.17	27.7	0.1	0.19-0.39	23.3	0.25	26.8	0.07	5.0	0.45	9.2
6	28.2	0.17	28.2	0.38	0.42-0.47	24.8	1	28.2	0.26	6.0	0.21	5.9
7	28.4	0.17	28.1	0.25	0.23-0.42	24.4	0.25	28.3	0.35	8.0	0.32	7.1
8	27.1	0.2	26.9	0.36	0.25-0.34	26.3	1.2	26.8	0.02	5.0	0.51	10.4

The Standard deviation in measured values Ta, Tg, do not exceed 0.4 °C in all scenarios which confirms that the occupants were in a stable temperature context. The results of air velocity confirmed that it is possible to produce air velocity more than 0.4 m/s through natural ventilation if it is assisted by a chimney effect (thermal stack effect and wind forces) [24]. The air velocity variations concur with researches like Peren *et al.* [33] and Galogahi *et al.* [34] when the air speed is directly proportional with the difference between exit and entrance orifices size in favor of the first. The analysis of thermal comfort was based on two axes:

4.4. Evaluation of thermal comfort AMV and PMV

The results of the 6th and 7th scenarios in figure 6 show that the difference between PMV measurement scale and AMV questionnaire remains almost constant between 0.03 and 0.05. This confirms the suitability of ASHRAE 55/2013, ISO 7730 model to evaluate the thermal comfort in similar conditions when air velocity $v_{air} \in [0.35, 0.8] m/s$ and by taking into account this difference in any future study to provide the internal thermal conditions of mosques in hot dry climate, where the local population feels comfortable in higher temperatures than those of the ASHRAE model, because of the effect of adaptation which was noted by some researchers and critics of the PMV and PPD model such as Al-Ajmi in a study conducted on air-conditioned mosques in dry desert [13].

Figures 6 and 7 show that the decrease of operative temperature in scenario 5 compared to scenario 6 from 27.8 °C to 26.8 °C has reduced the PMV measurement by 0.19 from 0.26 to 0.07 as well as the percentage of dissatisfaction from 6.94 % to 5 %. However, the AMV questionnaire increased by 0.24 from 0.21 to 0.45 and the percentage of dissatisfaction increased from 5.9 % to 9.2 % due to a decrease in air speed from 0.44 m/s to 0.29 m/s. In other words, the dissatisfaction between the questionnaire and the measurement is estimated at 4.2 % in favor of the questionnaire, which confirms the non-suitability of ASHRAE 55 model when the air movement is less than 0.35 m/s. Hence, it is necessary to expand the concept of thermal comfort to include the characteristics of some activities (such as the sense of stress in areas of high density without freedom of movement).

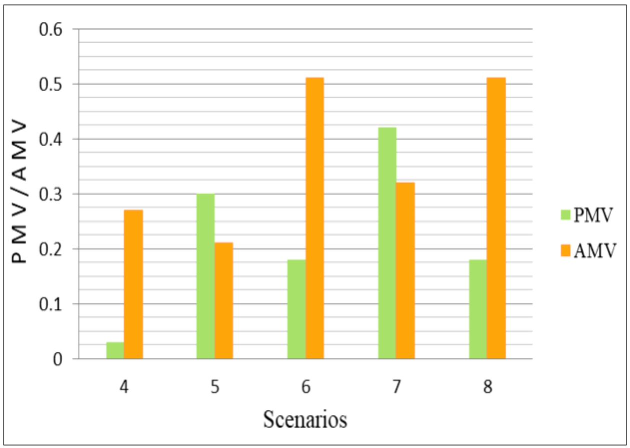


Figure 6. Comparison between PMV measured and AMV for scenarios 4, 5, 6, 7, and 8

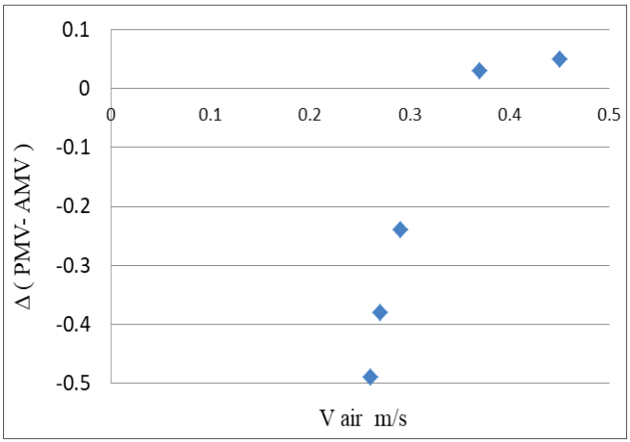


Figure 7. the difference PMV-AMV according to different internal air speeds

4.5. Actual mean vote of subjects AMV

The neutral temperature T_n can be deduced from the linear regression model obtained from the Actual Mean Vote AMV on thermal sensation with the operative temperature T_o recorded at the same time [28]. Figure 8 shows the correlation between the subjective variable AMV and the operative temperature T_o according to two ranges of air speed. They were classified after the study of all the results which yielded the following linear regression equations:

For: $v_{air} \in [0.1{,}0.35[\ \mathrm{m/s}$

$$AMV = 0.0972 \times T_o - 2.1107; \quad (R^2=0.9963) \qquad (5)$$

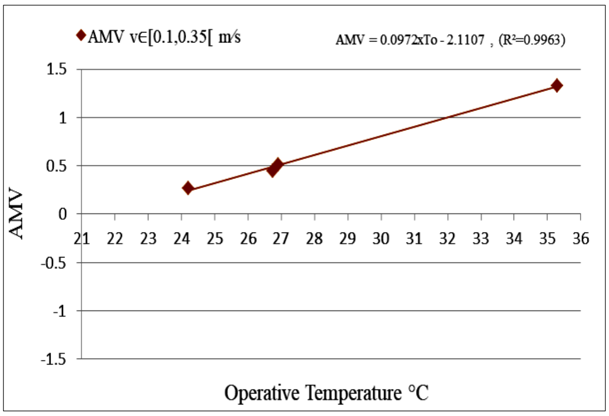
For: $v_{air} \in [0.35{,}0.8]\ \mathrm{m/s}$

$$AMV = 0.0785 \times T_o - 1.9128; \quad (R^2 = 0.87) \qquad (6)$$

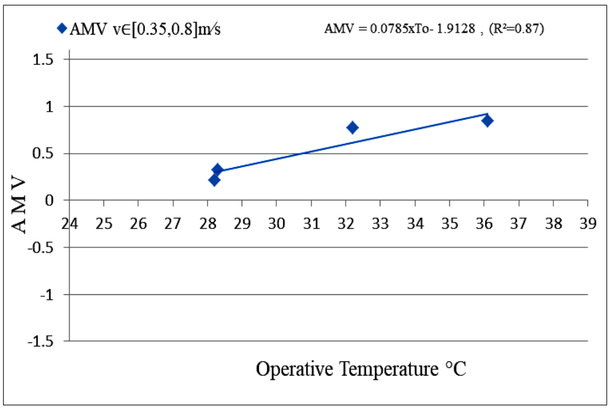
From these results, it appears that when $v_{air} \in [0.1,\ 0.35[\ \mathrm{m/s}$ the thermal sensation is strongly correlated to the operative temperature ($R^2 = 0.9963$) but it is less correlated when $v_{air} \in [0.35{,}0.8]\mathrm{m/s}$ ($R^2 = 0.87$). The gradient of the regression lines represents the sensitivity of the occupants with respect to operative temperature index, and it is found to be 0.097 °C and 0.078 °C for both equations (5) and (6) respectively. This means that the users are less sensitive to the values of operative temperatures when $v_{air} \in [0.35{,}0.8]\mathrm{m/s}$.

From these equations, we deduce that the neutral temperature T_n (AMV = 0) varies between 21.7 °C when $v_{air} \in [0.1{,}0.35]\ \mathrm{m/s}$ and 24.4 °C when $v_{air} \in [0.35, 0.8]\ \mathrm{m/s}$. These shows a difference of 2.7 °C that can be explained by the importance of air movement on thermal comfort in mosques (prayer activity). Moreover the neutral temperature T_n recorded when $v_{air} \in [0.1, 0.35[\ \mathrm{m/s}$ is less than the results of other studies carried out for other activities in hot climate regions such as those done by Ferghal and Wagner [35], Al-ajmi and Loveday [36] in Cairo, and Amr Sayed [37] in Assiut (Egypt), but higher when $v_{air} \in [0.35, 0.8]\ \mathrm{m/s}$.

In the end, if we consider the acceptance interval of sensitivity is 90 % when PMV= ± 0.5 [25], the upper limit (PMV= +0.5) of the thermal comfort zone for each range can be similarly determined: 26.8 °C when $v_{air} \in [0.1{,}0.35[\ \mathrm{m/s}$, and 30.7 °C when $v_{air} \in [0.35{,}0.8]\ m/s$.



(a)



(b)

Figure 8. Correlation of Actual Mean Vote (AMV) with the operative temperature T_o for:
(a) $v_{air} \in [0.1{,}0.35[m/s$ and (b) $v_{air} \in [0.35{,}0.8]m/s$

New found of neutral temperature T_n and upper limit of comfort range T_{max} was deduced from the linear regression model according to two air speed ranges in mosques in hot dry climate:

For: $v_{air} \in [0.1{,}0.35[\ m/s$

(T_n = 21.7 °C, T_{max} = 26.8 °C)

$$AMV = 0.0972 \times T_o - 2.1107; (R^2 = 0.9963) \quad (5)$$

For: $v_{air} \in [0.5{,}0.8] m/s$

(T_n = 24.4 °C, T_{max} = 30.7 °C)

$$AMV = 0.0785 \times T_o - 1.9128; (R^2 = 0.87) \quad (6)$$

These findings will contribute more efficiently to the development of mosques design codes.

Nomenclature

Symbol	Definition	Unit
D	Diameter of globe thermometer	m
F_{cl}	Clothing surface area factor	-
h_c	Convection heat transfer coefficient	W/ m2.k
I_{cl}	Clothing insulation	m2.k/ w
M	Metabolic rate	W / m2
P_a	Water vapor partial pressure	pa
T_a	Air temperature	°C
Ta	*Ta*	*Ta*
t_g	Temperature of globe thermometer	°C
T_r	Radiant temperature	°C
V_{ar}	Relative air velocity	m/ s
W	Effective mechanical power	W/ m2
Greek		
ε_g	0.95	-

5. Conclusion

The objective and subjective studies of air velocity effect on thermal comfort in mosques-hot dry climate revealed from its results that:

- The ASHRAE 55/2013, ISO 7730 model is suitable to evaluate the thermal comfort in mosques when $v_{air} \in [0.35{,}0.8]$ m/s with a difference: AMV = PMV-0.05.
- The ASHRAE 55/2013, ISO 7730 model is not suitable when the air velocity $v_{air} < 0.35$ m/s. So, it is necessary to expand the concept of thermal comfort to include the characteristics of some activities without freedom of movement such as praying, that is accompanied with the sense of stress if it is performed in areas with high density of occupants.

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