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Applying underfloor heating system for improvement of thermal comfort in historic mosques: the case study of Salepçioğlu Mosque, Izmir, Turkey

Khaled S. M. Bughrara[a] – Zeynep Durmuş Arsan[b]* – Gülden Gökçen Akkurt[c]

[a] Energy Engineering Programme, Izmir Institute of Technology, Gülbahçe, Urla, Izmir, 35430, Turkey
[b]Department of Architecture, Izmir Institute of Technology Gülbahçe, Urla, Izmir, 35430, Turkey
[c]Department of Energy Systems Engineering, Izmir Institute of Technology, Gülbahçe, Urla, Izmir, 35430, Turkey

Abstract

Mosques differ from other types of buildings by having an intermittent operation schedule. Due to five prayer times per day throughout the year, mosques are fully or partially, yet periodically, occupied. This paper examines the potential of using an underfloor heating system for improvement of indoor thermal comfort in a historic mosque, which is naturally ventilated, heated and cooled, based on adaptive thermal comfort method. The selected Salepçioğlu Mosque, housing valuable wall paintings, was built in 1905 in Kemeraltı, Izmir, Turkey. It requires specific attention with its cultural heritage value. Firstly, indoor microclimate of the Mosque was monitored for one-year period of 2014-15. Then, dynamic simulation modelling tool, DesignBuilder v.4.2 was used to create the physical model of the Mosque. The ASHRAE Guideline 14 indices were utilized to calibrate the model, by comparing simulated and measured indoor air temperature to achieve hourly errors within defined ranges. The results of calibrated baseline model indicate that the Mosque does not satisfy acceptable thermal comfort levels for winter months that provided by the adaptive method. Then, the effect of underfloor heating was examined in the second model by the

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Keywords: Historic mosque; low temperature electric radiant heating system; adaptive thermal comfort; dynamic simulation model.

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* Corresponding author. Tel.: +90 232 750 7020; fax: +90 232 750 7012.
E-mail address: zeynepdurmus@iyte.edu.tr

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1. Introduction

Mosques are the religious buildings functioning as the place of worship for Muslims. By having an intermittent occupancy schedule, they differ from other type of public buildings. The worshippers require feeling calm and comfortable to perform their prayers in tranquility and reverence. Hence, thermal requirements of a mosque should be carefully examined.

Historic mosques are naturally ventilated, heated and cooled. Limited research has been done on thermal comfort conditions of historic mosques. Since most comfort studies are likely conducted in other types of buildings such as dwellings, offices, and classrooms, more studies are needed for mosques, especially the historic ones. Any intervention for the improvement of thermal comfort in a historic building should be done without compromising its cultural heritage value. In line with this, thermal comfort study of historic mosques should be carried out with a special attention to heritage characteristics of buildings.

In most buildings, human thermal comfort is the paramount target. People can live and survive in very hot to cold conditions, that no absolute standard can be determined for their thermal comfort (5). As indicated in its definition, thermal comfort depends on the condition of mind that expresses satisfaction with thermal environment.

Several models have been used and developed in order to understand and determine the acceptable thermal conditions. The most recognized method of thermal comfort is the one presented by Fanger in 1970, which is based on the collection of experimental data and heat balance principles under the steady state condition in a controlled climate chamber. In Fanger model, two variables are necessary to be addressed: environmental variables such as air velocity, air temperature, radiant temperature, and relative humidity, and subjective variables such as activity level and clothing insulation (10), (3). Yet, the Fanger's model for predicting the thermal comfort provides better results in a mechanically ventilated building rather than a naturally ventilated building where indoor conditions directly follow outside environment, and whose occupants have the opportunities for adaptation. The discussions about the bias in PMV prediction differing by context suggest that the use of Fanger's model is no longer applicable for unconditioned buildings (4). Thus another method, i.e. adaptive thermal comfort model, was introduced by De Dear's team, based on the hundreds of field studies where the occupants were able to control their environment by means of clothing, sun shades, fans, operable windows and personal heaters (7). The concept of adaptive thermal comfort has emerged, when ventilating buildings naturally became more concerned because of the rising interest around energy efficiency and indoor air quality (12).

The adaptive model proposes that indoor comfort temperature can be estimated from the outdoor air temperature (13), (6). By plotting them tighter with the monthly or daily outdoor maximum, minimum and mean air temperatures, this can help reaching comfortable buildings. It enables to analyse the possibility of using passive cooling and/or heating design systems in the examined climate. The adaptive method is defined in The ASHRAE Standard 55 (3).

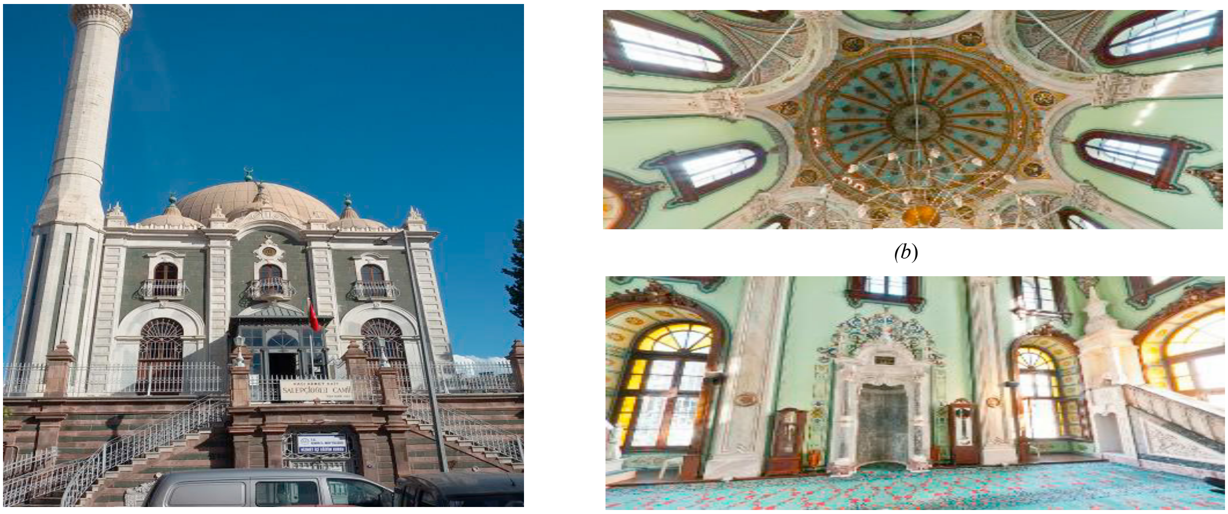
The recent studies mostly concern on permanently or periodically occupied/operated buildings such as houses, schools and offices. Few studies were noted on intermittently occupied/operated buildings such as mosques and churches. Ibrahim et al. (11) examine thermal comfort conditions in the mosque located at Kota Samarahan, Malaysia. They found that thermal comfort is not achieved. The simulation study is conducted by using EnergyPlus dynamic simulation software. The new materials are applied into digital model to enhance the thermal comfort (11). In 2009, Al-Homoud et al. (1) published the study on evaluation of thermal comfort and energy use in several mosques in hot humid climate. They conclude that in most of the studied mosques, specifically the one without insulated, thermal comfort is not accomplished. The addition of thermal insulation material to the mosques leads to improve in thermal comfort to the acceptable level. Beside to insulation material, the air conditioning system with intermittent operation can improve the level of thermal comfort with use of less energy.

The aim of this paper is to understand the indoor environment of historic mosques, and to evaluate and enhance their thermal comfort requirements. Therefore, the specific objective is to analyse the potential of using an underfloor active heating system for improvement of indoor thermal comfort in a historic mosque, i.e. Salepçioğlu Mosque in İzmir, Turkey, by using the adaptive thermal comfort model presented in The ASHRAE Standard 55. Modelling and simulations are conducted by the dynamic simulation software.

2. Methodology

2.1. Salepçioğlu Mosque

Salepçioğlu Mosque is the historic mosque located in Izmir, the city on the Aegean coast of Turkey, with the coordinates of 38°N - 27°E and 12.7 m from the see level. It is situated between the traditional housing fabric and old commercial area of Izmir. The Mosque was built in 1906 with a base area of 300 m². It is the load bearing monumental building with outside walls made of green and pinky granite stones, and decorated with white marble (Figure 1 (a)). The minaret was built separately from the structure of the Mosque, and located on the north corner of the building. The main worship space is covered with a single 12.5 m. diameter dome that internally decorated with engraving and painting (Figure 1 (b)). The *Mihrab* has the very plain niche with white and grey round pieces of marble, while the pulpit / *Minber* is adorned with geometric patterns on marble (Figure 1 (c)). Salepçioğlu Mosque differentiates from other mosques with its main worship space located in the first floor. The ground floor houses the smaller worship space and classrooms for religious purposes.



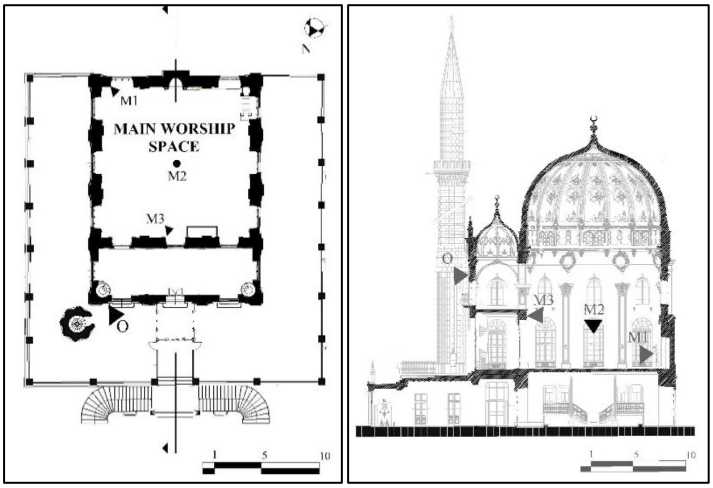
(b)

(a) (c)

Fig. 1. (a)Entrance view of Salepçioğlu Mosque; (b) dome paintings and engraving; (c) main worship space, Mihrab (middle) and pulpit / Minber (right)

2.2. Data Collection

Two parameters, i.e. temperature and humidity, are essential to be monitored in order to evaluate the indoor thermal comfort. Thus indoor and outdoor air temperature (T) and relative humidity (RH) data of Salepçioğlu Mosque was collected and measured through one-year period from October 1, 2014 to September 31, 2015. Onset Hobo U12 mini data loggers with the accuracy for air temperature of ±0.35°C at 25°C and relative humidity of ± 2.5% from 10% to 90% were used. Three of them (M1, M2, M3) were installed into different locations and levels of the main worship space, while the other (O) was placed on outside surface of the Mosque (Figure 2). The logger positions were determined according to ASHRAE 55 (2010). The data collected with ten-minute intervals was, then, converted into hourly averages. The logger #M2, located in the middle of worship space at 2.8 m., is chosen to represent the indoor thermal conditions.



(a) (b)

Fig. 2. (a) First floor plan of the Mosque and location of measurement points in horizontal plane (M1, M2, M3, O); (b) Section of the Mosque and location of measurement points in vertical plane (M1, M2, M3, O) (Source: Modified from the drawings provided by ENVAR Architecture and Engineering Inc.)

2.3. Construction and Modelling

The Mosque consists of two storeys: basement and first floor. The main worship space is located on the first floor, including the women's prayer area over the portico / *Revak*. It covers 178 m^2 area with the height of 21.5 m (Figure 2). The outer walls comprise two layers: lime plaster and granite from inside to outside with overall heat transfer coefficient of 2.144 W/m^2K. The partition wall next to *Revak* has the layers of gypsum plaster, lime stone and marble from inside to the outside, respectively. The overall heat transfer coefficient for the partition wall is calculated as 1.309 W/m^2K. The roof of main worship space and women's prayer area are covered with the main dome and three small domes, respectively. The domes contain four layers such as lead, Khorassan / *Horasan* mortar, brick and gypsum plaster from outer to the inner surface. The overall heat transfer coefficient for main dome is 1.522 W/m^2K.

The Mosque was modelled to evaluate the indoor environment and enhance thermal comfort conditions. The first model, i.e. 'baseline model,' exemplifies the present situation of the Mosque, while the second model, i.e. 'developed scenario model,' includes the improvement scenario which is the application of low temperature electric radiant heating system as underfloor heating to the main worship space. Dynamic simulation modelling tools, DesignBuilder v.4.2 and EnergyPlus v.8.1, were used to create the models (Figure 3) (8) and (9). All the input data required for the software (e.g. location, weather file data, model geometry, internal loads, material constructions, schedules for openings, occupancy, lighting, and HVAC system) is collected by the actual measurements, detailed site surveys, and authors' personal observations. In addition, the overall heat transfer coefficient values of building components are calculated by the dynamic simulation software, based on the material information indicated in the measured drawings of building, and material experiments such as X-Ray Fluorescence (XRF) and X-Ray Powder Diffraction (XRD) to define the material properties of the Mosque.

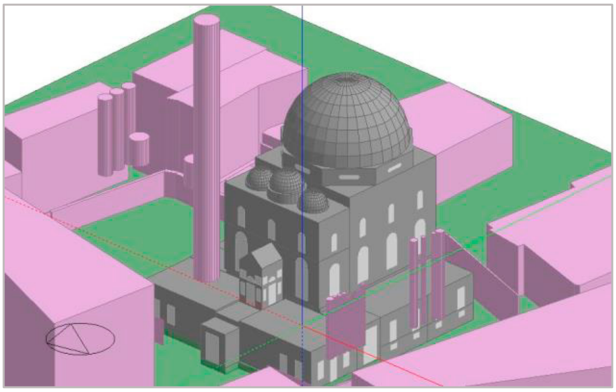


Fig. 3. DesignBuilder model of Salepçioğlu Mosque

2.4. Calibration

The calibration process requires the comparison of measured parameters with the simulated ones to understand how the model will differ from the actual case. In this paper, it was conducted in line with ASHRAE Guideline 14 (2). The guideline introduces two dimensionless error indicators: Mean Bias Error (MBE) and Coefficient of Variation of the Root Mean Squared Error CV(RMSE). MBE and CV(RMSE) were calculated by using Equation (1) and (2), respectively (ASHRAE, 2002).

$$\text{MBE}\ (\%) = (100/T_{ma}) * [\ \Sigma(T_s\text{-}T_m)]\ /N \qquad (1)$$

$$\text{CV(RMSE)}\ (\%) = (100/T_{ma}) * [1/N*(\Sigma(T_s\text{-}T_m)^{\ 2})]^{\ ½} \qquad (2)$$

Where:
N: is the number of observations
T_{ma}: is the average measured temperatures for N observations
T_s: is the simulated hourly temperatures
T_m: is the measured hourly temperatures

According to ASHRAE Guideline 14 (2), the acceptable range of MBE on hourly basis is up to ±10%. The CV(RMSE) is used to estimate how much the simulation data fits the measured data; thus the better calibration the lower CV(RMSE). The model is calibrated, if the CV(RMSE) value is within ±30% range when the hourly data is used. Once the 'baseline model' was calibrated, the 'developed scenario model' was created.

2.5. Underfloor Heating System

In order to analyse the potential of using an underfloor heating system for improvement of indoor thermal comfort in Salepçioğlu Mosque, 'developed scenario model' was created by using EnergyPlus v.8.1 (9). The calibrated baseline model was exported into EnergyPlus. The low-temperature electric radiant system was selected to represent the underfloor heating mat, applied under the carpet layer on the floor of the main worship space. The selected system is based on an electric resistance heating with wires embedded into the foldable mat. The model assumptions for underfloor heating system are stated as below:

1. Operation schedule is set active from 10:00 to 22:00 (continuously), and assigned as off at the rest of day.
2. Electrical power converted into heat is assigned as maximum 15000 Watt for all ground surface of main worship space.
3. Zone mean air temperature is selected to control the system.
4. Heating set point temperature is assigned as 22°C.

2.6. Adaptive Thermal Comfort

ASHRAE Standard 55 introduces the adaptive thermal comfort method to evaluate thermal comfort conditions for naturally conditioned spaces. It defines that thermal response for buildings without HVAC system depends on the outdoor conditions, and users' clothing preferences, availability of controlling immediate environment, and adaptability of user behaviors. The adaptive thermal comfort method can be applied under certain conditions as follows:

1. No mechanical cooling system in the space
2. The space in question with operable windows
3. No heating system in operation
4. Sedentary physical activities with the metabolic rate from 1 to 1.3 met
5. Indoor occupants can adapt their clothing (3).

For spaces that meet these criteria, the adaptive thermal comfort chart in Figure 4 can be used to determine allowable indoor operative temperature. The relation between the mean daily outdoor air temperature (T_{out}) (ºC), which is the arithmetic average of the mean daily minimum and mean daily maximum outdoor temperature, and the indoor operative temperature which is defined according to ASHRAE 55 is the measure of human thermal comfort.

ASHRAE 55 provides equations for the 80% and 90% upper and lower limit for the acceptable range of thermal comfort as shown in Figure 4. The 80% acceptable limits are used for the typical application. When a higher thermal comfort is required, the 90% acceptable limits are used (3). The 80% and 90% acceptable ranges are calculated by using Equations (3), (4), (5) and (6), and was drawn in Excel 2013 (Figure 4):

For the 80% upper and lower limit acceptable ranges:

$$\text{The upper limit (ºC)} = 0.31\ T_{out} + 21.3 \quad (3)$$

$$\text{The lower limit (ºC)} = 0.31\ T_{out} + 14.3 \quad (4)$$

For the 90% upper and lower limit acceptable ranges:

$$\text{The upper limit (ºC)} = 0.31\ T_{out} + 20.3 \quad (5)$$

$$\text{The upper limit (ºC)} = 0.31\ T_{out} + 15.3 \quad (6)$$

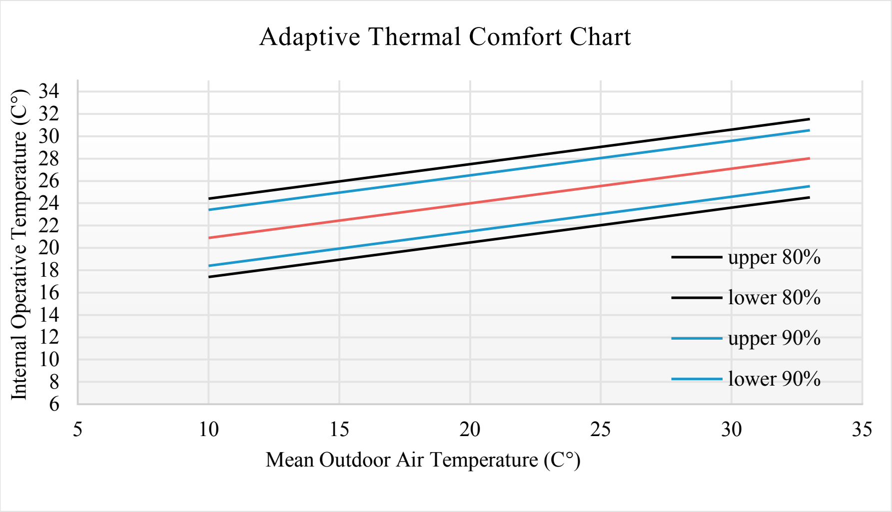


Fig. 4. Adaptive thermal comfort chart indicating acceptable operative temperature ranges

This study uses 80% acceptable limits as for the typical application. The hourly indoor operative temperature values obtained from simulation results of two models, i.e. 'baseline model' and 'developed scenario model,' are applied into the adaptive thermal comfort chart defined by ASHRAE 55 to calculate the discomfort hours. The number of hours out of 80% acceptable range is counted, and evaluated as the discomfort hours.

3. Results and discussions

3.1. Outdoor and Indoor Climate

Outdoor Dry Bulb Temperature (T): Figure 5 shows the outdoor dry bulb temperature of Salepçioğlu Mosque between 01.10.2014 and 30.09.2015. The outdoor T ranges from -2.4°C to 38.3°C with 19.7°C for the outdoor mean T. The minimum hourly outdoor T was monitored on 9th of January at 07:00, while the maximum was recorded on 22nd of July at 16:00.

Outdoor Relative Humidity (RH): the outdoor RH values ranged from 12% to 99.2%, while the average RH was 60.5% for the studied period. The minimum RH was monitored on the 19th of May at 16:00, while the maximum was recorded on 24th of January at 10:00.

Indoor Dry Bulb Temperature: according to the T measurement of logger #M2, the values varied between the minimum of 4.89ºC and the maximum of 35.94ºC, which was measured on 9 January at 08:00 and on 22 July at 19:00, respectively. Monthly mean indoor temperatures were between 11.29ºC and 31.61ºC. Mean yearly temperature has found 21.55ºC through the measurement period (Figure 5).

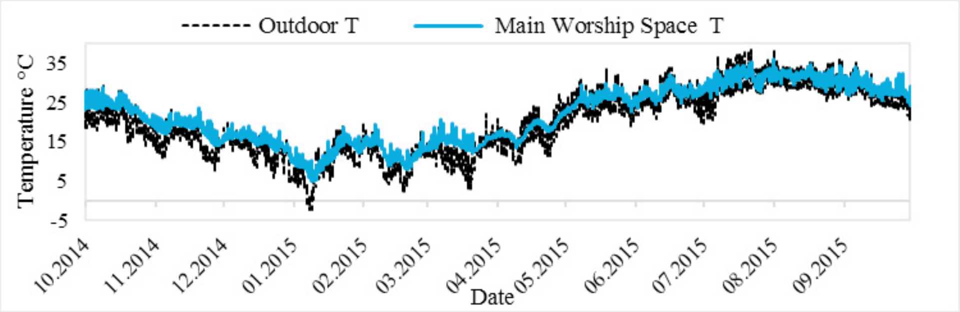


Fig. 5. Dry bulb temperature values for outside and main worship space

Indoor Relative Humidity: the measurements indicate that the values of RH changed between 18.85% and 83.03% through one year monitoring campaign. The maximum value for the RH was measured on 27 March at 13:00 and the minimum value was monitored on 19 May at 19:00. Monthly mean RH values varied from 43.96% to 69.37% on July and December, respectively. Mean yearly RH value was found as 56.09% (Figure 6).

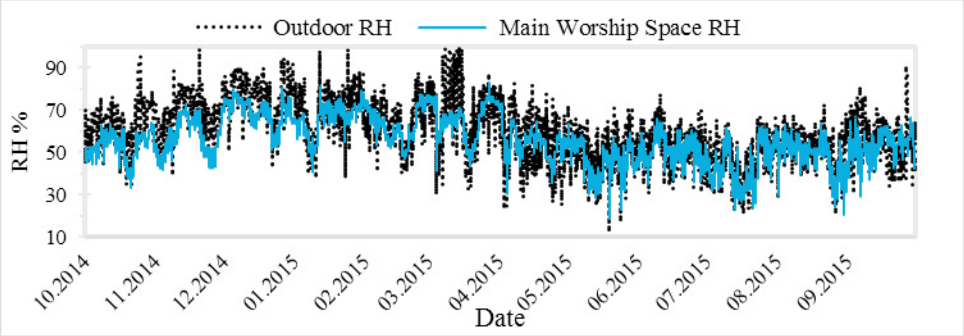


Fig. 6. Relative humidity values for outside and main worship space

3.2. Model Calibration

The baseline model was developed until the acceptable error ratios defined by ASHRAE Guideline 14 (2) were obtained. Table 1 indicates the results of MBE and CV(RMSE) indices derived from the comparison of simulated hourly temperatures of baseline model with the measured hourly data for the main worship space (logger #M2). The obtained results for 12 months convey that error ratios are within the acceptable range; thus the model is calibrated.

Table 1. Acceptable error ratios for hourly data calibration per each month

Month	MBE (%)	CV(RMSE) (%)
Oct 2014	-5.59	6.87
Nov	-9.26	10.56
Dec	-6.69	9.48
Jan 2015	-8.81	14.10
Feb	1.68	7.62
Mar	-5.00	11.98
Apr	5.48	9.38
May	0.60	3.70
Jun	0.97	3.52
Jul	1.30	4.47
Aug	1.87	3.92
Sep	4.12	6.81
ASHRAE Guideline 14	±10	30

3.3. Adaptive Thermal Comfort Analysis

3.3.1. Thermal Comfort Analysis of the Baseline Model

The simulation results of baseline model indicate that the highest number of discomfort hours for winter period occurred in December 2014 (744 hours), January 2015 (744 hours) and March 2015 (744 hours). In other words, the months of December 2014, January and March 2015 were completely out of 80% comfort limit defined by ASHRAE 55. The other uncomfortable months for winter period were November 2014 (717 hours), February 2015 (672 hours), and April 2015 (527 hours), respectively.

The most comfortable month was May 2015, while it was followed by June 2015 with 19 hours, September 2015 as 70 hours, October 2014 as 139 hours of discomfort. Totally 5618 hours of discomfort were calculated for one-year simulation period, representing that 64.13% of the year is out of comfort (Figure 7).

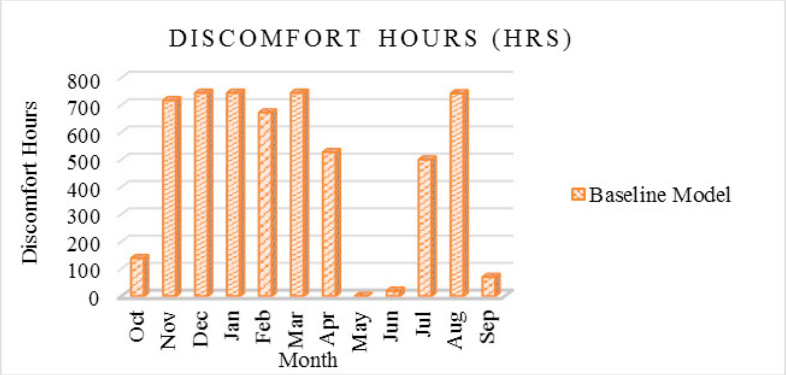


Fig. 7. Discomfort hours of the baseline model

3.3.2. Impact of Underfloor Heating System on Thermal Comfort

An underfloor heating system is tested for the winter period from the beginning of October 2014 to the end of March 2015, according to the overcooling months defined by the 'baseline model.' The simulation results of 'developed scenario model' indicate that the low temperature electric radiant system gradually increases the comfort levels (Figure 8).

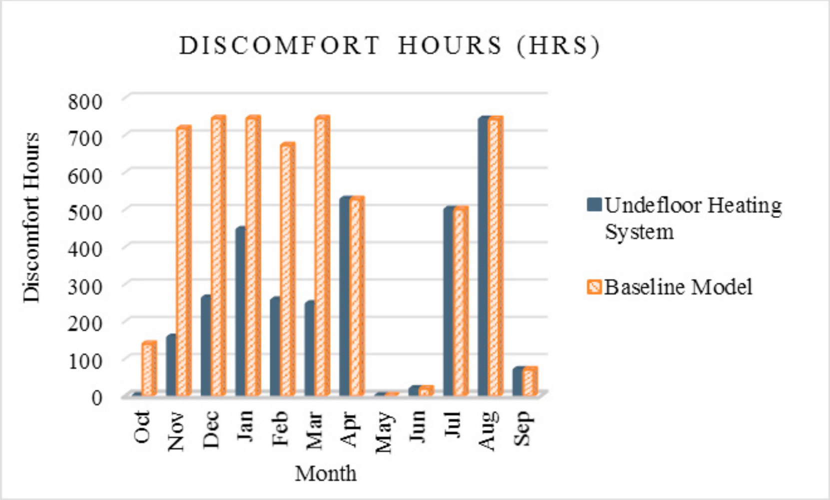


Fig. 8. Comparison of discomfort hours between two models

The lowest number of discomfort hours are obtained for October 2014, which satisfies the 80% comfort limit.

The highest number of discomfort hours are registered on January 2015 with 446 hours, while it was 744 hours in the baseline model. The discomfort hours for November and December 2014, February, and March 2015 are decreased into 157, 262, 257, and 247 hours, respectively (Figure 8).

Totally 1369 hours of discomfort are calculated for the winter period, representing that 31.34% of the year is out of comfort. However, it was reported 3760 hours for the baseline model signifying 86.08% of total hours of winter period. As a result, the application of underfloor heating strategy provided 54.74% of reduction compared to the present situation. Figure 9 illustrates the adaptive thermal comfort charts for winter months defined by the ASHRAE 55 (3) for both models. The grey and yellow dots, representing baseline and developed scenario models, indicate the intersection of indoor operative and outdoor temperatures per hour in each month of winter period.

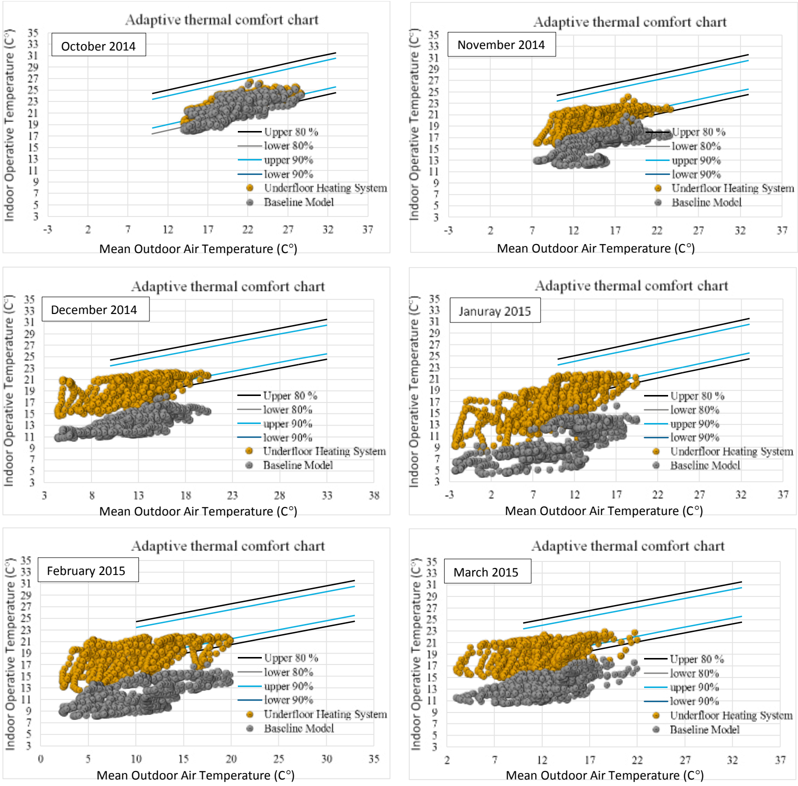


Fig. 9. Adaptive thermal comfort charts of two models for winter period

4. Conclusions

One-year adaptive thermal comfort analysis of the historic Mosque located in Izmir, Turkey was conducted to evaluate and enhance indoor thermal conditions. The adaptive thermal comfort method provided by ASHRAE Standard 55-2010 was selected to investigate the unconditioned Mosque where the prayers were able to control their environment by means of clothing and operable windows (3). The analysis was conducted via dynamic simulation modelling, using DesignBuilder and Energyplus software. The baseline model was calibrated according to the ASHRAE Guideline 14 (2). The adaptive thermal comfort charts were prepared, and the discomfort hours were calculated.

The rationale for selection of underfloor heating system is the fact that the mosques have big volumes, composed of large dome with huge height. In other words, the remarkable temperature stratification is seen in the worship space. For achieving better thermal comfort with low energy use, the Mosque is intended to be heated with an underfloor heating system to satisfy comfort levels only on the occupancy level with an intermittent operation schedule.

The thermal comfort analysis conveyed that there was overcooling in October, November and December 2014, and January, February, and March 2015. The simulation results indicate that the application of low temperature electric radiant system as underfloor heating substantially increased thermal comfort of the main worship space.

On the other hand, Salepçioğlu Mosque is the historic mosque, housing unique engraving and paintings on its dome. In the case of historic building, any mechanical system proposal should be carefully examined in order not to compromise the heritage value of the building. An option can be that the proposed system should firstly be simulated in the dynamic modelling tool. Besides, the deep and multidisciplinary cooperation is required for proposed system by considering the sensitivity and heritage value of building materials and ornaments peculiar to each historic building.

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