This study aims at evaluating the perceived thermal sensation of occupants with respect to thermal comfort standards, ASHRAE 55 and ISO 7730, for office buildings located in Mediterranean climate. A small office building in Izmir Institute of Technology Campus Area, Izmir, Turkey, was chosen as a case building and equipped with measurement devices to assess thermal comfort of occupants with respect to predicted mean vote and actual mean vote. Both objective and subjective measurements were conducted. The former included indoor and outdoor air temperature, mean radiant temperature, relative humidity and air velocity that were used for evaluating the thermal comfort of occupants. Oxygen concentration which can play an additional role in thermal comfort/discomfort, health and productivity of the office occupants, was also measured. Furthermore, occupants were subjected to a survey via a mobile application to obtain subjective measurements to calculate actual mean vote values. Based on objective and subjective measurements, the relationships among the parameters were derived by using simple regression analysis technique while a new combined mean vote correlation was also derived but this time by using multiple linear regression model. Neutral and comfort temperatures were obtained using indoor air temperature and actual mean vote values which were calculated from subjective measurements. The results showed that neutral temperature in the university office building was 20.9 °C whilst the comfort temperature range was between 19.4 and 22.4 °C for the heating season. By applying new comfort temperatures, energy consumption of the case building located in Mediterranean climate, can be reduced.

Key words: thermal comfort, human body exergy consumption rate, office buildings

Introduction

Thermal comfort is defined as the condition of mind in which satisfaction is expressed with thermal environment and depends on whole body sensation which is function of six parameters: indoor air temperature, $T_i$, relative humidity, $RH_i$, air velocity, $v_a$, clothing insulation, $clo$, metabolic rate, $met$, and mean radiant temperature, $MRT_i$ [1]. A considerable number of studies on thermal comfort have been published over the past 50 years. Fanger [2] developed two thermal comfort indices, predicted mean vote ($PMV$) and predicted percentage
of dissatisfied (PPD), which were later standardized in ISO 7730 [3] and ASHRAE 55 [1]. The PMV refers to a seven-point thermal sensation scale from −3 to +3 (where −3 is cold, 0 is neutral, +3 is hot). When PMV is in the range of ±0.5, 90% of the occupants feel thermally satisfied while 10% is dissatisfied (PPD). In this study which was based on the First law of thermodynamics, Fanger [2] conducted tests with a number of subjects at different ages and gender in an air-conditioned environmental test chamber which was monitored for indoor climate parameters like temperature, relative humidity, etc. On the other hand, Shukuya [4] suggested that human body exergy balance calculations (based on the Second law) represent thermal comfort more accurately than the First law. The method involves the use of outdoor temperature, $T_o$, and relative humidity, $RH_o$, as well as indoor environmental data, to calculate the human body exergy consumption, $HBexC$, rate, and PMV. Isawa et al. [5] showed the correlations between thermal comfort and $HBexC$. Another finding of their study suggested that the lowest exergy consumption occurred at thermal neutrality. Similarly, Prek [6] found that minimum $HBexC$ rates were near neutral thermal sensation votes.

Although PMV method is reliable in air-conditioned buildings in cold climates, de Dear et al. [7] demonstrated that the acceptance range of PMV of the occupants in naturally ventilated buildings in warmer climates is much wider than the standard PMV model based on objective ($T_i$, $T_a$, $RH_i$, $RH_a$, $MRT_i$, and $v_o$) and subjective measurements. Moreover, Heideri and Sharples [8] showed that the occupants in Iran achieved thermal comfort throughout the year, without the need for air-conditioning and the PMV values were much wider than the recommended values by international standards.

Actual mean vote (AMV) is the mean value of occupant’s actual thermal sensation votes by using ASHRAE seven-point thermal sensation scale [1]. Subjective measurements are surveys that aim to collect data from occupants about their thermal preferences and clo value which will then be used for calculation of AMV values [9]. In thermal assessment studies, a number of thermal comfort sensation scales have been proposed for assessment of occupant’s perceptions including ASHRAE thermal sensation scale [1], Bedford comfort scale [10], McIntyre 3-point preference scale [11], and acceptability scale [12]. Neutral temperature is the temperature where AMV value is zero while comfort temperatures are temperatures where AMV values are between ±0.5. Occupants prefer to be in neutral temperature or in comfort temperature zone [13]. Corgnati et al. [9] indicated that the students of an Italian university preferred neutral temperatures while in another study conducted in China, Yao et al. [14] showed that the perception of occupants was much lower than the PMV values and occupants preferred to be in neutral temperature.

Indoor air quality (IAQ) along with the perception of thermal comfort has a substantial impact on the health and productivity of occupants. The type and the amount of contaminants such as CO, CO2, NO2, radon (Rn), and SO2 affect IAQ. Elevated CO2 concentration stimulates human respiratory system and increases met values. The O2 and CO2 are both present in the atmosphere and when CO2 concentration increases, O2 concentration decreases. Gauthier et al. [15] claimed that the gap between PMV and AMV could be because of the IAQ parameters. Based on their measured CO2 concentrations in an office building and calculated AMV values, they concluded that there was no significant relationship between CO2 and AMV due possibly to the limited number of participation in the experiment. Hence, they recommended further experiments to be done with increased participation.

Regression analysis is a common data analysis approach in thermal comfort studies. Nicol and Humphreys [16] used regression analysis to determine the comfort temperatures in the UK. Singh et al. [17] derived a regression formula for indoor climate and thermal comfort
in residential buildings of Liege, Belgium. Heideri and Sharples [8] correlated AMV and PMV values in Iran. Van der Linden et al. [18] used regression analysis for evaluation of thermal indoor climate with \( T_o \) values. The aim of the regression analysis is to investigate relationships among parameters used in thermal comfort models. Hence, the model minimizes sum of squares of the differences between observed and estimated values of a parameter by the least squares method [19]. The most frequently used regression analysis techniques are simple (SLR) and multiple linear regression (MLR) methods. McCartney and Nichol [20] applied SLR techniques on thermal comfort with one independent parameter, \( T_v \). Fanger [2] used \( T_i \) values to find an SLR equation for thermal comfort. Similarly, Singh et al. [17] correlated PMV values with \( T_i \). In spite of the fact that \( T_i \) is known to be the strongest factor affecting thermal comfort, inclusion of factors like RH, MRT, \( v_a \), and even IAQ in the regression model should be expected to improve the fit.

The main purpose of this study was to assess thermal comfort preferences of occupants in a university office building, in Izmir, Turkey, which is located in Mediterranean climate. Another aim was to improve the correlation between PMV and AMV by introducing \( O_2 \) concentration in the regression model for PMV.

**The case building**

The case building is located at Izmir Institute of Technology Campus, Izmir, Turkey (at 38.3 °N and 26.6 °E), fig. 1, which is in Mediterranean climate (a k a Csa type climate zone under the Koppen-Geiger climate classification [21]). The minimum and maximum average annual temperatures are 5.7 °C and 33.1 °C, respectively with a mean temperature of 17.8 °C [22].

![Figure 1. The case building; (a) location, (b) plan, and (c) outer view](image)

Dimensions of the square shaped case building are 6 m (width) × 6 m (depth) × 2.8 m (height). There are four external walls with six windows and two equally sized rooms in the building. The indoor environment is controlled by an air-conditioner to keep \( T_i \) at 22 °C from 09:00 to 12:30 and 13:30 to 17:00 during weekdays in heating/cooling seasons. The air-conditioner is operated at high fan speed in the morning and at low fan speed in the afternoon. In order to prevent air velocity disturbances on the occupants, the fan is fixed to blow straight up. External walls of the building consist of cement plastering, pumice concrete and cement screed. The innermost layers of the floor are cast concrete, floor screed and limestone. Layers of the roof consist of plasterboard, air-gap, glass wool and asphalt and all the window frames.
are PVC with double glazing (13 mm air-gap). Similarly, the external door has PVC frame. The airtightness of the building is assumed as 0.5 air changes per hour which is a moderate rate for naturally ventilated office buildings [23].

**Methods**

A measurement campaign was conducted from February 6th, 2017 to April 7th, 2017, in the case building during office hours. Objective measurements ($T_o$, $RH_o$, $RH_i$, $T_i$, $v_a$, $O_2$) were recorded with 5-min intervals while subjective measurements (surveys) were conducted twice a day. Objective and subjective measurements were used to calculate $PMV$, $HBexC$, and $AMV$. Then, $AMV$ values were compared with $PMV$ values. Neutral and comfort temperatures were obtained using $T_i$ and $AMV$ values which were calculated from subjective measurements. A new combined mean vote ($CMV$) correlation was derived by regression analysis techniques based on objective and subjective measurements. The $CMV$ was proposed in this study as a means of improving the correlation between $PMV$ and $AMV$. Finally, sensitivity analysis was applied to the regression model of $CMV$ to evaluate the influence of parameters on the dependent parameter.

**Measurements**

The data were collected by four mini dataloggers which record $T_i$, $T_o$, $RH_i$, and $RH_o$ data [24] and a thermal comfort module (TCM) [25] which contains $T_i$, $v_a$, $RH_i$, and operative temperature ($OT_i$) sensors. The case building was occupied by two male occupants during office hours. All the windows and doors were kept close during the measurements. All sensors were deployed close to the occupants positioned at 1.1 m height from the ground level. The $OT_i$ sensor was installed in inclining position with 30° to the vertical direction to simulate a person in sitting position, fig. 2(a). Concentration of $O_2$ was measured by a Grove-Gas Sensor, figs. 1(b) and 2(a) [26]. The normal $O_2$ concentration in the air is 20.9% whilst the acceptable upper and lower bounds of $O_2$ concentration in a room is 23.5% and 19.5%, respectively [27].

![Figure 2. (a) Location of the sensors and (b) screenshots of mobile application interface](image)

Subjective measurements were conducted via a mobile application which was designed as an occupant sensing application for smartphones according to ISO 10551 [28]. The mobile application adopts preferences of occupants regarding thermal comfort by inherently
incorporating the sensor data and the feedbacks of the occupant with ambient conditions. The interface of the mobile application was originally designed using ASHRAE sensation scale which gives the AMV values of the occupants. Moreover, the application enquires the name and garments of the occupant and easily calculates the clo value of each occupant according to ASHRAE 55 [1]. The mobile application was developed exclusively for Android-based smartphones and helped store the data in a web server, fig. 2(b).

**Data analysis**

The $OT_i$ is a simplified measure of thermal comfort derived from $T_i$, $MRT_i$, and $v_a$. The $T_i$ is commonly accepted as the most effective factor on thermal comfort but $MRT_i$ has impact as high as $T_i$ [17]. Since $OT_i$ was measured by TCM, $MRT_i$ could be extracted from eq. (1) as given in ASHRAE 55 [1]:

$$ OT_i = A \cdot T_i + A \cdot MRT_i $$

where $A$ is the weighting factor for various $v_a$. If $v_a < 0.2$ then $A = 0.5$, if $0.2 < v_a < 0.6$ then $A = 0.6$ and if $0.6 < v_a$ then $A = 0.7$ [1].

The TCM calculates PMV values based on the measured parameters, clo and met values (as inputs) [25]. Daily average clo and AMV values were obtained from the surveys whilst met values were taken from ASHRAE 55 [1] for regular work when sitting in an office. $RH_i$, $T_i$, clo and met values were used to calculate a secondary $PMV_{CBE}$ value using Centre of Building Environment (CBE) thermal comfort tool [29]. The CBE thermal comfort tool uses ASHRAE 55 calculation steps and allows users to calculate PMV values. The third $PMV_E$ value was calculated with a human body exergy balance contour calculation tool developed by Iwamatsu and Asada [30]. The tool uses $T_o$, $RH_o$, $T_i$, $MRT_i$, $RH_i$, $v_o$, clo and met values as well as room dimensions. The outputs of the tool are $HBexC$ rate and $PMV_E$. Further information about the calculation method can be found in [30]. Lastly, three PMV values were compared with AMV values. To be able to determine the effect of $O_2$ concentration on AMV values, objective parameters were set constant for one day (April 3rd, 2017) and $O_2$ concentration and AMV change over time was observed. The relationship between thermal comfort and $O_2$ concentration was investigated by deriving a new correlation called CMV, based on objective and subjective measurements using SLR and MLR analysis techniques in MATLAB [31].

The SLR is a statistical method that allows us to obtain the relationships between two quantitative parameters [32]. An SLR equation is given:

$$ y = ax + \beta $$

The MLR is used to explain the relationship between one dependent variable and two or more independent parameters [32]. A general expression for a regression equation involving multiple parameters can be expressed:

$$ y = b_0 + b_1 x_1 + b_2 x_2 + \ldots + b_i x_i + \epsilon $$

where $y$ is dependent (output) variable, $x_i$ are independent (input) parameters, $b_i$ are linear regression-model coefficients, and $\epsilon$ is error term. The commonly used statistical criterion, coefficient of determination, $R^2$, can be used to evaluate the performance of the regression models, eq. (4), [32]:

$$ R^2 = \frac{\sum_j (t_j - o_j)^2}{\sum_j (o_j)^2} $$
Sensitivity analysis is applied to the regression model to evaluate the influence of parameters on the dependent variable. Regarding the impact size of the main variables in regression model, response of the dependent variable to one standard deviation (SD) increase in the explanatory variables is investigated. Further information about the sensitivity analysis can be found in [33]. The neutral and comfort temperatures were defined as $T_i$ corresponding to 0 and ±0.5 AMV values, respectively. Both temperatures could be calculated according to the Griffiths [34] method since the method is quite useful with small data sets, eq. (5):

$$S = aT_i + \beta$$

### Results and discussion

A total number of 3780 data (from February 6th, 2017, to April 7th, 2017) were recorded during the measurement campaign. The minimum, average, maximum and SD values of measured ($T_i$, $RH_i$, $RH_o$, $T_o$, $v_a$, $O_2$) and calculated data ($MRT_i$, $HBexC$, $PMV_{TCM}$, $PMV_E$, $PMV_{CBE}$) are shown in tab. 1.

The developed mobile application was performed to the occupants to obtain their names, garments and thermal comfort preferences, twice a day at 10:45 and 15:15, fig. 3.

![Figure 3](image)

**Figure 3. Timeline of the measurements in a day**

The metabolic rate of each occupant was chosen as 1.2 met ($M = 70 \text{ W/m}^2$) corresponding to regular work when sitting in an office [1]. The thermal insulation effect of wooden stools for occupants seated on chairs (0.01 clo) was added according to ISO 7730 [3] since the study was conducted during the heating season. Figure 4 presents the comparison of AMV with $PMV_{TCM}$, $PMV_E$, and $PMV_{CBE}$ values with respect to time. The figure indicates that the ranges of thermal comfort acceptance of occupants (AMV) are higher than the PMV values.

Figure 5(a) shows the change of $O_2$ concentration and AMV values with time. As it can be seen from the figure, occupants feel warmer when the $O_2$ concentration decreases while objective parameters are kept constant. As an example, a 3.3% decrease in $O_2$ concentration, increases the AMV value from −0.5 to 0.5. Thus, there would be a significant relationship between AMV and $O_2$ concentration.
Regression analysis was conducted to predict AMV values and according to the results, AMV values are highly-correlated with PMV values, eqs. (6)-(8):

\[
AMV = 1.103 \text{PMV}_{\text{TCM}} + 0.2374 \quad (R^2 = 0.79) \quad (6)
\]

\[
AMV = 1.012 \text{PMV}_{\text{CBE}} + 0.1749 \quad (R^2 = 0.77) \quad (7)
\]

\[
AMV = 1.006 \text{PMV}_E + 0.1465 \quad (R^2 = 0.81) \quad (8)
\]

Equations (6)-(8) exhibit that the occupants live in Mediterranean climate, perceive the environment at a higher thermal sensation. For instance, in eq. (6), AMV is equal to 0.24 when PMV_{TCM} = 0, and PMV_{TCM} is equal to −0.21 for AMV = 0. These results infer that PMV values are higher than perceived AMV which can result in unnecessary energy consumption in the case building because of the higher set temperatures. Variation in AMV with \(T_i\) is shown in fig. 5(b) and their correlation is given:

\[
AMV = 0.3356 T_i - 7.015 \quad (R^2 = 0.82) \quad (9)
\]

The slope in eq. (9) is found as 0.3356 °C. Based on the findings, the neutral temperature of the case building was calculated to be 20.9 °C while the comfort temperature range lied from 19.4 to 22.4 °C. These results are quite in-line with the study for office buildings located in Mediterranean climate in Iran [8]. By applying new comfort temperatures, energy consumption of the case building could be decreased since the set temperature was 22 °C.

Figure 6(a) shows the relationships between \(HBexC\) [Wm\(^{-2}\)], \(T_i\) [°C], and \(MRT\) [°C] which were derived by Shukuya et al. [4]. Fine lines with numbers depict \(HBexC\) rates. The bold line represents a comfortable indoor thermal condition that gives a good thermal comfort for occupants. The neutral AMV value is shown with red shaded area on the graph. The neutral temperature, \(T_n\), of 20.9 °C gives the minimum \(HBexC\) and \(MRT\), as 2.63 W/m\(^2\) and 22.1 °C, respectively. Calculated \(MRT\) values were between 18.5 and 22.2 °C which are in a good agreement with fig. 6(a). It is worth to note that for air-conditioned indoor spaces, \(v_e\),
values could be higher than the measured values in this study. Since $MRT_i$ was calculated from eq. (1) which mainly depends on $v_a$ values, for higher $v_a$ values, $HBE_xC$ rates could be higher for the same $T_i$ compared with fig. 6(a). A sensitivity analysis on the results was conducted in order to observe the impact of $v_a$ on $HBE_xC$ rates. A 0.1 m/s increase in $v_a$ increases the $HBE_xC$ rate by 3.3%.

Figure 5. The $O_2$ concentration and $AMV$ (a); $AMV$ values vs. $T_i$ (b)

Figure 6. The $HBE_xC$ of an average occupant in winter condition [8] (a) and human body exergy consumption dependent on indoor air temperature (b)
Figure 6(b) represents the $T_i$ change with $HBexC$ rate. When $T_i$ increases, $HBexC$ rate decreases until $T_i$ reaches the neutral temperature. Then, $HBexC$ rate shows an increasing trend similar to the [4].

Regression analysis was carried out to determine the relationship between thermal comfort and $O_2$ concentration. A total of 3780 data were split into two categories, 80% of the data for calibration and 20% of the data for validation of the model. In addition to $O_2$ concentration, there were two more independent parameters selected for regression analysis, $T_i$ and $RH$, which are known to be the most effective parameters on thermal comfort [2]. Recalling eq. (3), $CMV$ can be written as given in eq. (10):

$$CMV = b_0 + b_1 T_i + b_2 RH + b_3 O_2 + \varepsilon$$

Note that the data set contains measurements for $T_i$, $RH$, and $O_2$ concentration whilst the noise component $\varepsilon$ is comprised of factors that are unobservable, or at least unobserved. The optimal values of the regression coefficients of both SLR and MLR models were obtained by employing calibration data. Performing the calibration data, the eq. (11) was derived to interpret $CMV$ with three independent variables:

$$CMV = 0.241 T_i + 0.238 RH - 0.112 O_2 - 5.512 (R^2 = 0.76)$$

<table>
<thead>
<tr>
<th>Dependent parameter</th>
<th>Regression coefficient</th>
<th>$p$-value</th>
<th>$t$-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>$-5.512$</td>
<td>0.005</td>
<td>-3.9</td>
</tr>
<tr>
<td>$T_i$</td>
<td>$0.241$</td>
<td>0.000</td>
<td>4.94</td>
</tr>
<tr>
<td>$RH_i$</td>
<td>$0.238$</td>
<td>0.016</td>
<td>2.49</td>
</tr>
<tr>
<td>$O_2$</td>
<td>$-0.112$</td>
<td>0.035</td>
<td>-2.17</td>
</tr>
<tr>
<td>$R^2$</td>
<td></td>
<td>0.76</td>
<td></td>
</tr>
</tbody>
</table>

Notes: *** significance at 1%, ** significance at 5%

$RH_i$ has a significant and positive coefficient. However, the impact of $O_2$ concentration is negative and significant at 5% on the $CMV$. In other words, decrease in $O_2$ concentration caused an increase in $CMV$ value similar to those reported in [15]. Sensitivity analysis showed that $CMV$ increased by 0.56 and 0.03 when $T_i$ and $RH$ were raised by one SD, respectively. The effect of one SD increase in $O_2$ concentration, however, led to a reduction in $CMV$ by 0.001. Another observation from the sensitivity analysis was that the most effective parameter was $T_i$.

**Conclusion**

This study presents thermal comfort preferences of occupants in a university office building located in Mediterranean climate. The office room with two male occupants was assessed by both objective and subjective measurements in order to perceive thermal sensation of the occupants. The objective measurements including $T_i$, $T_a$, $RH_i$, $RH_a$, $O_2$, concentration and $v_o$ were used to calculate the $PMV$ values by TCM, CBE thermal comfort tool and human body exergy balance contour calculation tool. A mobile application which uses the seven-point scale of ASHRAE 55 was run to obtain $AMV$ values of the occupants. The $PMV$ values were correlated with $AMV$ values. Correlations showed that $PMV$ values underestimated the perceived thermal sensation of the occupants in Mediterranean climate. The highest
correlation rate was obtained by human body exergy balance contour calculation tool since it considered $MRT_i$ and minimum $HBexC$ rate together. In addition, the objective and subjective measurement data were treated through SLR and MLR analysis to derive the new $CMV$ values. The values for $R^2$ and $p$ indicated that $CMV$ was correlated/associated with $T_i$, $RH_i$ and $O_2$ concentration. If $AMV$ values were taken into consideration, the energy consumption in the case building could be reduced. Even though the study was limited to one office building, two male occupants and two-months of measurement campaign, it still gave an idea that in warmer climates $AMV$ should be considered for energy saving and $IAQ$ parameters should also be included in thermal comfort analysis. In this study, $T_i$ was used in Griffiths method, however, $OT_i$ could be also used in order to define neutral temperatures for larger sample sizes since it is a key parameter which uses indoor surface temperatures, air velocity, clothing, metabolic rates and $T_i$, together. Larger sample size that accounts for gender should be expected to improve the correlations. Studies on a larger population of occupants with different age and gender, collection of data over longer periods of time and long term surveys are planned to further justify the findings in the future.

Nomenclature

$clo$  – clothing insulation, [–]
$MRT$  – mean radiant temperature, [°C]
$met$  – metabolic rate, [–]
$O_2$  – oxygen concentration, [%]
$OT$  – operative temperature, [°C]
$RH$  – relative humidity, [%]
$S$  – comfort votes, [–]
$T$  – air temperature, [°C]
$x$  – independent parameter
$v$  – velocity, [ms$^{-1}$]
y  – dependent parameter, [–]

Greek symbols

$\alpha$  – slope
$\beta$  – constant (intercept)
$\varepsilon$  – error, [-]

Subscripts

$a$  – air
$i$  – indoor
$o$  – outdoor

Acronyms

$AMV$  – actual mean vote
$CBE$  – center of building environment
$CMV$  – combined mean vote
$HBexC$  – human body exergy consumption, [Wm$^{-2}$]
$IAQ$  – indoor air quality
$MLR$  – multiple linear regression
$PMV$  – predicted mean vote
$PPD$  – predicted percentage of dissatisfied
$Rn$  – radon
$SD$  – standard deviation
$SLR$  – simple linear regression
$TCM$  – thermal comfort module

References


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