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The relation between thermal comfort and human-body exergy consumption in a temperate climate zone

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ABSTRACT

Human body exergy balance calculation method gives minimum human body exergy consumption rates at thermal neutrality (TSV = 0) providing more information on human thermal responses than other methods. The literature is lacking the verification of this method in various climatic zones. The aim of this study is to investigate the relationship between thermal comfort and human body exergy consumption in a temperate climate zone. A small office building in Izmir Institute of Technology campus, Izmir/Turkey, was chosen as a case building and equipped with measurement devices. The occupant was subjected to a survey via a mobile application to obtain his Thermal Sensation Votes. Objective data were collected via sensors and used for predicting occupant thermal comfort and for exergy balance calculations. Under given conditions, the results show that Thermal Sensation Votes are generally zero at a T_i range of 21–23 °C and, are mostly lower than Predicted Mean Votes in summer while the opposite is observed in winter. Predicted Mean Votes at minimum Human Body Exergy Consumption rates were on slightly warm side while Thermal Sensation Votes are zero. It means that for given case, the HBexC rate calculation gave a better prediction of the environmental parameters for the best thermal comfort.

1. Introduction

Thermal comfort is described as *“the condition of mind that expresses satisfaction with the thermal environment”* [1]. In this satisfied environment, physical and mental productivity of human increases [2]. Individual, psychological, social and organizational parameters affect thermal sensation of the occupants and each occupant feel different even in the same environmental conditions [3]. For instance, comparative studies with regard to gender conducted by Wang et al. [4] showed that males are less sensitive to temperature variations than females. The neutral operative temperature of males was obtained as 1.1 °C lower than that of females. Hwang et al. [5] investigated thermal comfort criteria of ASHRAE 55 [6] in hospitals and stated that thermal sensation votes by patients exceeded the Standard’s 80% criterion, regardless of whether the physical conditions were in or out of the comfort zone. The preferred temperatures of patients were higher than neutral temperatures, suggesting that patients expected a warmer environment than neutrality.

Thermal comfort is strongly related to the thermal balance of the human body with its environment. Traditional methods of human thermal analysis are based on the First Law of Thermodynamics [7-11]. These methods use an energy balance of the human body to determine heat transfer between the body and the environment [12-13]. The international comfort standards are based on theoretical analyses of energy balance performed in mid-latitude climatic regions in North America and Northern Europe [7,14]. They are based primarily on mathematical models developed by Fanger [7] on the basis of experimental studies in a controlled climate chamber.

Energy is conserved in a thermodynamic process while exergy can be consumed due to the degradation of energy (irreversibility) during the process (2nd Law of Thermodynamics) [7,15-18]. Exergy analysis is a significant thermodynamic analysis to evaluate a thermodynamic process or system. The exergy concept can also be applied to the human body system. The human body works to regulate the entropy generated inside the body by e.g. metabolism, in order to keep the body core temperature as constant as possible. The ability to do this is affected by the personal parameters (body mass, skin surface, activity, clothing value etc.) and articulated as the thermal comfort [15-16].

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Nomenclature

C	Weighting factor (-)
clo	Clothing insulation clo
HBexC	Human body exergy consumption W/m^2
met	Metabolic rate met
MRT	Mean radiant temperature °C
OT	Operative temperature °C
P	Pressure kPa
PID	Proportional-Integral-Derivative
PMV	Predicted mean vote (-)
RH	Relative humidity%
T	Temperature °C
TSV	Thermal sensation vote (-)
U	Thermal transmittance W/m^{2}K
X	Exergy rate W

Subscripts

a	Air
abs	Absorbed
c	Convection
cl	Clothing
cons	Consumed
cr	Body core
dis	Radiant exergy discharged through the surface
exh	Exhalation
i	Indoor
in	Input
inh	exergy contained in the inhaled humid air
M, met	Metabolism
o	Outdoor
out	Output
r	Reference state
sh	Exergy generated in shell by metabolism
sk	Skin
st	Stored
sw	Sweating
w	Water, water vapor

Shukuya et al. [19] suggested a new approach for human thermal comfort which is based on the First and Second Law of Thermodynamics. The approach considers human body system as a complex model with circular nodes and uses outdoor temperature (T_o) and relative humidity (RH_o) as well as indoor environmental conditions, then calculates human body exergy consumption (HBexC) rate (Fig. 1). Comparing with PMV method, there are limited combinations of thermal comfort parameters that give minimum HBexC rate and PMV = 0 value (thermal neutrality) [18].

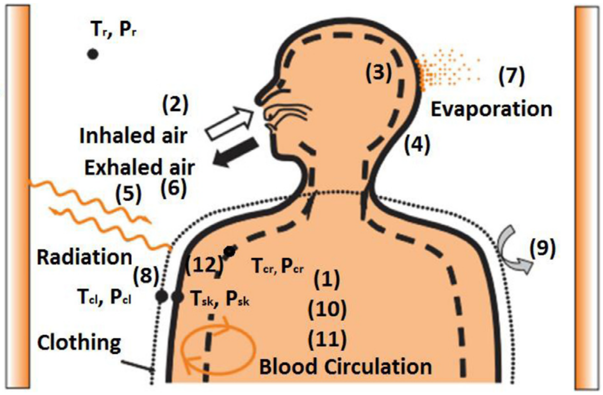

Fig. 1. Modelling of human body system [19].

The HBexC rate is obtained by human body exergy balance calculation which needs eight parameters as input; T_i, T_o, RH_i, RH_o, MRT_i, v_a, metabolic rate (met) and clothing insulation (clo). The calculation method uses Gagge's model described in [8].

A chronological overview of the development of the HBexC rate method for thermal comfort analysis is summarised below.

The first studies on the calculation of HBexC rate for thermal comfort analysis were conducted by Batato et al. in 1990s [20]. The authors applied exergy analysis to the human body system and concluded that the metabolism produces the same energy and exergy magnitude; however, energy flow to the environment significantly exceed the exergy flow which confirm that exergy analysis gives more information about the thermal comfort than conventional methods. Isawa et al. [21] derived correlations between thermal comfort and HBexC. The authors concluded that the lowest exergy consumption rate occurred at thermal neutrality (PMV = 0) . In 2004, exergy consumption of human body dependent on personal and environmental factors were analysed by Prek [22]. The author indicated that exergy is consumed as a consequence of heat and mass transfer and/or conversion on human body and exergy analysis showed clearly how human exergy consumption is related to environmental conditions. Prek [23] used thermal sensation votes (TSV) instead of PMV and obtained that minimum HBexC rates were at near zero TSV values. The author indicated that there is no one combination but limited number of combinations of T_i and MRT_i which gives the minimum HBexC rate. Shukuya et al. [19] studied HBexC rate on thermal comfort and the results indicated that the minimum HBexC rate gives neutral thermal comfort. Furthermore, the study compared HBexC rate with PMV method for various combinations of T_i and MRT_i. The authors showed that there is only one optimal combination between HBexC rate, T_i and MRT_i while many combinations of PMV = 0, T_i and MRT_i exist [19]. In 2011, Simone et al. [24] used data from previous studies to derive a relationship between HBexC rate and TSV and obtained a second-order polynomial relationship, however, recommended further studies to quantify the HBexC rate for different climatic regions. In 2013, Caliskan [25] performed an energy and exergy analyses to the human body system for summer season in Izmir-Turkey to observe the differences between two methodologies. The authors stated that exergy point of view is very important to completely understand the human body like a thermodynamic system at dynamic conditions. The minimum HBexC rate was obtained at a PMV value of 0.028 which is very close to the thermal neutrality. In 2014, Ala-Juusela and Shukuya [26] investigated the relationship between PMV and HBexC rate in an office in typical and extreme cases for continental subarctic weather conditions. They concluded that in summer, the minimum HBexC rate occurs on slightly cool side of the thermal votes predicted by PMV calculation (PMV = −0.3), and the same for winter, although then a bit closer to PMV = 0. In another study conducted in 2017 by Prek and Butala [27], the HBexC method were compared with PMV method and the authors indicated that the Second Law determines thermal comfort more accurately than the First Law since exergy loss is expressed by a single value which gives the thermal neutrality. In 2018, Ekici and Bilgili [28] applied exergy analysis to contribute to design of air-conditioning systems. The authors stated that the HBexC rate increases when temperature decreases. On the other hand, the relationship between thermal comfort parameters and HBexC rate has not been investigated in detail for Turkey.

Limited number of studies on limited number of climate zones conducted to derive relationship between HBexC rate and thermal comfort, e.g. for typical and extreme cases for continental subarctic weather conditions in both summer and winter [26], for warm and

Table 1
Exergy balance for human body system [19,22,24].

Terms	Notations in Fig. 1	Terms	Explanations
X_{in}	(1)	$X_{in,\ met}$	Exergy generated by metabolism
	(2)	$X_{in,\ inh}$	Exergy contained in the inhaled humid air
	(3)	$X_{in,\ w,\ cr}$	Exergy contained in the liquid water generated in the body core by metabolism
	(4)	$X_{in,\ w,\ sh}$	Exergy contained in sum of liquid water generated in the shell by metabolism (sweat)
	(5)	$X_{in,\ abs}$	Radiant exergy absorbed through the surface (skin and clothing)
X_{out}	(6)	$X_{out,\ exh}$	Exergy contained in the exhaled humid air
	(7)	$X_{out,\ sw}$	Exergy contained in the humid air leaving the body surface (evaporated water from the sweat)
	(8)	$X_{out,\ dis}$	Radiant exergy discharged through the surface (skin and clothing)
	(9)	$X_{out,\ c}$	Exergy transferred by convection from the surface to the surrounding air
X_{cons}	(10)	X_{cons}	Exergy consumed by the human body
X_{st}	(11)	$X_{st,\ cr}$	Exergy stored in the core
	(12)	$X_{st,\ sk}$	Exergy stored in the skin

Fig. 2. Location of the case building.

Fig. 3. The case building and the surroundings.

humid weather conditions in summer [29], cold weather conditions in winter [30], oceanic climate in winter [31] and temperate climate in winter [32]. However, to the best of authors' knowledge, there is no study in temperate climate zones considering both winter and summer seasons on determining the relationship between thermal comfort and HBexC rate.

This study aims to provide information on the relationship between HBexC rate and thermal comfort in temperate climate zones and investigates thermal sensation of an occupant in an office building exposed to different combinations of T_i and MRT_i.

2. Thermodynamic relations for human body system

The processes related to human thermal comfort are heat and mass transfer and/or conversion processes which depend on the human thermoregulatory system and the state of the environment. Heat is transferred from the human body via exhaled air, water diffusion and sweat evaporation which cause evaporative mass transfer. Heat is also transferred by blood flow through the skin, then the blood returns to the body core. Thus, exergy is transferred to the environment and controlled by the environmental conditions via heat and mass exchanges [22].

Fig. 4. Inside of the case building.

Table 2
Overall heat transfer coefficients and thicknesses of the walls, floor, doors and windows of the case building.

Building elements	Thickness (m)	U value (W/m^{2}K)
External walls	0.25	0.84
Roof	0.36	2.93
Floor	0.19	2.07
Partition wall	0.25	0.84
Windows	–	1.92
Doors	–	1.9

Considering the human body shown in Fig. 1, general form of exergy balance is given in Eq. (1) [15,19,33]:

$$X_{in} - X_{out} - X_{cons} = X_{st} \tag{1}$$

The terms in Eq. (1) and their explanations are described in Table 1 for human body system as shown in Fig. 1. Under steady-state conditions, exergy balance of the human body is calculated for given environmental conditions assuming that heat storage is negligible [22]. Using terms given in Table 1, Eq. (1) is converted into Eq. (2) and HBexC (X_{cons}) rate can be calculated using this equation.

$$X_{cons} = X_{in,met} + X_{in,inh} + X_{in,w,cr} + X_{in,w,sh} + X_{in,abs} - X_{out,exh} - X_{out,sw} - X_{out,dis} - X_{out,c} \tag{2}$$

Further details and correlations of each term of Eq. (2) can be found in [19,24].

3. The case building

The case building is located in Izmir Institute of Technology campus Izmir/Turkey at latitude 38.3°N and longitude 26.6°E (Fig. 2) which has a typical temperate climate. Based on the data between 1938 and 2018, the yearly average temperature is encountered as 17.9 °C, with 8.7 °C in January and 28 °C in July [34].

The case building consists of an office room which have a total dimension of 6 m (width) × 6 m (depth) × 2.8 m (height), six windows and four external walls. The outside view of the case building is shown in Fig. 3.

The indoor environment of the case building is controlled by an air-conditioner operated with a conventional Proportional-Integral-Derivative (PID) controller which is set at 22 °C for both summer and winter seasons from 09.00 a.m to 12:30 p.m and 13:30 p.m to 17:00 p.m during weekdays (Fig. 4).

Overall heat transfer coefficients of building elements are given in Table 2. The airtightness of the envelope is assumed as 0.5 ACH (air change per hour) which is a moderate rate for naturally ventilated buildings [35].

The case building is occupied by one male occupant during office hours on weekdays. The personal parameters of the occupant are given in Table 3. The air-conditioner is on during the office hours and the case building is ventilated naturally twice a day for 15 min at 09:00–09:15 and 13:30–13:45. A personal computer (70 W) exists in the office and two fluorescent lamps (50 W each) are used for lighting.

4. Materials and methods

An experimental study was designed to show the relation between thermal comfort and HBexC rate in a small office building in Izmir Institute of Technology campus, Izmir/Turkey which is located in temperate climate zone.

Flow diagram of the methodology is presented in Fig. 5.

First, objective (T_i, T_o, v_a, RH_i, RH_o, OT_i,) measurements and thermal sensation votes (surveys via mobile application) were conducted in the case building from July 3rd, 2017 to November 1st, 2018 covering winter and summer seasons. In the literature, the HBexC rate is characterised by MRT_i and T_i variations [24-26]. The MRT_i is the most affecting factor on thermal comfort since it summarizes the effects of all radiant heat fluxes reaching the body [21]. The most accurate way to determine a parameter is to measure it. In the study, MRT_i is not measured but calculated because of the complicated measurement methods [36-37]. The calculation is carried out by Eq. (3) which is modified from ASHRAE Standard 55 [6] using measured T_i and OT_i data [6].

$$MRT_i = \frac{OT_i - CxT_i}{(1 - C)} \tag{3}$$

where C is the weighting factor for various v_a;

If $v_a < 0.2$ m/s then $C = 0.5$, If 0.2 m/s $< v_a < 0.6$ m/s then $C = 0.6$ and if 0.6 m/s $< v_a$ then $C = 0.7$ [6].

Then, objective measurements and personal parameters were used as input data for human-body exergy balance contour calculation tool developed by Asada [38], and skin and clothing surface temperatures, input–output exergy fluxes from the human body and HBexC rates were calculated. The tool uses the human body exergy balance principle presented by Shukuya et al. [19]. Finally, the HBexC rates as a function of T_i and MRT_i were plotted as a

Table 3
Personal and physiological parameters used in the study.

Personal parameters		Unit	
	Gender		Male
	Body mass	(kg)	82
	Skin surface	(m^2)	2.09
	Activity level	(met)	1
	Clothing insulation	(clo)	0.54 for summer, 0.79 for winter
Physiological parameters			
	Average skin temperature	(°C)	33.6
	Average clothing temperature	(°C)	29.6

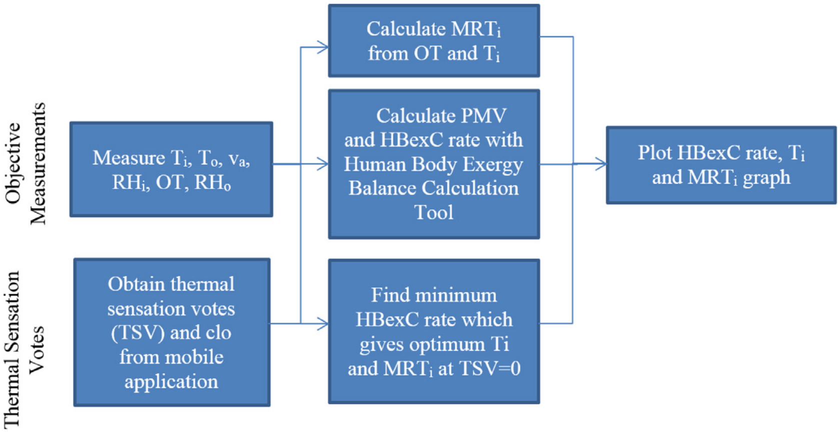

Fig. 5. Flow chart of the methodology.

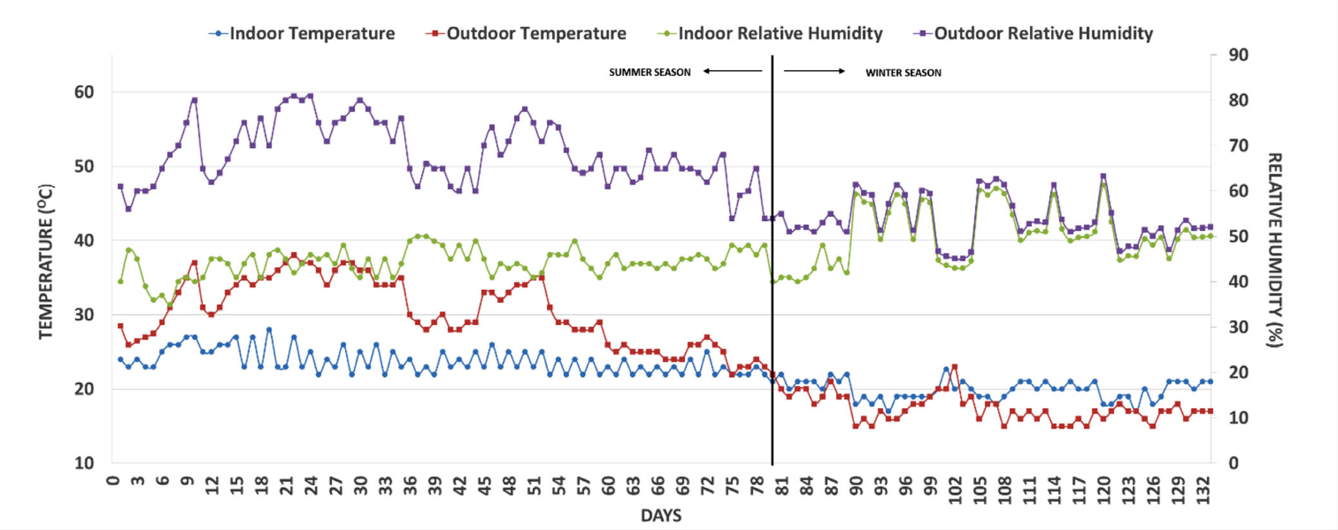

Fig. 6. Distribution of indoor and outdoor T and RH data for winter and summer seasons.

Table 4
The range of parameters used in the calculation.

Parameter	Symbol	Unit	Range
Outdoor temperature	T_o	(°C)	15–38
Outdoor relative humidity	RH_o	(%)	45–81
Indoor temperature	T_i	(°C)	17–28
Indoor relative humidity	RH_i	(%)	35–61
Operative temperature	OT_i	(°C)	15–31
Mean radiant temperature	MRT_i	(°C)	16–34
Air velocity	v_a	(m/s)	<0.2

graph. PMV values were also calculated by the human-body exergy balance contour calculation tool in order to compare the results with TSV values.

The operative temperatures (OT_i) were measured by a thermal comfort sensor (INNOVA 1221) [39]. The air temperature module (Innova, MM0034), air velocity module (Innova, MM0038) and air humidity module (Innova, MM0037) are used to measure T_i, v_a and RH_i (in term of vapour partial pressure). The OT module (Innova, MM0060) (which has an ellipsoid shape of 160 mm long and 54 mm in diameter) is also used to measure the OT_i (temperature of an imaginary environment that transfers dry heat at the same rate as the actual environment) of the case building. The OT transducer is installed in the inclining position making 30° to the

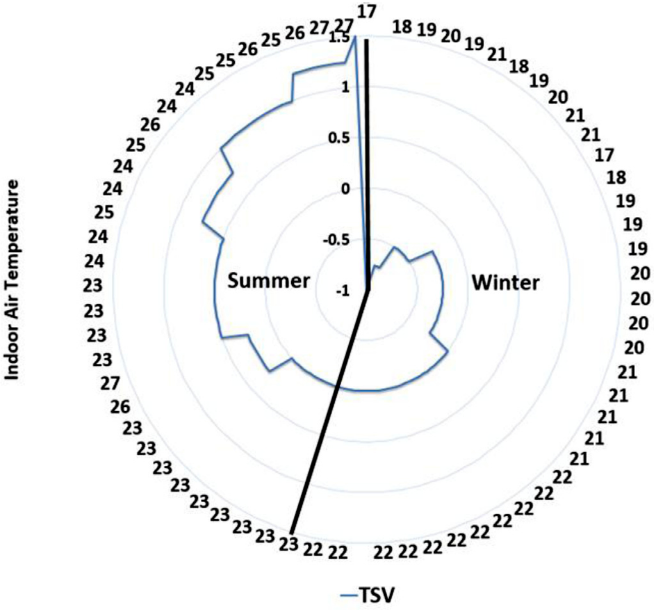

Fig. 7. Variation of TSV with T_i for winter and summer seasons.

Table 5
The values of measured and calculated parameters which give minumum HBexC rate in summer and winter.

Parameters	Unit	Value	
		Summer season	Winter season
T_i	(C)	21.8	22.7
MRT_i	(C)	23.2	24.1
HBexC rate	(W/m^2)	2.41	2.68
PMV	(–)	0.15	0.08
TSV	(–)	0	0

vertical direction to simulate a person in the sitting position. The metabolic rate of the person is chosen to be 1 met ($M = 58\,W/m^2$) corresponding to normal work when sitting in an office [6]. In order to prevent air velocity disturbances on the occupant, the fan of the air-conditioner is fixed to blow straight up during the experiments.

A mobile application has been developed for Android-based smartphones to obtain TSV values and garments of the occupant according to ISO 10551 [40] and the values were stored in a web server. The clothing insulation (clo) was calculated via the mobile application to be 0.54 and 0.79 clo for summer and winter seasons, respectively. The online surveys were conducted twice a day at 10:45 and 15:15. Table 4 shows the input parameters and their values for the HBexC rate calculations. The T_i and MRT_i was plotted in the range of 15–28 °C even though the measurement ranges were wider since outside of this range is considered to be “very uncomfortable” and creates temperature differences between clothing, skin and core which results in higher HBexC rates [21,26,41].

5. Results and discussion

As indicated in Section 4; objective parameters (T_i, T_o, RH_i, RH_o, OT_i, v_a) were measured and stored between July 3rd, 2017 and November 1st, 2018, including winter and summer seasons. It is worth to note that measurements were taken during working hours on weekdays only in the course of the measurement period.

Fig. 6 depicts daily averages of measured indoor and outdoor T and RH data. The T_o values vary between 22 and 38 °C, and 15 and 23 °C for summer and winter seasons, respectively. In addition, RH_o is between 54–81% in summer while 45–63% in winter. However, the ranges of T_i and RH_i change between 22–28 °C and 35–50% and 17–23 °C and 40–61% for summer and winter seasons, respectively. The figure shows that the difference between indoor and outdoor environmental parameters in winter season are lower than summer. The variation of RH_i values are higher within a narrow range at T_i values.

The TSV data are collected by a mobile application asking the occupant to rate his thermal sensation on the ASHRAE seven point scale. Fig. 7 depicts the variation of TSV with T_i. The TSV values are generally zero at a T_i range of 21–23 °C while a seasonal range is encountered as (-)1–0 for winter and 0–1.5 for summer.

The measured data and, personal and physiological parameters given in Table 3 were used as input data for human-body exergy balance contour calculation tool [38]. The values of measured and calculated parameters that give minimum HBexC rate for summer and winter seasons are presented in Table 5. The minumum HBexC rates were calculated as 2.41 W/m^2 and 2.68 W/m^2 in summer and winter seasons, respectively. Additionally, the minimum HBexC rate was obtained at $T_i = 21.8$ °C in summer and $T_i = 22.7$ °C in winter (Fig. 7). The PMV values were on slightly warm side and calculated as 0.15 for summer and 0.08 for winter season while TSV = 0. It means that for this case, the HBexC rate calculation would have given a better prediction of the environmental parameters providing the best thermal comfort. The reason for slightly positive PMV values at minumum HBexC rate could be the choice of input values such as natural ventilation schedule and clo values, and sample size (only one male occupant).

Fig. 8 gives calculated MRT_i, PMV and HBexC rates along with measured indoor and outdoor T and RH data. The figure exhibits that TSV values are generally lower than PMV values in summer season while the opposite is observed in winter. Moreover, MRT_i is highly affected from T_i and T_o values, however, it also depends on the metarial proporties of the case building. The MRT_i values are calculated based on Eq. (3) which includes a constant

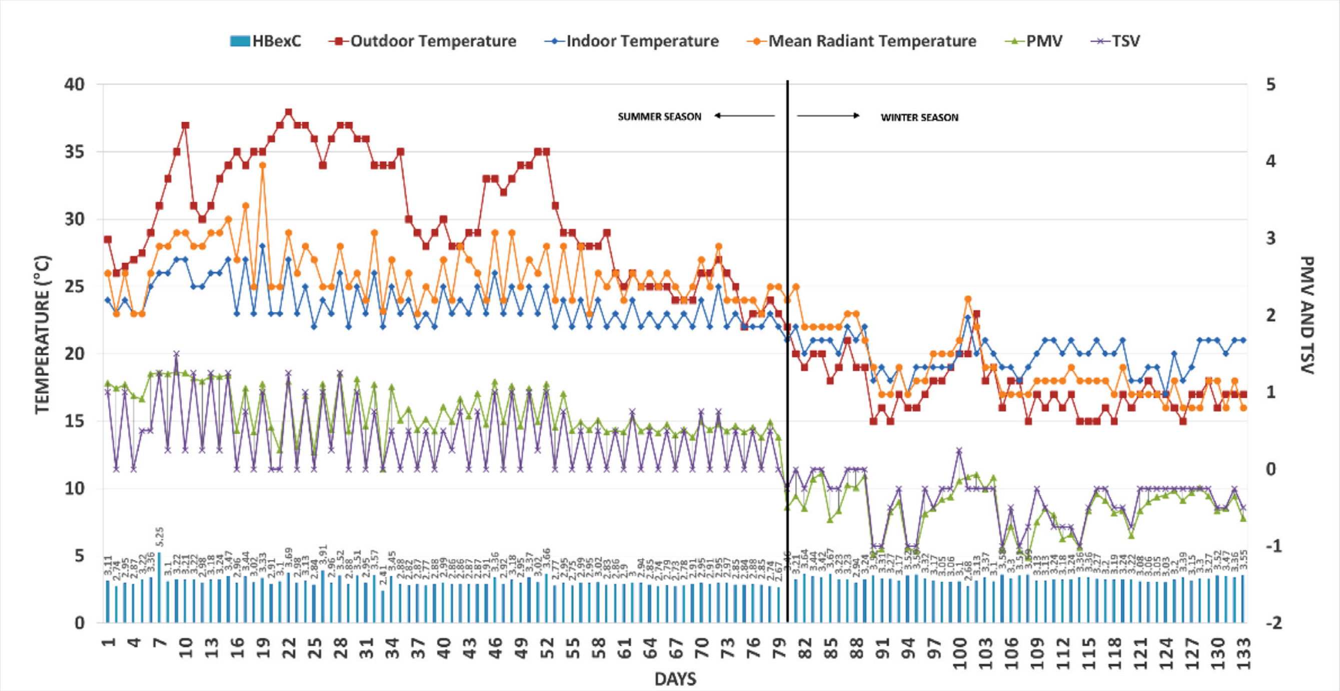

Fig. 8. Measured environmental and thermal comfort parameters and calculated HBexC rates for summer and winter seasons.

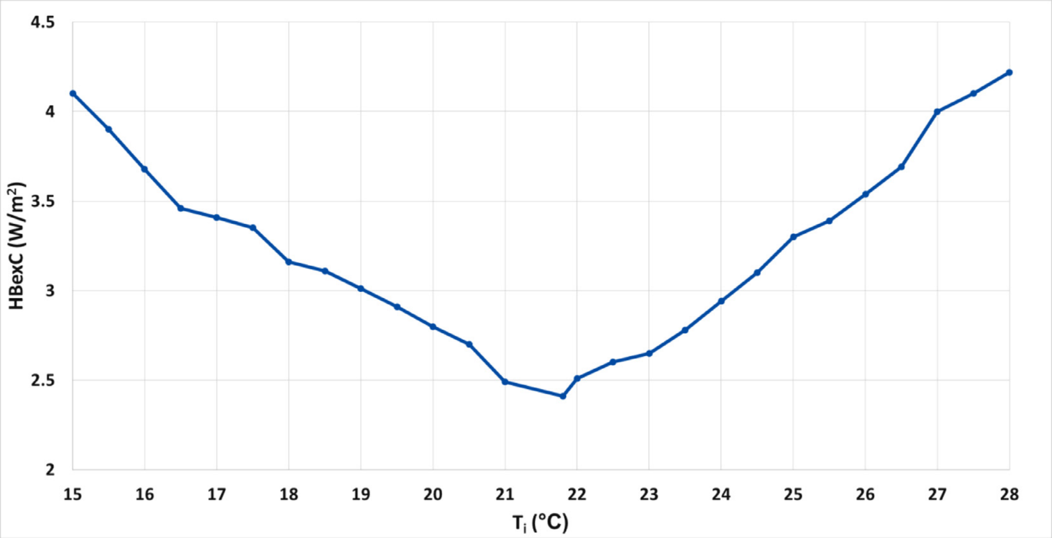

Fig. 9. HBexC rate change with T_i (summer season, $MRT_i = 23.2$ °C).

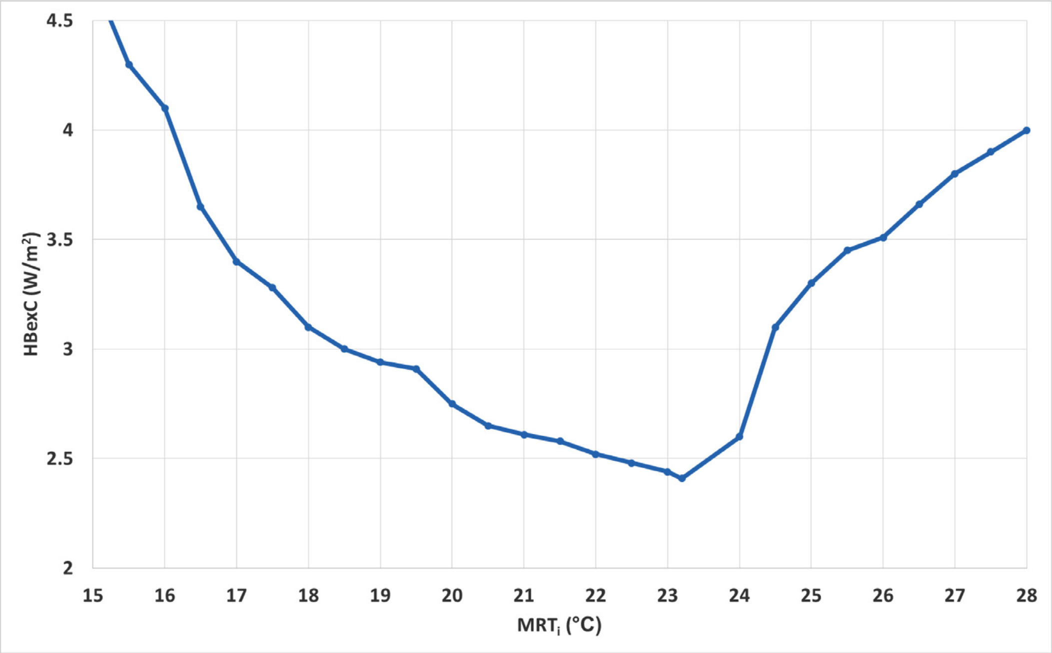

Fig. 10. HBexC rate change with MRT_i (summer season, $T_i = 21.8$ °C).

weighting factor (C) as a function of v_a. In the study, since v_a is kept below 0.2 m/s, C factor is chosen as 0.5. If higher v_a values are encountered, HBexC rates could be higher. Furthermore, calculation of MRT_i from easily measurable parameters like T_i and OT_i, could bring some significant measurement error to the calculation depending on the accuracy of the sensors.

Fig. 9 and 10 exhibit the change in HBexC rate with T_i (at constant $MRT_i = 23.2$ °C) and MRT_i (at constant $T_i = 21.8$ °C) (for summer season), respectively. Constant values of T_i and MRT_i that give minimum HBexC rate for summer season, are taken from Table 5. When T_i and MRT_i increases, HBexC rate decreases until T_i (21.8 °C) and MRT_i (23.2 °C) reach the point where the occupant's TSV reaches thermal neutrality. Then, HBexC rate shows an increasing trend which is in a good agreement with the literature [15,21,23,42]. Similarly, HBexC rate shows a decreasing trend until the MRT_i (23.2 °C) reaches the point where TSV equals to zero.

Exergy input, output and consumption is calculated by Eqs. (1-2) for various environmental conditions. Fig. 11 demonstrates an example for environmental conditions of $T_i = 21.8$ °C, $T_o = 23.1$ °C and $RH_i = 55\%$ which gives the minimum HBexC rate on 12th of June 2018. For an exergy input of 100%, exergy consumed which represents HBexC rate, constitutes 60% while outgoing exergy (convection+exhaled&sweat+warm radiation) has a share of 40%. For comparison, the same analysis were conducted with $T_i = 22.7$ °C, $T_o = 17.6$ °C and RH_i=50% which gives the minumum HBexC rate on 21th of February 2018 for winter season (Fig. 12). The figure indicates that the increase in heat transfer from skin to ambient temperature by radiation and convection in winter season reduces the consumed exergy share.

The HBexC rate with the combination of T_i and MRT_i of an occupant in the case building is plotted in the Matlab [43] environment and shown in Figs. 13 and 14 for summer and winter seasons, respectively. Fine lines with numbers depict HBexC rate

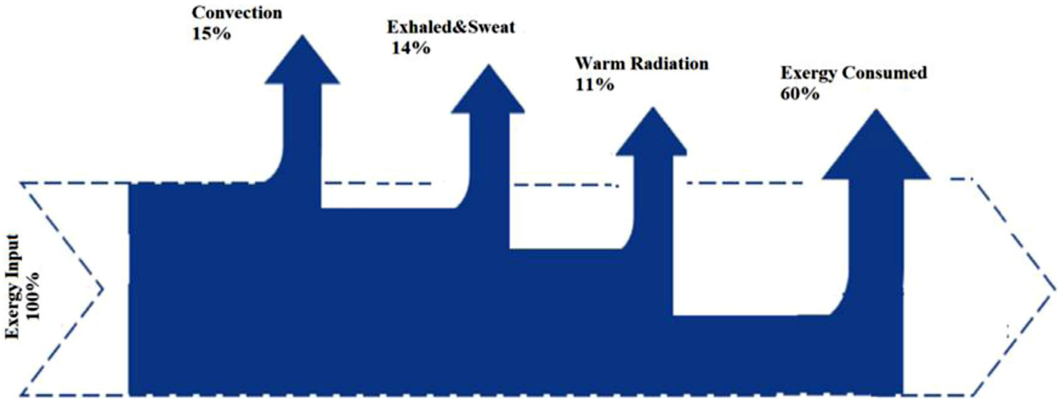

Fig. 11. Exergy balance on 12th of June 2018 (T_i = 21.8 °C, T_o = 23.1 °C, RH_i = 55%, TSV = 0) (summer season).

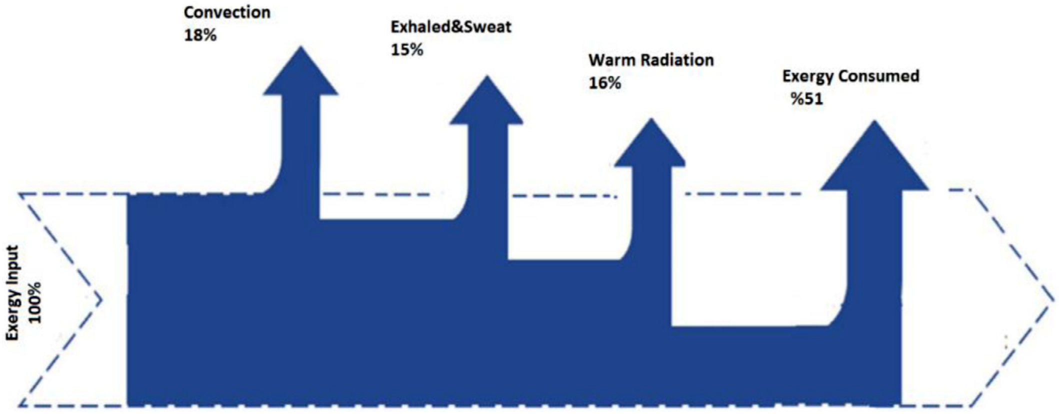

Fig. 12. Exergy balance on 21st of February 2018 (T_i = 22.7 °C, T_o = 17.6 °C, RH_i = 50%, TSV = 0) (winter season).

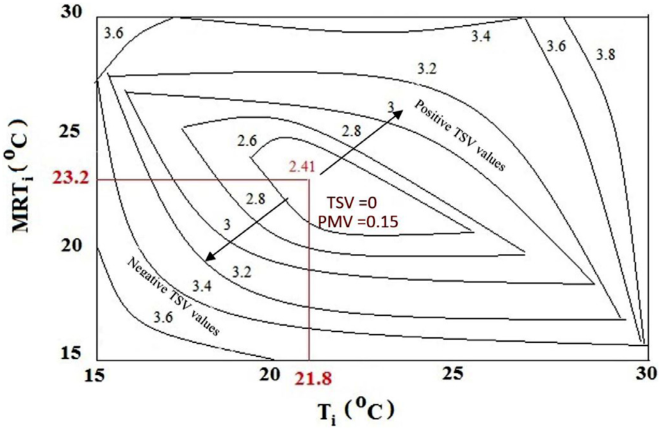

Fig. 13. HBexC rate of an occupant in the case building (summer season). (For interpretation of the references to color in text, the reader is referred to the web version of this article.)

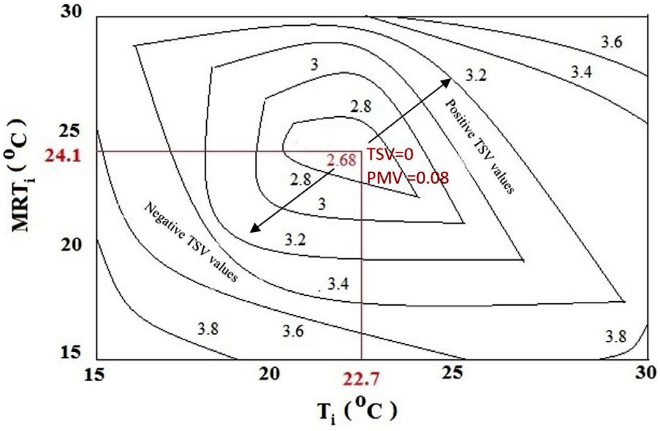

Fig. 14. HBexC rate of an occupant in the case building (winter season). (For interpretation of the references to color in text, the reader is referred to the web version of this article.)

whilst the neutral TSV value is shown with red with respect to T_i and MRT_i on the graph. Fig. 13 illustrates the HBexC rate with respect to T_i and MRT_i for summer season. The HBexC rate of an occupant in the case building for cooling season were plotted by using constant values of v_a = 0.1 m/s, RH = 55%, met = 1 and clo = 0.54. The slope of the curves depicts the interaction of T_i and MRT_i on HBexC rate. Similar to the studies in [19,21], there is a trend for HBexC rate to be minimum when MRT_i is higher than T_i. Negative value-range of TSV is towards the lower left corner from zero TSV value on Figs. 13 and 14 when T_i and MRT_i are lowered and the occupant feels the environment cooler. Similarly, when T_i and MRT_i are increased, TSV values are positive which indicate that the occupant feels warmer. In addition, Fig. 14 shows that the difference between T_i and MRT_i is low since v_a is kept below 0.2 m/s during the experiments. It means that the impact of T_i is greater than MRT_i on HBexC rate.

The change of HBexC rate in winter season with the combination of T_i and MRT_i is shown in Fig. 14. Environmental conditions and personal parameters are kept constant in order to plot HBexC rate with respect to T_i and MRT_i (v_a = 0.1 m/s, RH_i = 50%, met = 1,

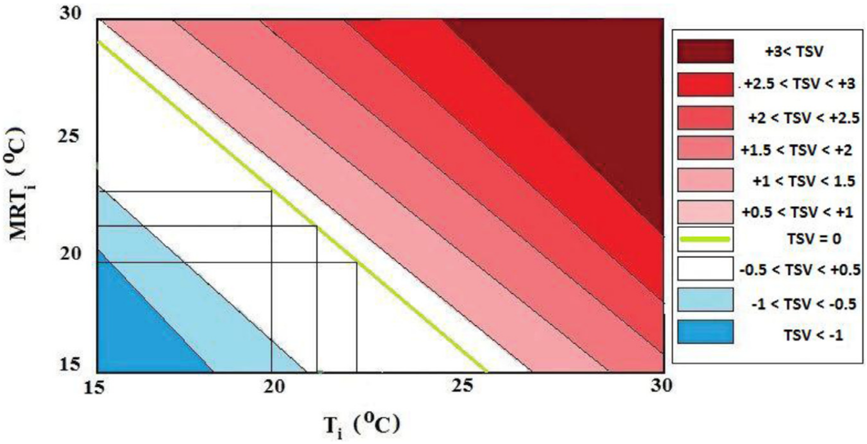

Fig. 15. The change of TSV with respect to T$_i$ and MRT$_i$ by using energetic thermal comfort approach. (For interpretation of the references to color in text, the reader is referred to the web version of this article.)

clo = 0.79). The minumum HBexC rate was found as 2.68 W/m^2 with a combination of T$_i$ = 22.7 °C and MRT$_i$=24.1 °C.

It can be concluded from Figs. 13 and 14 that the HBexC rate is higher in winter season than summer in temperate climate zones similar to the previous studies conducted in other climate zones [25,26].

For both winter and summer seasons, the results showed that the lowest HBexC rates were obtained when the difference between T$_i$ and MRT$_i$ is 1.4 °C. However, this temporal difference was found above 1.5 °C for v_a < 0.2 m/s in the literature for other climate zones, i.e. 7.5 °C for cold temperate climate zone [27], 7.8 °C for oceanic climate [31] and 1.6 °C for humid subtropical climate [21]. The difference between T$_i$ and MRT$_i$ creates heat stress which affects thermal comfort of the occupant [44]. Therefore, this distinctness should be carefully taken into account in order to achive better thermal comfort.

To compare the energetic and exergetic approach of thermal comfort, iso-TSV maps with respect to T$_i$ and MRT$_i$, are created. Fig. 15 does not show the distribution of TSV values, but the combinations of T$_i$ and MRT$_i$ which gives TSV = 0 for energetic approach. The readers can easily find which T$_i$ and MRT$_i$ values give TSV = 0 value by drawing vertical and horizontal lines with intersection of iso-TSV lines. The green line shows the combinations of the T$_i$ and MRT$_i$ where occupant gives neutral vote for thermal comfort. Comparing both approaches show that while the lowest HBexC rate is reached at one combination of T$_i$ and MRT$_i$ that give thermal neutrality in exergetic approach (Figs. 13 and 14), there are many combinations of TSV = 0, T$_i$ and MRT$_i$ values in energetic approach (Fig. 15). This result shows that the exergetic analysis based on the 2nd Law of Thermodynamics provides more useful information regarding human physiological behaviour and responses than other analyses. Such an extension better determines the connection between environmental conditions and predicted thermal sensation [45].

6. Conclusions

The aim of this paper is to find a relation between HBexC rate and thermal comfort for a temperate climate zone. A small office building in Izmir Institute of Technology campus, Izmir/Turkey, is chosen as a case building and equipped with measurement devices to assess the thermal comfort of one male occupant with respect to PMV and TSV. The objective measurements including T$_i$, T$_o$, RH$_i$, RH$_o$, and v_a are used to calculate PMV values, and HBexC rates which are calculated by using Human Body Exergy Balance Contour Calculation Tool. A mobile application which includes the seven-point scale of ASHRAE 55 Standard is used to obtain TSV and clo values of the occupant. The results indicate that there is a correlation between HBexC rate and TSV given by the occupant. Furthermore, exergetic approach gives better prediction of the comfort conditions than energetic approach (PMV) since TSV = 0 point coincides with the minumum HBexC rate. Only one combination of environmental parameters ensures the minimum HBexC rate under conditions in which PMV is predicted to be slightly warm in both summer and winter.

It has been seen that each approach has its potentials and limits. However, it is worth to note that individual differences and experimental conditions have significant influence on HBexC rate. This study was conducted in an office building with only one male occupant by taking average clo and constant met values for each season. In fact, the individual state of mind that expresses satisfaction with the thermal environment is too diverse for that when small groups are considered. Therefore, larger data sets and larger group of occupants are required in order to confirm the applicability of the findings in this study. Additionally, a further study would be interesting to show if use of the actual clo values would have made a difference on HBexC rate or PMV.

Giving the significance of MRT$_i$ on thermal comfort, it is recommended to measure MRT$_i$ rather than to calculate. This way, cumulative measurement errors could possibly occur for each measured parameters used in calculation, could be prevented.

By using the outcomes of this study, HVAC systems could be designed to provide the best thermal conditions for the occupants at the lowest HBexC rate with a combination of T$_i$ and MRT$_i$. The set temperatures could be defined based on exergy analysis to obtain thermal neutrality in the heated/cooled spaces.

Declaration of Competing Interest

None.

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