Academic Article

Modification of physiologically equivalent temperature

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ABSTRACT

Thermal indices have been applied in the field of human-biometeorology since several decades (e.g. for environmental evaluations, climate assessment for tourists, as well as assessments of climate change). Physiologically Equivalent Temperature (PET), which is based on a time-saving and two-node model, is a widely applied thermal index. However, variations in air humidity and clothing insulation show weak influence on PET. Other thermal indices also show limitations in their applicability. Thus, this study aims to develop a modified PET (mPET) on thermo-physiological mechanisms and clothing factors for universal applications in all climate zones.

Physiological thermoregulation of mPET is adapted to a simple multi-segment body model including a blood pool element and a bio-heat transfer principle instead of the two-node human body model used in PET. Furthermore, a multi-layer clothing model with clothing insulation and vapour resistance is established for mPET. It replaces the single-layer clothing model applied in PET. Due to those two modifications, mPET can evaluate thermal conditions influenced by vapour pressure and clothing insulation.

Key Words : Physiologically Equivalent Temperature, Modified Physiologically Equivalent Temperature, Thermal index

1. Introduction

Thermal indices are essential evaluating factors in the field of human-biometeorology, especially for assessments of the thermal conditions intermediating human and environments. Recently, Physiologically Equivalent Temperature (PET) (1) (2) which is a thermal index based on a 2-node thermoregulation model is the widest applied to evaluate thermal conditions. Previous studies investigated tourist climate (3), urban climate (4) and climate changing according to the PET and the other parameters. However, PET predicts weak influence of the variance of clothing and humidity on the assessments of thermal conditions. Moreover, the Universal Thermal Comfort Index (UTCI) (5) (6) (7) is recently a further developed thermal index in purpose of a universal application in climatic zones. The UTCI is actually an operative regression function based on a complicated 343-nodes multi-segments thermoregulation model, which is Fiala's thermoregulation model, and more than 1000 simulations cases. The limitations of this regression function are that the air temperature is from -50 °C to 50 °C, the wind speed is from 0.5 m/s to 17 m/s at the height of 10 m, the mean radiant temperature is 50 °C below than the air temperature to 70 °C above than the air temperature, and relative humidity is from 0 % to 100 % or 0 hPa to 45 hPa. This limitation leads to restricted applications of the UTCI on the evaluation of some extreme thermal conditions. PET and UTCI have been both restricted on the evaluation of the influence on the some changing of biometeorological factors and also lack of the influence of clothing behavior. Therefore, this study aims to carry out a thermal index based on modifications of PET for universal applications in all climate zones and also to reflect the influence of clothing behavior.

2. YCC-thermoregulation model

In order to improve the simulation of PET on thermoregulation, humidity physic and clothing factors, a modified multi-segments thermoregulation model combining multi-layers clothing model is applied to replace these mechanisms in Munich Energy-balance Model for Individuals model (MEMI) [(1) (2)]. This validating model has been named YCC-thermoregulation model. Fig. 1 shows the principle of YCC-thermoregulation model. The core of this evaluation is a 16- to 26- nodes passive body model based on Pennes' bio-heat equation [(8)] applied in Fialas model and convective and radiant principles in MEMI model. For application of this model, these boundary conditions which are core temperature of body, operative temperature, and inner clothing temperature are necessary to be given initially. To identify inner clothing temperature, initial skin temperature and operative temperature are indeed required. The operative temperature is consisted of convective and radiant heat exchanging terms. Therefore, the influence of vapor pressure and sweating evaporation are excluding in dry process and are proposed to additionally be considered. After given all those boundary conditions into the modified passive body model, the body temperature profile at next time step is able to be simulated. The calculation is processed until achieving at energy equilibrium, the heat transfers, mean skin temperature, and mean outer clothing temperature are given into energy balance equation to compare the basically standard thermal conditions indoor and evaluate a physiologically equivalent temperature. The differences between mPET and PET result from skin temperature, clothing temperature, and evaporative heat transfer. Mean skin temperature and mean clothing temperatures lead to modify sensible heat transfer in model of mPET. Changing of evaporative heat transfer adjusts sensibility of PET to variable of humidity.

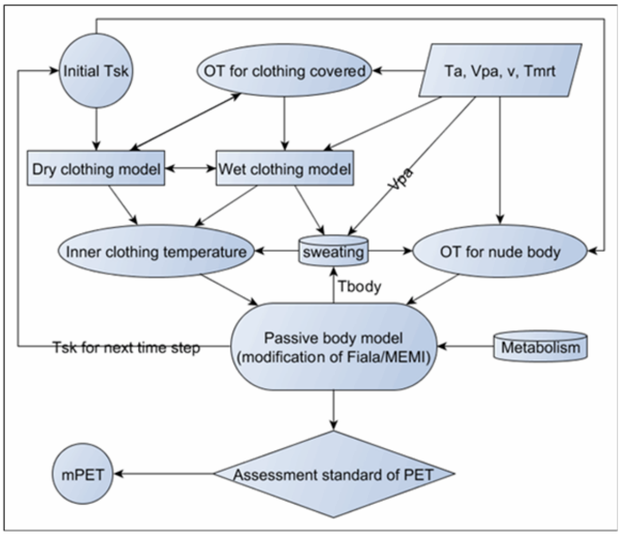

Fig. 1 The calculating principle and flow chart of YCC-thermoregulation model

2.1 Body thermoregulation model

For assessment of an inhomogeneous skin temperature profile due to multi-layer clothing over body, a multiple-nodes thermoregulation is necessary. For this purpose, pennes' bio-heat equation [(8)] is suggested to be applied to conduct the heat exchanging fluxes for each segment in human body. The equation is given by the following:

$$k\left(\frac{\partial^2 T}{\partial r^2}+\frac{\omega}{r}\frac{\partial T}{\partial r}\right)+q_m+\rho_{bl}w_{bl}c_{bl}\left(T_{bl,a}-T\right)=\rho c\frac{\partial T}{\partial t} \qquad \text{(Eq. 1)}$$

k is conductive coefficient of tissue.

T is temperature of tissue.

r is radius of tissue.

ω is geometric coefficient of tissue. If tissue form is cylinder, ω is equal to 1. If tissue form is sphere, ω is equal to 2.

q_m is metabolic rate of tissue.

ρ_{bl} is blood density.

w_{bl} is perfusion rate of blood.

c_{bl} is heat capacity of blood.

$T_{bl,a}$ is temperature of arterial blood.

ρ is tissue density.

t is time step.

Despite of the human bio heat-transfer equation, a human body model is necessary to be conducted for the parameterization of the description of human body on physiological heat transfer from inside body over body surfaces and clothing to the environments. A simple two cylinders model with variable multiple nodes based on clothing layers is applied hereby to represent a human body. The two cylinders body model is including a small cylinder occupying 8 % of total body surface to present head and a small cylinder occupying 92 % of total body surface to present trunk and external segments of body. Moreover, this body model is covered by a variable multiple-layers clothing model which is shown in table 1. Beside of two cylinders body model, each cylinder has not only shell and core segments but core, fat, and skin segments. Body Mass Index (BMI) is applied in this model to provide the percentage of fat segment and determines also the percentage of skin and core segments. Integrating the above principles of the body model and human bio-heat equation, a body temperature profile is able to be simulated under the influence of environmental thermal conditions.

Table 1 Surface partials of the different clothing layer covered and uncovered segment

Clo	1 layer area	2 layer area	3 layer area	Cap area	Nude area
0.3 – 0.6	62%	-	-	-	38%
0.6 – 0.9	36%	45%	-	-	19%
0.9 – 1.2	42%	45%	-	-	13%
1.2 – 1.6	30%	22%	35%	-	13%
1.6 - 2.0	26%	22%	45%	-	7%
2.0 – 2.5	12%	25%	55%	5%	3%

2.2 Clothing model

A simple multiple layer clothing model is applied in YCC-thermoregulation model. This clothing was suggested by Wissler and Havenith in 2009 [9] and a two-layer reference garment is able to be illustrated as Fig. 2. This figure shows the placement with six nodes for the two-layer reference garment. By this clothing model, two boundaries are respectively skin node and ambient air node. While the skin temperature and air temperature are known, the total sensible heat transfer over multiple garments is able to be represented as the Eq. 2.

$$Q_{c,1} = \frac{T_1 - T_6}{\hat{R}_{c,5}} \quad \text{(Eq. 2)}$$

Correspond to the Fig. 2, T_1 is the skin temperature and T_6 is the air temperature. $\hat{R}_{c,5}$ represents the total clothing insulation from node 1 to node 6. Practically, air temperature is replaced by operative temperature. Hence, dry heat transfer principle of this clothing model can dominate also radiant heat transfer over clothing. Moreover, the latent heat transfers over multiple layers clothing can be given as the Eq. 3.

$$Q_{e,1} = \frac{P_1 - P_6}{\hat{R}_{e,5}} \quad \text{(Eq. 3)}$$

Correspond to the Fig. 2, P_1 is the skin vapor pressure and P_6 is the air vapor pressure. $\hat{R}_{e,5}$ represents the total clothing vapor resistance from node 1 to node 6. In summary, the total heat transfers from skin over clothing to the environments can be given as the following equation.

$$Q_{sk} = \frac{T_1 - T_{ic}}{\hat{R}_{c,ic-1}} + \frac{P_{v,1} - P_{v,ic}}{\hat{R}_{e,ic-1}} \quad \text{(Eq. 4)}$$

Additionally, the occurrence of the vapor condensation is able to be considered according to this simple clothing model with multiple garments. The changing of latent and sensible heat transfers due to the occurrence of the vapor condensation can be also indentified by this clothing model. [9]

Therefore, based on this simple clothing model, one clothing model with variable layers from single layer to triple layer is applied in YCC-thermoregulation model. The variable covered partial of clothing surface for each layer is shown in table 1.

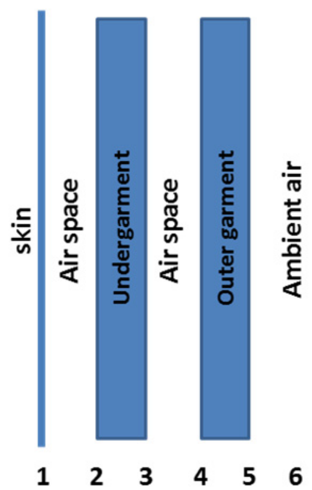

Fig.2 Placement of six nodes for the two-layer reference garment (source: Wissler and Havenith, 2009)

2.3 Vapor evaporation principle

In MEMI model, sweating evaporation and skin diffusion are individually calculated and the relationship between these two terms refers to the skin wettedness. In YCC-thermoregulation model, the relationship between these two terms refers simply to Eq. 5. The total latent heat transfers over body surface can be regarded as sweating evaporation and skin diffusion and is able to be given by the Eq. 5.

$$Q_e = \frac{(P_{sk} - P_{air})}{R_{e,cl}} = evap \times \frac{dm_{sw}}{A_{sk} \cdot dt} + \frac{P_{sk,sat} - P_{sk}}{R_{e,sk}} \quad \text{(Eq. 5)}$$

In the left term of this equation, the total latent heat transfers over body surface are definitely evaluated by the actual skin vapor pressure, air vapor pressure and water vapor resistance of the clothing or skin vapor resistance. The left term represents the actual latent heat transfer limited by water vapor resistance of the clothing or skin vapor resistance. In the right terms of this equation, there are the sweating evaporation and skin diffusion. Hereby, the skin diffusion is represented as the difference between statured skin vapor pressure and actual skin vapor pressure dividing the skin vapor resistance. The only unknown term in Eq. 5 is P_{sk} and can be solved by Eq. 5 without an assumed actual skin vapor pressure. However, MEMI model assumed that the skin vapor pressure keeps at the statured situation and evaporates at the uncovered segments, if no sweating occurs. The statured skin vapor pressure is given by the following equation.

$$P_{sk,sat} = 100 \times exp\left(18.956 - \frac{4.030}{T_{sk,out} + 235}\right) \quad \text{(Eq. 6)}$$

Another right term of Eq. 5 describes the energy exchanging of sweating evaporation. The sweating rate is able to given by Eq. 7 in YCC-thermoregulation model.

$$\frac{dm_{sw}}{dt} = 6.92 \cdot 10^{-5} \cdot (T_{body} - 35.8) \cdot A_{sk} \quad \text{(Eq. 7)}$$

T_{body} is calculated by mean skin temperature T_{sk} and core temperature T_{core} given by

$$T_{body} = 0.2 \cdot T_{sk} + 0.8 \cdot T_{core} \quad \text{(Eq. 8)}$$

Using these above equations, the total latent heat transfers over clothing covered and uncovered segments of YCC-thermoregulation model can be considered.

3 Simulation results and Discussions

The most essential modifications of YCC-thermoregulation model are latent heat transfers, clothing insulation, and physiological principles. Therefore, to estimate the performances of mPET on the changing of biometeorological factors and clo is important. A simple way to investigate it is comparing mPET to the other thermal indices, such as PET and UTCI. Fig. 3 shows the comparison between PET, mPET and UTCI in different air temperature above -50 °C to 50 °C under variance of wind speed from 0.5 m/s to 17 m/s, relative humidity at 50 % and the mean radiant temperature equal to the air temperature. The x-axis represents the variable of air temperature and the y-axis represents the variable of air thermal indices. The bar plots in Fig. 3 mean the variance of thermal indices due to changing of the wind speed under different air temperature and the line in these bar plots represent median value. The mPET is different to the other two thermal indices according to the changing of the air temperature under cold thermal conditions due to the effect of the modified clothing model. The influence of the variance of the wind speed on mPET is smaller than UTCI but greater than PET. Fig. 4 shows the comparison between PET, mPET and UTCI in different air temperature above -50 °C to 50 °C under wind speed at 0.5 m/s, relative humidity at 50 % and the mean radiant temperature according to the simulation of global radiation from 0 W/m^2 to 800 W/m^2 at 1th July. The influence of the variance of the mean radiant temperature on mPET is smaller than PET but greater than UTCI. Fig. 5 shows the comparison between PET, mPET and UTCI in different air temperature above -50 °C to 50 °C under wind speed at 0.5 m/s, the variance of relative humidity from 0 % to 100 % and the mean radiant temperature equal to the air temperature. The influence of the variance of the relative humidity on mPET is smaller than UTCI but greater than PET. Fig. 6 shows the comparison between PET, mPET and UTCI in different air temperature above -50 °C to 50 °C under variance of wind speed from 0.5 m/s, relative humidity at 50 %, the mean radiant temperature equal to the air temperature and variance of clo from 0.3 to 2.4. The influence of the variance of the clo on mPET works very well, while changing of clo cannot vary the other two thermal indices.

For the assessment of the sensible heat transfer over human, the mPET performs weak variance due to the changing of the air temperature and the mean radiant temperature to compare to PET. Otherwise, the mPET refers to a strong variance due to the changing of the latent heat transfer over human to compare to PET. The simulating result of the mPET is more realistic performance corresponding to subjective experiences than PET. Furthermore, the changing of clothing insulation results more variance of mPET than PET especially under cold conditions. The mPET has solved the weak variance of the PET due to the changing of the relative humidity and the clothing insulation.

To compare to the UTCI, mPET performs a weak variance on the changing of humidity but realistic sensibility. Moreover, mPET has considered the influence of specific clothing insulation on human thermal sensation. At the same time, UTCI has ignored specific clothing behavior instead of a standard clothing behavior according to an empirical investigation based on the changing of the air temperature.

In summary, mPET has modified the weakness of PET on the performance of clothing and humidity and kept the well performance on air temperature, mean radiant temperature, and wind speed. The other index, UTCI, changes violently due to the variance of wind speed and slightly according to the variance of mean radiant temperature. Besides, there is almost no difference between PET and UTCI, if clo was given in 0.9 to calculate PET. This means the auto changing clothing model in UTCI doesn’t work.

4. Conclusion

A new thermal index, mPET, was delivered by this study and based on YCC-thermoregulation model which has applied physical factors of sensible heat transfers by MEMI model [(1) (2)], a simple multi-layer garment-model [(9)] and simplified human thermoregulation-model by Fiala [(6) (7)] to evaluate the thermal condition for human being. The mPET was evident to be regarded as a useful und realistic thermal index for universal applications.

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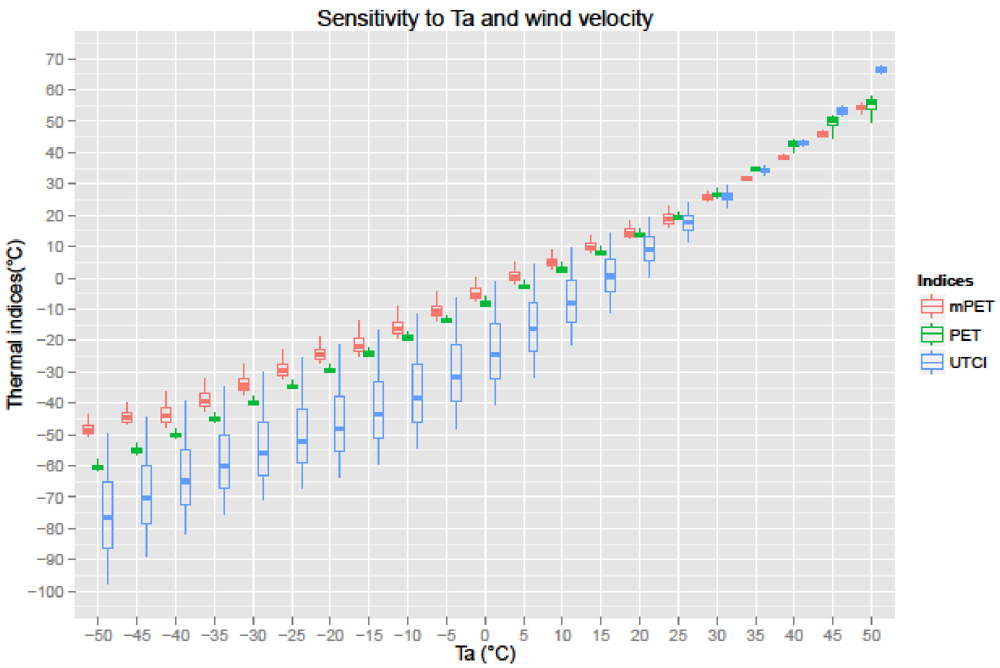

Fig. 3 The box plot graphic of PET, mPET, and UTCI, which were simulated with input variables of the air temperature from -50 °C to 50 °C, the wind speed from 0.5 m/s to 17 m/s, the mean radiant temperature equal to the air temperature, the relative humidity at 50 %, and clo auto changing for calculation of mPET. The variance of these box plots were caused by the changing of the wind speed.

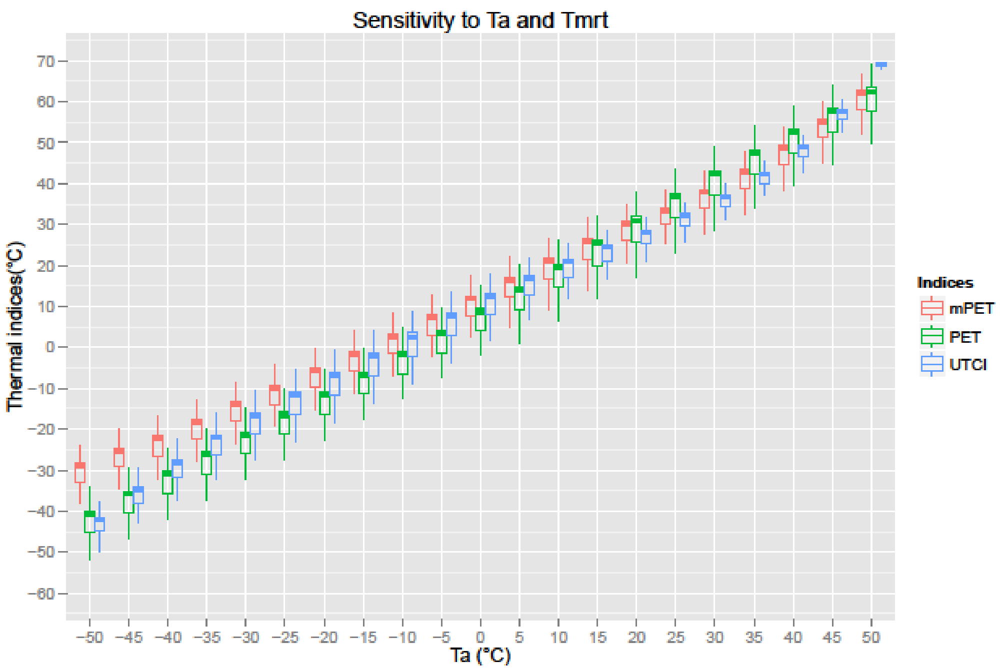

Fig. 4 The box plot graphic of PET, mPET, and UTCI, which were simulated with input variables of the air temperature from -50 °C to 50 °C, the wind speed at 0.5 m/s, the mean radiant temperature varied by global radiation from 0 w/m^2 to 1000 w/m^2 on 1th July, the relative humidity at 50 %, and clo auto changing for calculation of mPET. The variance of these box plots were caused by the changing of the mean radiant temperature.

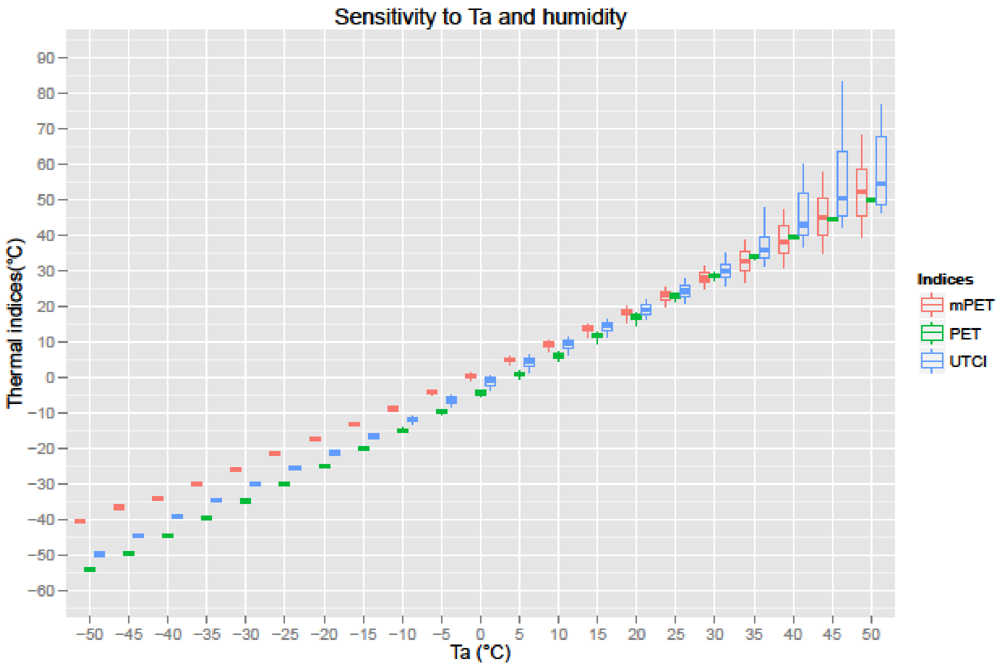

Fig. 5 The box plot graphic of PET, mPET, and UTCI, which were simulated with input variables of the air temperature from -50 °C to 50 °C, the wind speed from 0.5 m/s, the mean radiant temperature equal to the air temperature, the relative humidity from 10 % to 90 %, and clo auto changing for calculation of mPET. The variance of these box plots were caused by the changing of the relative humidity.

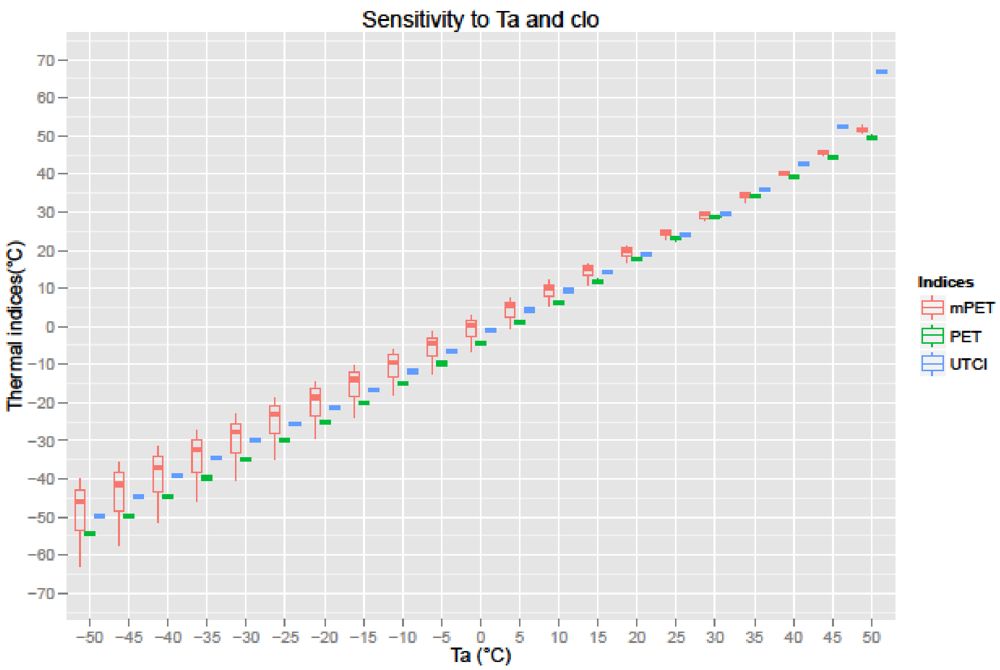

Fig. 6 The box plot graphic of PET, mPET, and UTCI, which were simulated with input variables of the air temperature from -50 °C to 50 °C, the wind speed from 0.5 m/s, the mean radiant temperature equal to the air temperature, the relative humidity at 50 %, and clo changing from 0.3 to 2.4. The variance of these box plots were caused by the changing of clo.