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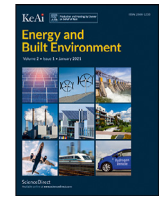

Thermal comfort models and their developments: A review

Qiantao Zhao, Zhiwei Lian*, Dayi Lai

Department of Architecture, School of Design, Shanghai Jiao Tong University, China

A R T I C L E I N F O

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A B S T R A C T

In the past several years, thermal comfort, especially development and application of thermal comfort model, has been a research focus of building environment. Since the 1970s, a series of thermal comfort models based on people's thermal sensation to environment have been established, and gradually became an important part of the field of thermal comfort research. In this review, the existing thermal comfort models are summarized from various perspectives, such as models applied in different environments like sleeping environment and outdoor environment. Besides, models used for different groups people, such as elderly and different races are discussed. In the part, adaptive models are mentioned. In additions, data-driven models were reviewed. This paper introduced the advantages and disadvantages of each model. Based on the above review, future research work of thermal comfort model is proposed.

1. Introduction

Thermal comfort has gradually become an independent research field, providing an important support to build a good environment [1]. In the process of research, scholars found that subjective initiative of people has a great impact on thermal comfort. Even because of different subjective purposes to use air conditioner, different thermal neutral range has been formed for the same environment. Human beings are homeotherms, therefore, in different environment, even in extreme cold or hot, people can maintain core temperature in a narrow scope through thermoregulation. The core temperature is kept at about 36.5 °C [2]. When the human body is in extreme thermal disorders, and the regulation of human body is out of balance, the core temperature will be much higher or lower than normal value. When the core temperature exceeds a certain limit in a long time (more than 1 hour and higher than 38.5°C or lower than 35°C), the human body will be damaged to a certain extent [3]. Therefore, the human body's thermal and cold reaction and its interaction with the environment has been the focus in many studies [4]. It is very important to establish thermal comfort model in case extreme thermal disorders. In addition, it is important to predict thermal comfort in a built environment, because, thermal comfort model has great potential for energy saving. If the comfort temperature in different environment can be predicted accurately, a reasonable set temperature can be determined. Human beings can be exposed to different environments with various thermal environment. Through thermal comfort model, comfortable environment can be predicted for different environment [5]. Therefore, human thermal comfort model is an important part of built environment research.

Thermal comfort model has developed quickly in recent decades. Models for different environments have been purposed and verified based on separate experimental dataset, but the models may have inaccuracies when applied outside the original climate scope [4,6,7]. As a result, not all models are recognized in international standards [8]. This paper seeks to review the existing thermal comfort models and present their advantages and disadvantages, so that the applicability of models can be shown. At present, the most cited thermal comfort standards: ASHRAE 55-2016 [9] and ISO 7730 [10] are based on the Fanger's model. This model is one of the most classical models, but it is not applicable to nonuniform environment, outdoor environment and sleep environment. For elderly, Fanger's model is not suitable because the data used to develop Fanger's model was from adults. In the current standard, all the problems have one or several unified solutions, so to give more solutions based on actual environments is one of the purposes in the paper. Data-driven thermal comfort model a new trend. It took advantage of data to enhance the prediction accuracy, and whether the new models would be brought into standard is of important consideration. In order to implement these goals, this paper reviews the development of thermal comfort models.

This paper is divided into four parts. In Section 2.1, the physiological basis of thermal comfort model and some classical thermal comfort models is introduced, including PMV-PPD model, two-node model and multi-node model. From Section 2.2–Section 2.6, the thermal comfort model used for different aspects, including indoor sleep environment, outdoor environment, and for the elderly, thermal comfort models for different races, and data-driven model is introduced. Finally, the future trend is discussed.

* Corresponding author.
E-mail address: zwlian@sjtu.edu.cn (Z. Lian).

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Nomenclature

ASV/ASV_{Europe}	Actual Sensation Vote
AC	Air-conditioned
CL	Cooling
COMFA	Comfort Formula
DI/DI_{ndex}	Discomfort Index
DISC	Thermal Discomfort
ECG	Electrocardiogram
ECFhta	Heat transfer area combining effective conductive field
EEG	Electroencephalogram
ETF	Modified effective temperature
ETFe	Enhanced conduction-corrected modified effective temperature
FR	Free-running
GOCI	Global Outdoor Comfort Index
HI	Heat Index
HSI/HSI_{ASHRAE}	Heat Stress Index
MDI	Discomfort Index
MOCI	Mediterranean Outdoor Comfort Index
NREM	Non-Rapid Eye Movement
NV	Naturally ventilated
r_a	Aerodynamic resistances
r_c	Clothing resistances
r_t	Tissue resistances
T_n	the predicted neutral temperature
T_{out}	average outdoor temperature for the months
T_0	the exponentially weighted running mean outdoor temperature for the day
OT	Operative Temperature
HT	Heating
OUT_SET	Outdoor Standard Effective Temperature
PET	Physiological Equivalent Temperature
PhS	Physiological Strain
$PMV/PMV_G/PMV_{solar}$	Predicted Mean Vote
PPD	Predicted Percentage of Dissatisfied
PT	Perceived Temperature
PTS-WPD	Partial Thermal Sensation-Whole Percent Dissatisfied
REM	Rapid Eye Movement
SET_{ASHRER}	Standard Effective Temperature
ST	Subjective Temperature
STI	Subjective Temperature Index
$ST_{preferred}$	Subjective Temperature
TEP	Temperature of equivalent perception
T_{eq}	Equivalent temperature
T_a	Air temperature
T_c	Core temperature
$\bar{T}_{sk}$	Mean skin temperature
TCV	Thermal Comfort Vote
TSV	Thermal Sensation Vote
TVF_{hta}	Convective heat transfer area combined thermal velocity field
UTCI	Universal Thermal Climate Index
WBGT	Wet Bulb Globe Temperature

2. Thermal comfort model and its research progress

In order to comprehensively review thermal comfort models, literature search was performed in the following scientific databases: Springer Link, Elsevier, CALIS, Science Direct, Web of Science, PubMed and Scopus. The key word is "Thermal Comfort model", and the number of relative papers is 2,578. The search was limited to papers published from 1950 to 2019. After correlation analysis and reading the abstracts, 152 full papers were read. The papers are published in the Building and Environment, Energy and Buildings, International Journal of Thermal Sciences, Science of the Total Environment, Comprehensive physiology, and so on. After a final screening, 117 papers are further selected and analyzed.

2.1. Basic classic models

Thermal comfort research can be traced back to Blagden and his laboratory members to evaluate thermal tolerance [11]. Since then, the study of thermal comfort has been continuously performed. From 1960s to 1970s, Fanger [12] established an mathematical formula related to thermal comfort with six parameters: air temperature, radiation temperature, relative humidity, wind speed, clothing thermal resistance and activity. While former researchers proposed as many as hundreds of influencing factors, Fanger [12] selected only the main factors, including not only physical environmental factors, but also human physiological parameters. It changed the study of thermal comfort from qualitative research to quantitative research. The first classic thermal comfort model is PMV model (Predict Mean Votes), based on the Fanger's human thermal balance equation. the PMV model is discussed in detail by Hoof et al. [13]. Fanger's PMV model is combined with the thermal regulation theory of the human body, and the human body achieves thermal comfort in the building under certain heat and humidity conditions. Therefore, the PMV model is widely used to evaluate the thermal comfort of indoor human body [14]. The PMV model is developed on the basis of experiments where human body is close to thermal neutral state, when there is a linear relationship between skin temperature, perspiration rate and human activity intensity. The PMV model adopts the ARSHER55-2004 Standard 7-point scale [9]. When PMV is greater than + 2 (warm), due to the obvious enhancement of the evaporative heat dissipation of sweat, there is a significant difference between the PMV value and the actual value, so the accuracy of PMV prediction is questioned by many researchers [13], and the applicable scope of the PMV model is limited in the relevant standards [10]. The PMV model is aimed at the uniform and steady-state traditional air-conditioning environment, and does not consider the non-uniform and non-steady-state environment, let alone the effect of local hot and cold sensation on the overall thermal sensation. Therefore, PMV is not applicable to dynamic environments [15].

PMV model is the most classical thermal comfort model. In addition to PMV model, two-node model and multi-node model are widely used. For two-node model, it simplifies the human body into a two-layer structure with skin and core, which is represented by a concentric cylinder. Multi-node model abstracts the human body into multiple segments, and each segment is divided into skin, fat, muscle, bone and other layers. Each layer in each segment is regarded as a heat transfer node with thermal physiological parameters, and is controlled by energy and mass conservation equations. The relationship is shown in Fig. 1.

The three types of models are the most classical ones in thermal comfort. In different built environment, the three kinds of models have been continuously developed.

Thermal comfort model requires the cooperation of two systems: active system and controlled passive system. The details are shown in Figs 2 and 3. The two systems exist in PMV model, two-node model and multi-node model. For PMV model and two-node model, the two system are fuzzy and incomplete, so the prediction of two models is only high accurate in the steady-state environment. As for the multi-node and multi-segment model, Fiala [4] comprehensively introduced the active and passive system (Fig. 3).

Passive system: passive system describes the process of heat and moisture exchange between the human body and the surrounding physical environment. Heat is produced in the body through metabolism and is constantly lost to all parts of the body through the blood circulation system. The calculation of this part of heat is closely related to the pa-

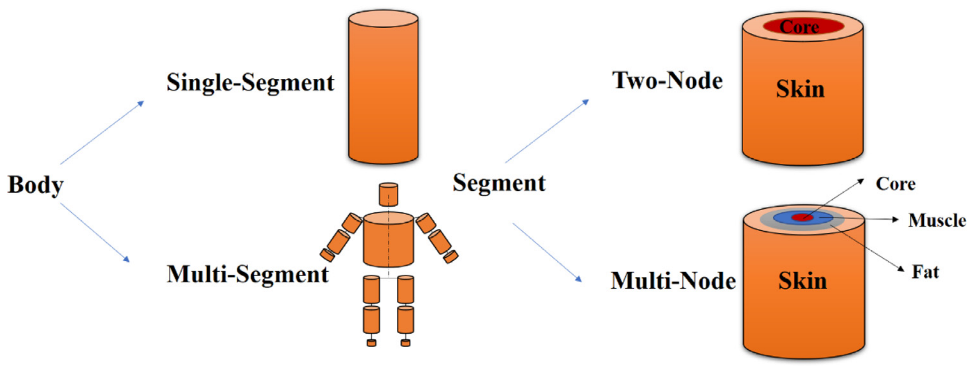

Fig. 1. The details of model segments for two-node and multi-node models.

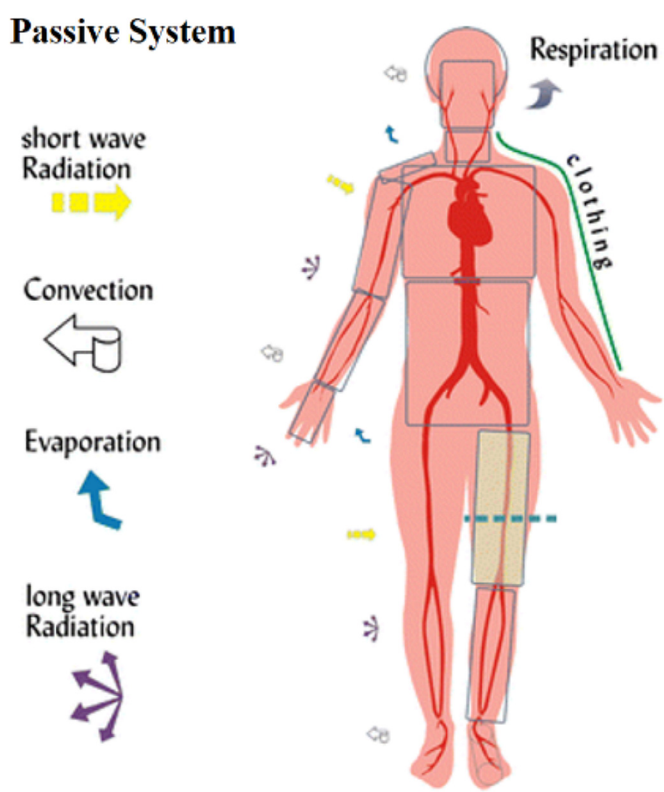

Fig. 2. Passive system for thermal comfort model modified from [17].

rameters of the body. The parameters considered are blood index and blood flow, bone, fat, muscle and so on. It is lost to the surface of the skin through heat conduction inside the body. The exchange of heat between the body surface and the outside world is a series of complex processes, including heat conduction, heat convection, radiation and sweat evaporation [16]. Among them, the thermal resistance of clothing affects the heat exchange between the human body and the environment.

Active system: the active system controls the passive system. The active system controls the physiological activities such as vasoconstriction, relaxation, trembling and sweating of the human body [6]. The temperature in the active system (core temperature, skin temperature) is used as the output index and feedback signal. The physiological regulation mentioned above is controlled through the change of temperature and its rate of change, and finally the temperature is controlled in a preset reasonable range.

Two-node model mainly appeared in the 1970s, such as Hsu and Jai et al. [19,20], but Gagga's model [21] has been widely used. The mechanism of thermal regulation is greatly simplified, with the goal of maintaining the core temperature of the human body at about 36.5 °C, and the feedback adjustment is carried out by controlling heat generation and heat exchange. However, two-node model uses the lumped parameter method. The human body surface is regarded as a whole, so it is only fit to the uniform environment. Gagga's two-node model was proposed in 1971 and improved in 1986. Zolfaghari and Maerefat [22] added the biological equation (Pennes Equation) to Gagga's model. Two-node model has been developed in varying degrees in body segments. Kaynakli and Kilic [23, 24] plus Foda and Sirén [25] developed the two-node model of Gagga, which developed body segments from two-segment to multi-segment.

Multi-node model appeared with the appearance of two-node model. There is a great influence on multi-node human thermal regulation model established by Stolwijk to meet the design requirements of human protective clothing in the space environment [26]. Based on Stolwijk's work, Fiala model [27], Tanabe model [28] and UCB model [29] were developed. These models improve Stolwijk's model in varying degrees. For example, the UCB model recalculates the heat exchange between the arteries and veins of the trunk, and Tanabe introduces the central blood system as the 65th node of the model. Several important multi-node model features are listed in Table 1.

2.2. Thermal comfort model of sleeping environment

In addition to working, sleeping is also one of the main indoor activity of human being. From people's whole life, humans spend more than one-third of lifetime sleeping. Sleeping environment is therefore one of the most important built environments, along with indoor and outdoor environments. Many scholars have conducted a lot of research on sleeping thermal comfort.

However, when people are sleeping, the surrounding environment is very different from the indoor office environment. The physiological state of people is different from the awake state [33,34,35]. The most obvious point is that the metabolism is apparently slower than that in the awake state. People wear significantly different from that in the awake state. When sleeping, mattresses and quilts are also part of thermal insulation layer. Due to these aspects, scholars have proposed some thermal comfort models for sleeping different from the awake state.

Scholars have deduced and developed the sleeping thermal comfort model from the indoor sitting or working environment. The physiological parameters when sleeping are the closest to the ones of indoor sitting state, and the sleep thermal comfort model has only entered the research field of scientists in the past decade.

Lin et al. [36] propose a thermal comfort model for sleeping based on Fanger's comfort model. The thermal comfort model requires that the human body reaches thermal neutrality during sleep, so the heat balance equation is also established based on steady state assumption. Due to the gap between sleeping state and the awake state, metabolism decreases accordingly in the heat balance equation because of the metabolic slowness. Clothing thermal resistance includes the quilt and mattress. In this model, the relationship between the thermal resistance of the quilt mi-

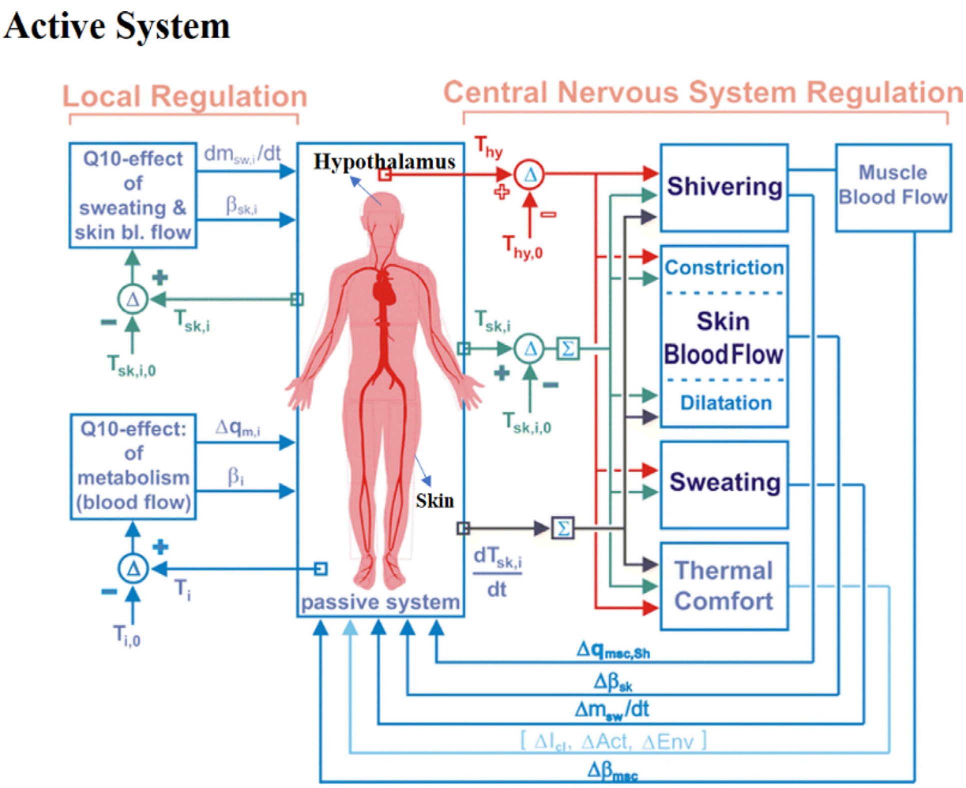

Fig. 3. Active system for thermal comfort model modified from [17] and [18].

Table 1
The characteristics of Main Multi-node and Multi-segment Thermal Comfort Models (Arranged and Modified from [8]).

Model	Description	Environmental conditions	Active System
Tanabe 2002[28]	-16 segments - 65-node - Four layers: -Core, muscle, fat and skin	Transient and non-uniform conditions	Based on Stolwijk
Fiala 1999[4] [6]	- 15 segments - 187-node - three sectors: anterior, posterior and inferior - Seven tissues: brain, lung, bone, muscle, fat, skin and viscera	Steady-state and transient conditions	Regression based
UC Berkeley 2001[29],[30]	- Multi-node (arbitrary number of segments) - Five layers: core, muscle, fat and skin and clothing layer	Transient and non-uniform	Based on Stolwijk
ThermoSEM 2004 [31,32]	- Multi-node - 19 segments - Spatial subdivision: anterior, posterior and interior	Transient and non-uniform conditions	Incorporates neurophysiology of thermal reception in the skin blood flow model

croenvironment and the temperature, which is also a unique influencing factor of the sleep thermal comfort model, is discussed. However, using the Thermal Comfort Vote (TCV) and Thermal Sensation Vote (TSV) as model outputs remains debatable, people may have deviations in their memories of sleeping after waking up.

In addition to the PMV-PDD model, some scholars have built and developed the sleep thermal comfort model based on the two-node model of Gagge. Pan et al. [37] established four-node thermoregulation model for sleeping adults on the basis of the two-node model of Gagge. The four-node model also incorporates the characteristics of people asleep. As shown in Fig. 4, the main reason for changing from two-node to four-node is the specific discussion of the thermal resistance of clothing outside the human skin layer. It is distinguished by whether the skin is in contact with the mattress system, whether it is covered by a quilt, clothing, or exposed when the human body is sleeping. The four-node thermoregulation model for sleeping divides sleeping periods into several states, including Non-Rapid Eye Movement (NREM) stage and Rapid Eye Movement (REM) stage. This division has some practical implications, just as the importance of different types of activities to the thermal comfort model in the awake state. Four-node thermoregulation model for sleeping adults uses skin temperature and core temperature as the output of the model, which is more objective and accurate than using TCV and TSV. This is also the difference between the thermal comfort model of sleep and the thermal comfort model of other scenes. However, using only the skin temperature of a certain area may not reflect the true thermal comfort of the human body.

Skin temperature is a good objective parameter that reflects people's cold and hot feelings and the degree of hot and cold comfort. However, there may be some errors in one or two measurement points. In the field of sleep thermal comfort, Liu et al. [38] proposed an average skin

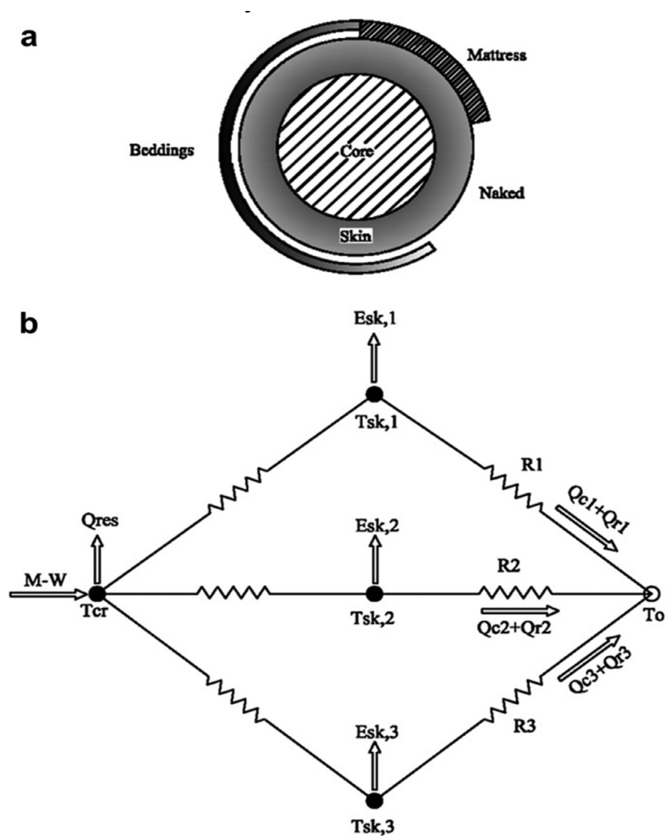

Fig. 4. Schematic diagrams of the four-node thermoregulation model for sleeping applications (a) The four-node thermoregulation model (b) Thermal resistance network modified from [37].

temperature method to predict the thermal comfort of the human body during sleep. Ten different parts of the body were used, and their different weights were summed as the average. There is some innovation in this method for predicting the thermal comfort model of the human body based on the skin temperature while the verification is acceptable for experimental values. However, in the selection of the weights, only the relative sizes of the various parts of the human body are considered, and the differences in the sensitivity of cold and heat in each part and the genders are ignored; Lan et al. [33] established a model using these physiological parameters, especially the discussion of neutral mean skin temperature is worth referring. The model divides the human body into two parts, contacting with bed and not-contacting with bed, and establishes a model for predicting the optimal sleeping thermal environment, by using physiological parameter values measured from sleeping participants, including respiratory ventilation rate, skin temperature, metabolic rate, and sweat rate, rather than awake subjects. Using this model, the thermal sleep environment is divided into four categories related to human thermal load and sleep quality, providing a direction for the evaluation and prediction of sleep thermal comfort.

The previous studies of sleep thermal comfort models, few scholars considered the feelings of body parts during sleep during the establishment of the model. In the establishment process, the overall cold and hot feeling is the mainstream to consider and evaluate thermal comfort. Song et al. [39] proposed the percent dissatisfied model (Partial Thermal Sensation-Whole Percent Dissatisfied PTS-WPD model). This model is also developed based on the principle of human thermal balance. The PTS model provides local thermal sensation for head and whole-body during sleep, and the WPD model integrates each individual local thermal sensation into a comprehensive index for thermal environment evaluation. In the past ten years, the development process of human thermal comfort model of sleep is shown in Fig. 5.

2.3. Thermal comfort model of outdoor environment

Section 2.1 describes three types of classic thermal comfort models. The development of these models is for indoor environment. However, the application of the model is not limited to the indoor environment. Some scholars use these models for outdoor environments. However, there are great difference between the outdoor and the indoor environments. The greatest difference lies in the mean radiant temperature and the wind speed. At the same time, people in indoor and outdoor environments different degrees of thermal tolerance. Many scholars have developed thermal comfort model suitable for outdoor use based on indoor thermal comfort model.

Jendritzky [40] et al. used the thermal comfort model of the human body in the study of outdoor thermal comfort in 1981. The model is an improvement based on the PMV model, long-wave radiation term which is easy to measure in outdoors is added to the PMV equation using Short-wave radiation intensity, and named it "Klima-Michel-Model" [40]. This is also the first time; physiological parameters were considered in the pure physical environment when studying the outdoor environment. Brown and Gillespie [41, 42] proposed a COMFA outdoor thermal comfort model, which assumes four conditions: (a) a comfortable perspiration, (b) a comfortable core body temperature, (c) a comfortable skin temperature, and (d) a near-zero energy budget.

In the mid-1990s, Hoppe proposed the Munich energy balance model (MEMI) based on parameters of the human energy balance equation and Gagge's two-node model. MEMI provided a physiological-based evaluation model for outdoor thermal comfort [43]. At the same time, the concept of physiological equivalent temperature (PET) was proposed for outdoor thermal comfort research [43], but PET cannot accurately predict outdoor thermal comfort [44–50]. For example, Kenz et al. [44] adopted physiological Equivalent temperature PET to count number of people in outdoor space. Under the same outdoor parameters, the thermal comfort obtained is significantly different ($P < 0.01$). In Nikolopoulou and Lykoudis's research [45], when using physiologically equivalent temperature PET, subjects across Europe were in a thermoneutral vote, with a large neutral temperature difference (over 10°C) (for more examples see the literature [46–50]). Many scholars proposed indicators suitable for outdoor thermal comfort, for example, modified ET* [51]. This model considers the average outdoor radiation temperature including solar radiation and physiological indicators defined by Jeong and the human body whose relationship of psychological response; the OUT_SET* [52], OUT_SET* was developed from SET*, mainly indoor SET* added solar and infrared radiation temperature, reflecting outdoor differences from indoors; UTCI [53], UTCI is defined as isothermal air temperature that causes the same dynamic physiological response calculated by the model under reference conditions. It is based on contemporary science, and its use will set up human biometeorology. The standardization of applications in the main areas makes the research results comparable and physiologically relevant.

Huang considered the impact of outdoor wind speed on the human body and convection and radiation heat dissipation in the heat balance equation separately. Huang also accounted the behavior of the human body to actively reduce the thermal resistance of clothing outdoors – a more reasonable outdoor human thermal comfort model was established [54]. Huang converts all human parameters into physiological equivalent temperature (PET) to predict human thermal comfort. This is convenient for calculation under actual practices. However, it is not validated by human experiments.

Many scholars (Nikolopoulou et al. 2001; Spagnolo and de Dear 2003a; Thorsson et al. 2004, 2007; Nikolopoulou and Lykoudis 2006) [45,47–50] have given their built and developed models. A series of outdoor models were used based on Hoppe [43], but their research focused on low metabolism. This may be because the physiological and its feedback of people with high metabolic rates is easily confused in outdoor conditions [44]. Brown and Gillespie [41,42] conduct research on high-metabolism groups engaged in strenuous exercise outdoors to validate

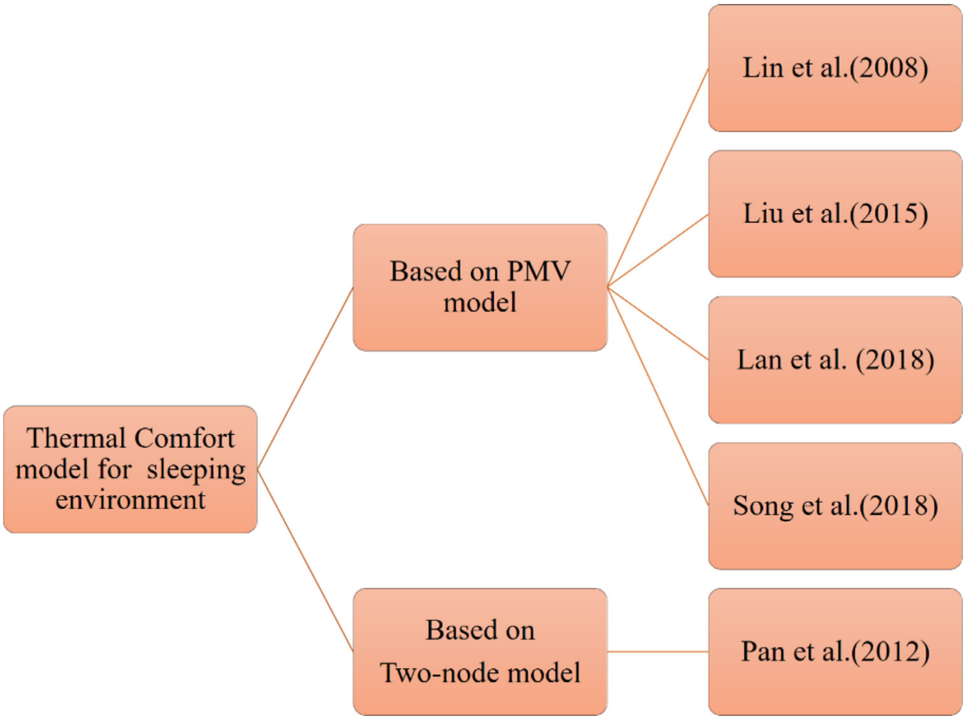

Fig. 5. Schematic diagram of the development of thermal comfort models for sleep people through the recent decade.

and improve the COMFA outdoor thermal comfort model. The improved COMFA model considers gender, age, weight, the amount of activity, clothing thermal resistance, air temperature, radiation temperature, relative humidity, wind speed, activity intensity, metabolic rate and other factors on the human thermal comfort. The COMFA outdoor thermal comfort model has achieved 85% accuracy in predicting thermal sensation under intense exercise. For the predicted deviation, Kenny et al. [55] revised the clothing insulation and vapor resistance to improve the accuracy of outdoor heat sensation prediction for the strenuous exercise for COMFA model.

In the evaluation of human thermal comfort, core temperature and average skin temperature are more accurate objective evaluation indicators [55]. Vanos [56] et al. Proposed the use of MST (mean skin temperature) to predict human outdoor thermal comfort (medium activity intensity) in 2010. A COMFA outdoor thermal comfort model was used to predict the average skin temperature, as shown in Eq. (1). The four-point average method was used to measure the average skin temperature, as shown in Eq. (2) [57], and a corresponding correlation analysis was performed. Meanwhile, it was related to the subjective vote of the human body to obtain the reliability of the model.

$$\bar{T}_{sk} = \left(\frac{T_c - T_a}{r_t + r_c + r_a}\right)(r_c + r_a) + T_a \tag{1}$$

$$T_{sk} = 0.3T_{chest} + 0.3T_{arm} + 0.2T_{leg} + 0.2T_{thigh} \tag{2}$$

T_c is core temperature, T_a is air temperature, and r_t, r_c and r_a are tissue, clothing and aerodynamic resistances, respectively (s m^{-1}). Kenny [58] et al used Eq. (1), which makes use of Ohm's Law Analogy and T_a. Each participant had fast response thermocouples (SA1-T Omega Engineering, Stamford, CT) attached to their left calf, right thigh, right upper arm and left chest. T_{sk} was calculated using the Ramanathan 4-point weighting method (Eq. (2)). This was found to produce values consistent with research completed by Mairiaux [59] et al., and Sparks [60] et al.

Kurazumi et al. [61] proposed ETF (effective temperature) and come out the index that correlates ETF with human thermal comfort. This kind of sensory and physiological climate environment index enhances conduction correction the modified effective temperature ETFe can convert various forms of various effects of temperature-air velocity, long-wave radiation in outdoor space, short-wave solar radiation, and the temperature and humidity of the surface of the contact part. The effect of the five environmental factors on human thermal balance can be expressed by the newly defined comprehensive evaluation index TVFhta of the thermal environment in the heat conduction area, which is related to the air velocity. The radiation heat exchange area combines the effective radiation field of long-wave radiation in outdoor space, that is, outdoor space long-wave radiation. Radiation heat transfer area refers to the effective radiation field related to short-wave solar radiation in outdoor space, which involves short-wave solar radiation. Heat transfer area combining effective conductive field (ECFhta), which is related to the contact part surface temperature, increase the effective humidity field of the conductance-the effective temperature for correction is related to humidity. Therefore, the temperature conversion factors can be added, and on the same evaluation axis, the combined effect of each meteorological element on outdoor space and physiological feelings and the discrete effect of each meteorological element can be quantified. Kurazumi et al. [59] emphasized the effects of solar radiation and wind speed on human physiological and psychological temperature in summer in the ETFe indicator system.

Nagano and Horikoshi [62] proposed an outdoor thermal comfort model index ETVO, which considers the influence of separation, whereas the previous research focused on the combined influence of various factors. ETVO was improved based on ETV [61] by considering the influence of solar radiation in addition to traditional indicators such as air temperature and humidity, specific differences are shown in Fig. 6. The ETVO model had the separate system and universal system, but the previous model only had the universal one. The best advantage of the ETVO model is that it can indicate the degree of various environmental factors affect to the overall environment. Nagano and Horikoshi [63], in addition to considering the overall and separation conditions, also proposed that the ETU considers the non-uniform thermal environment. Lai et al. [64] established an outdoor thermal comfort model considering the impact of outdoor thermal environment fluctuations and heat transfer on different parts of the human body, which is a two-dimensional heat transfer calculation model of the human body in a transient non-uniform thermal environment. Lai's model also includes an updated calculation model for outdoor radiant heat transfer and clothing transient heat transfer.

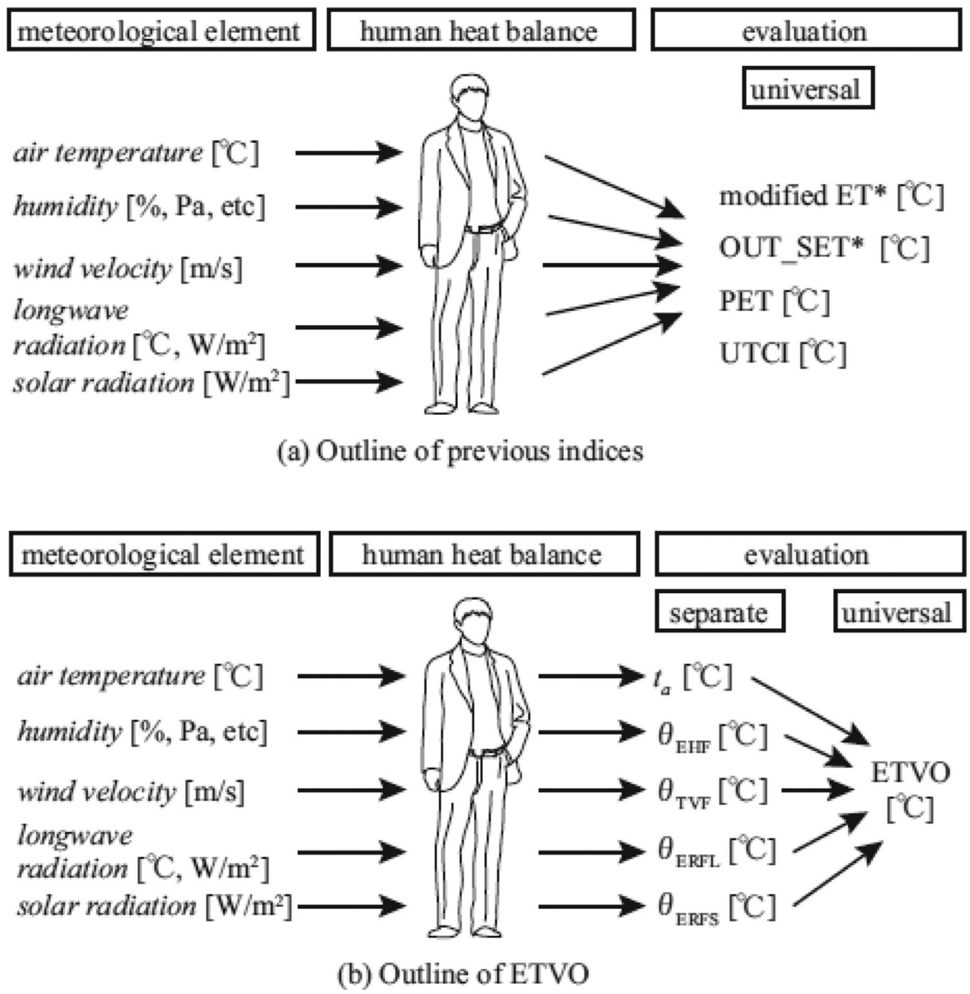

Fig. 6. The different between ETVO and previous models before 2011 modified from [62].

After 2012, the improvement of outdoor thermal comfort models more focused on the regional characteristics of the climatic zone. For example, Jacobs et al. [65] combined meteorological and environmental characteristics to continue improvement for the Oceania climate. Golasi et al. [66] summarized the thermal comfort model applicable to the Mediterranean climate by analyzing data, and provided a revision of UTCI model applicable to the Mediterranean climate. Pearlmutter et al. [67] conducted research and improved of the outdoor thermal comfort model of the hot-arid Negev region of Israel. Niu et al. [68] explored and improved of the model of the subtropical monsoon city. Ruiz and Correa [69] explored the situation of multiple trees in the dry and hot Mendoza Metropolitan area, and Salata et al. [70] proposed the Mediterranean Outdoor Comfort Index (MOCI) for the dry and hot Mendoza Metropolitan area. So many regional studies have also proved the necessity of the regional thermal comfort model. Golasi et al. [71] proposed the Global Outdoor Comfort Index (GOCI) on the previous models. This model integrates the differences of various regions, and considers latitude, annual average temperature, and maximum temperature based on the original variables. For coldest and hottest months, GOCI is a comprehensive model of outdoor thermal comfort models based on regional differences, and has made a certain contribution to the development of thermal comfort models in different regions.

The outdoor thermal comfort model has been developed rapidly in the past 20 years – models are shown in Table 2. The outdoor thermal comfort model is developed based on the indoor thermal comfort model, through the improvement, update and considering for the specific outdoor complex conditions. Constantly proposing suitable thermal comfort models for outdoor usage has brought more applied models to scholars in physiology, environment, architecture, and urban planning, and has gradually differentiated into a theoretical system suitable for their own thermal comfort models. And the outdoor thermal comfort models have adaptive models, the details can be seen in the Ref. [72]. In the Ref. [72], firstly, it reviewed outdoor thermal comfort model for different regions including Europe, Japan, Taiwan, Israel and so on. Second, it reviewed the semi-outdoor thermal comfort. Finally, it gave an adaptive model and emphasized the influence of wind to outdoor and semi-outdoor thermal comfort.

2.4. Thermal Comfort model about Mongoloid and adaptive models

Thermal comfort model has evolved to varying degrees in different building environments. In fact, there will be changes when the research objects are different. It is also mentioned from Sections 2.1–2.3 that there are some thermal comfort models that are only applicable to adults. For the rise and development of sleep thermal comfort, most of the models are suitable for the white race. Most of the models introduced are based on the regression, verification and prediction of the Caucasian, but there are a series of physical and cultural differences among the Mongoloid, Caucasoid, Negroid and Australoid race, resulting in a big difference in their thermal comfort temperature comfort zone. Therefore, the model suitable for the white race will have some errors for other races. In fact, the different races would lead different models which developed different adaptive thermal comfort models. The adaptive thermal comfort models established and developed more than 30 years [90]. Living different climatic region led different adaptation, so the adaptive models generated and developed [91].

Table 2
Summary of outdoor thermal comfort models.

Index for outdoor models	Abbreviation	Authors/Ref.s
Actual Sensation Vote	ASV/ASV_{Europe}	Nikolopoulou [73]
Comfort Formula	COMFA	Brown and Gillespie [41]
Discomfort Index	DI/ DI_{ndex}	Thom [74] and Giles et al. [75]
Thermal Discomfort	DISC	Fountain and Huizenga [76]
Heat Index	HI	Vernon [77]
Heat Stress Index	HSI/HSI_{ASHRAE}	Fountain and Huizenga [76] Malchaire et al. [78]
Discomfort Index	MDI	Masterson [79]
Operative Temperature	OT	ISO 7933 [80]
Outdoor Standard Effective Temperature	OUT_SET	de Dear and Pickup [52]
Physiological Equivalent Temperature	PET	Höppe [44]
Physiological Strain	PhS	Błażejczyk [81]
Predicted Mean Vote	$PMV/PMV_{G}/PMV_{solar}$	Fanger [12] Fountain and Huizenga [76] and Parsons [82]
Predicted Percentage of Dissatisfied	PPD	Fanger [12]
Perceived Temperature	PT	Staiger et al. [83]
Standard Effective Temperature	SET_{ASHRER}	Fountain and Huizenga [76]
Subjective Temperature	ST	Mclntyre [84]
Subjective Temperature Index	STI	Błażejczyk [81]
Subjective Temperature	$ST_{preferred}$	Givoni and Noguchi [85]
Temperature of equivalent perception	TEP	Monteiro and Alucci [86]
Equivalent temperature	T_{eq}	Bründl and Höppe [87]
Universal Thermal Climate Index	UTCI	COST Action 730 [88]
Wet Bulb Globe Temperature	WBGT	Yaglou [89]
Global Outdoor Comfort Index	GOCI	Iacopo et al. [71]
Mediterranean Outdoor Comfort Index	MOCI	Salata et al. [70]

The development of thermal comfort originated in Europe and North America. Therefore, the establishment of early thermal comfort models were based on the physical state, psychological state, cultural and historical background of Caucasoid. Mongoloid, Negroid and Australoid will have deviations in using models based on Caucasoid. This paper takes the thermal comfort model of Mongoloid as an example.

Nicol [92] established adaptive thermal comfort model in Pakistan, Mui and Chan [93] established adaptive thermal comfort model in Hong Kong, China. Yau and Chew [94] established local adaptive thermal comfort model in Malaysia. Rijal et al. [95] established a local adaptive thermal comfort model in Japan stick to different buildings, such as dwellings and offices. Indraganti et al. [96] established a local adaptive thermal comfort model in India. Every countries and regions based on adaptive models complied their standard, such as China (Chinese GB/T 50785 [97]), America (ASHRAE Standard 55 [9]), Europe (CEN standard [98]), England (CIBSE [99]) and so on. Singh et al. [100] put forward school adaptive models, based on different models' origin as mentioned above. Damiati et al. [101] put forward a mixed thermal comfort model. The data was based on Malaysia, Indonesia, Singapore, and Japan during hot and humid season. The model is fitted in humid season in Asia area. This series of models are based on the adaptive thermal comfort model of de Dear [92,102,103] according to the local climate variations. The models all put forward the relationship between indoor neutral temperature and outdoor climate temperature on the basis of PMV model, which makes a certain contribution to the correction of local neutral temperature. However, the difference between different races in the building environment is only a simple relationship between the best indoor neutral temperature and outdoor climate. It doesn't involve the psychological differences caused by cultural differences and regional differences in human habits. Therefore, the essential differences are not involved in the establishment of this kind of model, the expression relationship between neutral temperature and average outdoor temperature established by the five adaptive models is shown in Table 3.

T_n is the predicted neutral temperature and T_{out} means average outdoor temperature for the months. $T_0$is the exponentially weighted running mean outdoor temperature for the day (°C)

The most important step to establish the human thermal comfort model of other races is to modify and redefine the parameters on the physiological level. A good example is the Chinese human thermal comfort model developed by Zhou et al. [105] based on Fiala's multi-node model. The Chinese human thermal comfort model re-combs the human physiological data parameters in Fiala's model. It adds Chinese standard human data parameters to establish a thermal regulation model suitable for Chinese people, and establishes a thermal sensation model considering individual differences and thermal psychological characteristics. The two models can predict Thermal Sensation Vote (TSV) and skin temperature in non-uniform environment. They significantly improve the accuracy of thermal comfort prediction of Chinese. The prediction error is reduced from the large deviation of PMV model (more than one voting value) to less than 0.5 scale in dynamic environment and less than 0.2 in uniform environment. Ma et al. [106,107] based on Zhou [105], added the body parameters of the elderly, and verified the model. The deficiency of two models (Ma's and Zhou's models) is that the evaluation of thermal sensation needs to combine subjective thermal sensation and physiological parameters (such as skin temperature), while the studies on thermal comfort in China rarely involve the validation of physiological parameters. Therefore, more Chinese thermal comfort data combined with physiological parameters (skin temperature, blood pressure, ECG, etc.) need to be carried out to further improve the study of Chinese thermal comfort.

The establishment of thermal comfort model of the yellow race provides a new model supporting for Chinese scholars in thermal comfort and reference experience for the establishment of thermal comfort models of other races (black and brown races).

2.5. Thermal comfort model for elder people

Most developed countries in the world have entered or are entering an aging population society. The elderly and young people have different physiological states, so there should be differences in thermal comfort conditions. Many scholars have carried out extensive research, for example: Stevens et al. [108] studied for different age groups: young people (18-28 years old), middle-aged people (40-60 years old) and elderly people (over 65 years old). It is found that the older the people were, the lower the threshold of temperature was. Tsuzuki et al. [109] was conducted on young people and the elderly exposed to different temperatures (23/25/27/29/31°C). It is found that the thermal perception vote was lower in the elderly at 31°C, while in the environment below 27°C, the thermal perception vote of the elderly was lower

Table 3
The relationship between neutral temperature and outdoor temperature based on the adaptive thermal comfort models in some countries.

Country/Region	Buildings	Formula	Ref.
The United Kingdom	All types	$T_n = 11.9 + 0.534T_{out}$ $R^2 = 0.97$	[92]
Australia	All types	$T_n = 17.6 + 0.31T_{out}$	[102]
Pakistan	All types	$T_n = 18.5 + 0.36T_{out}$ $R^2 = 0.73$	[92]
Hongkong, China	Dwellings	$T_n = 18.303 + 0.158T_0$ $R^2 = 0.59$	[93]
Malaysia	Dwellings	$T_n = 14.858 + 0.3314T_{out}$ $R^2 = 0.0535$	[94]
India (AC Mode)	Dwellings	$T_n = 21.4 + 0.26T_{out}$	[96]
India (NV Mode)	Dwellings	$T_n = 21.4 + 0.26T_{out}$ $R^2 = 0.058$	[96]
Japan (FR Mode)	Offices	$T_n = 20.8 + 0.206T_{out}$ $R^2 = 0.42$	[95]
Japan (CL & HT Mode)	Offices	$T_n = 23.9 + 0.065T_{out}$ $R^2 = 0.1$	[95]
Japan (NV mode)	Dwellings	$T_n = 12.5 + 0.531T_0$ $R^2 = 0.68$	[104]
Japan (AC mode)	Dwellings	$T_n = 18.8 + 0.297T_0$ $R^2 = 0.06$	[104]
Japan (HT mode)	Dwellings	$T_n = 16.5 + 0.012T_0$ $R^2 = 0.11$	[104]
CIBSE	Offices	$T_n = 22.6 + 0.09T_0$	[99]
CEN	Offices	$T_n = 18.8 + 0.33T_0$	[98]
ASHRAE	Offices	$T_n = 17.8 + 0.31T_0$	[9]

than that predicted by PMV. Schellen et al. [110] proved that the elderly have different feelings of hot and cold stimulation than the young; Novieto [111] explained the reasons for the differences in mechanism, including basal metabolic rate, blood flow, cardiac pumping capacity, fat distribution, surface area and so on, resulting in hot and cold differences between the elderly and young people. Therefore, there is a great difference between the human thermal comfort model for the elderly and the usual mannequin, and it is meaningful to study the human thermal comfort model for the elderly.

The research on thermal comfort model of the elderly is very limited. Therefore, the model research related to evaluation and prediction should be the main point of the next step in the field. The earliest thermal comfort model for the elderly is Ma et al. [106] based on the thermal comfort model of human body proposed by Zhou [105],modified the physiological parameters including basal metabolic rate, cardiac output, body fat content and physical size of human body,and established the thermal regulation model and thermal sensation model of the elderly. The main advantage is that the model has a high accuracy in predicting the elderly, the experimental verification in this paper shows that the accuracy of the average skin temperature in summer is more than 85.9%. The psychological consideration of the model is not comprehensive. The physiological parameters such as subjective thermal sensation and skin temperature of the elderly are quite different from those of the young when they deviate from the state of thermal comfort, and the physiological and psychological factors that cause this difference are worth exploring, so as to improve the mechanism in the field of thermal comfort of the elderly.

Wang et al. model [112] established a thermal comfort model involving the elderly: based on data-driven model–with air temperature, wind speed, CO_2 concentration, illuminance, health status of the elderly and living time in nursing homes as inputs, thermal perception voting and skin temperature as outputs. The prediction accuracy of this model is 56.6%, higher than that of the traditional PMV model (31.7%). However, the model also has some shortcomings. All the data are from the elderly in hot summer and cold winter areas in China, so there may be deviations in the prediction for other climate zones in China and other countries and regions. All the subjects were in a sedentary state, and the metabolic rate and sweating were not considered in this model. Due to the limitations of the experimental conditions, the model did not take the high humidity into account.

2.6. Thermal Comfort Model by machine learning algorithm

Traditional models are based on a series of mathematical deductions (PMV model algorithm, thermal adjustment model algorithm, etc.) based on certain inputs (ambient temperature, wind speed, clothing thermal resistance, etc.) and then obtain outputs (TSV, TCV, skin temperature, etc.). Such models are called white box or gray box models, however, due to the complexity of the intermediate mechanism, scholars simplify the model algorithm when they obtain the model algorithm. Because it involves human physiology, many theories at the mechanism level cannot see its core, resulting in some errors in the traditional model. In the second decade of the 21st century, the rapid development of statistics has brought new research ideas to the field of human thermal comfort. Since 2016, machine learning, big data and other means have introduced the study of human thermal comfort model. This series of studies are based on the explanation of desalination mechanism and replaced by pure mathematical statistical algorithms, emphasizing the high matching of input and output. As a result, the accuracy of the prediction is improved, and the structure of the traditional model is shown in Fig 7.

Since 2016, the models based on the concepts of machine learning and big data are mainly due to the differences in prediction accuracy caused by different algorithms. There are about 40 articles about machine learning from 2016 to 2018. The main algorithms used in these articles are Naïve Bayes, K-Nearest Neighbor, Decision Tree, Support Vector Machine, Random Forest and six high precision models commonly used in neural network methods, among which the prediction accuracy of the algorithm using decision tree can be more than 90%. Some scholars who study the algorithm have proposed the improved algorithm [113] for prediction, but the prediction accuracy needs to be verified by data.

3. Discussion

Through different classification models, this paper summarizes the development of thermal comfort models and their advantages and disadvantages. For the indoor environment, the human thermal comfort model rises from the usual indoor hot and humid environment. The overall development trend of human thermal comfort model is from lumped model to multi-node model.

For the indoor environment, the uniform and steady-state environment was the focus of the research in the past. However, with the increasing demand for energy conservation, non-uniform and unsteady environment has gradually entered the field of vision of researchers. The same is true of the development of the model, from the uniform steady-state indoor environment model to the unsteady-state and non-uniform model. Researchers have explored the indoor environment for the longest time, but with the development of the research on unsteady and non-uniform environment in the past 10 years, researchers have gradually found that many mechanisms are still not perfect and are worth exploring. The accuracy of many models suitable for uniform environment decreases when people are in non-uniform environment. For example, Wang et al. [112] uses the classical PMV model to predict,

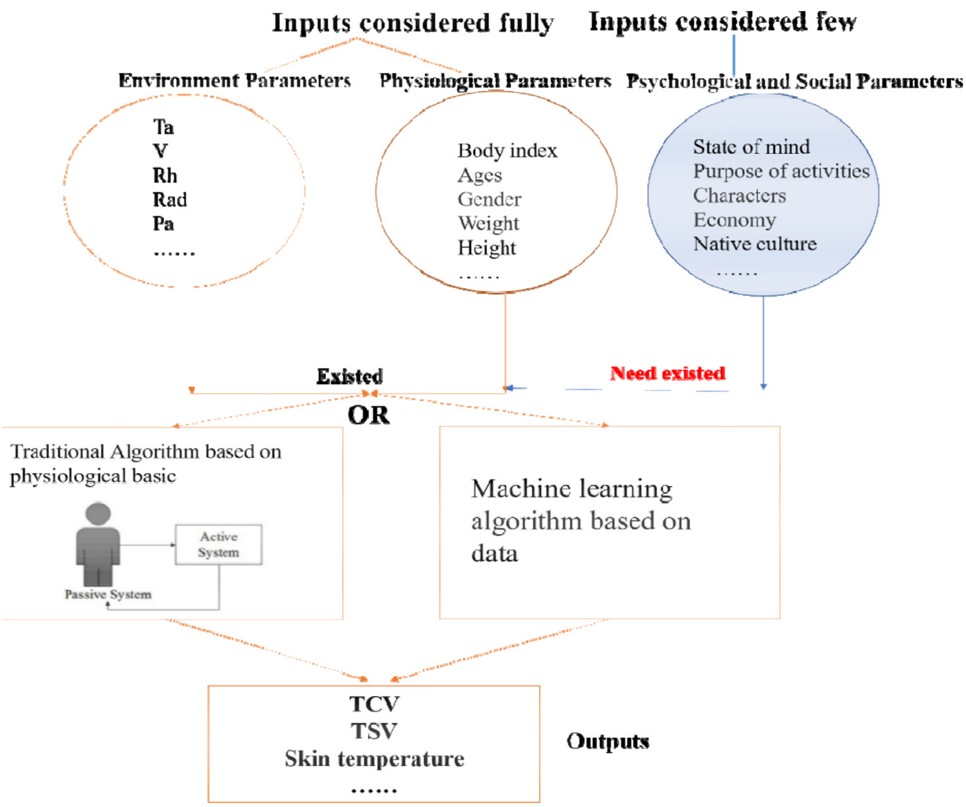

Fig. 7. Schematic view of the inputs and outputs for traditional model and machine learning algorithm.

and the accuracy is only 30.1%. The reason is that when simplifying the model, the researchers ignore many actual physiological states of the human body, such as the simplification of metabolic rate and sweating. At the same time, there is less consideration of people's psychological state, for example: people's consideration of the actual hot and cold tolerance, the influence of culture on people's cold and hot feelings, etc. Therefore, in the non-uniform environment, the establishment of human thermal comfort model and the construction of human physiological mechanism is one of the development directions in the future. Nowadays, the climate chamber study and field study are main method to research thermal comfort. For non-uniform environment, certain control in the chamber can get more precise physical results, but in the field study, psychological feelings and actual situation can be acquired. So how to balance and combine the two methods may be a crux to get a more real prediction for models in the non-uniform environment.

The thermal comfort model of human body has different extension in different environments. Due to limited length, this paper takes the outdoor environment and sleep environment as examples for discussion. In addition, vehicular, aerial environment or semi-outdoor environment is also worth discussing [74]. For the outdoor environment, the research on the thermal comfort model is abundant. Based on the indoor thermal comfort model, a series of models with the consideration of outdoor thermal comfort are developed. In the process of the development of this model, the differences of physical parameters and human physiological aspects are fully considered [114,115], and a series of indicators suitable for outdoor thermal comfort are put forward. However, when human body is in the outdoor environment, the physiological state is more complex than in the indoor environment. For different purposes of outdoor work, the research on human psychology is also more complicated. The proposed thermal comfort model has not explored the physiological mechanism of the human body in the outdoor environment. Most cases are still based on indoor thermal comfort model. Therefore, the psychological factor in the future is one of the researches focuses on improving the prediction and evaluation of human thermal comfort model. In terms of mechanism, the sleep environment is more complex than the usual indoor or outdoor environments. The research on sleep thermal comfort is still in the early stage, so there are few sleep thermal comfort models, and only five models about sleep thermal comfort are defined in this paper. The existing models are improved from the traditional PMV model or two-node model to adapt to the sleep environment. The improvement of the multi-node model did not appear in sleeping thermal comfort. It may be that there is a great difference between the sleep state and the awake state, and the multi-node model is explored in detail for the physiological state, so it is difficult to improve the multi-node model in the sleep state. Therefore, the sleep thermal comfort model has great potential for improvement in the future. The researchers found that in the sleep environment, the bedding system and the microenvironment creating are the important factors that affect the thermal comfort of the human body. It should be the key consideration in the model. Although in the existing model, it is only regarded as a fixed parameter. In the future research, it is very likely to become an independent variable. It is also found that TSV and TCV are often used as output parameters in the sleep thermal comfort model, but there is a deviation in people's recall after waking up, which may bring errors to the prediction. Therefore, some objective indicators are needed to eliminate the uncertainty caused by subjective evaluation. Some of the current studies use the average skin temperature as the output parameter, and more objective parameters can be added in future studies, such as Electroencephalogram (EEG) and so on [35]. At the same time, using the average skin temperature is an effective method, but the calculation method of the average skin temperature and the comfort zone corresponding to the average skin temperature still worth discussing, especially in the sleep environment, the human body will have different sleep stages. This kind of study is not only a challenge but also an opportunity for the sleep thermal comfort model.

For different race groups, the thermal comfort model also presents a new possibility of development. The thermal comfort model of different races is proposed because the research on thermal comfort is expanded all over the world, and there is a large error when the thermal comfort model is applied to other races based on the principles summarized from Caucasoid experiments. Therefore, it is necessary to re-establish the thermal comfort model suitable for all kinds of races. The Chinese thermal comfort model mentioned in this paper re-establishes the thermal comfort model suitable for Chinese based on the human body parameters [105], which provides support for the study of thermal comfort in China. However, the differences in psychological and cultural levels such as thermal adaptation, thermal tolerance and thermal preference have not been fully considered, which may be the development direction of thermal comfort models for different race groups. For different race group, ultimately, it is the different climates and different cooking culture. So, for the different regions, the adaptation is very important for the local people, thus, the adaptive models are the embody of climate. For different region and different indoor environment, it is normal to have different thermal zone. And the adaptive thermal comfort models show the temperature differences. For the recent research of adaptive models, different types of buildings should be excavated, especially the traditional buildings, such as Yaodong to China. Combined the character of local and people's mental state maybe a best way. The adaptive model shows that comfort temperatures are diverse and variable rather than single and fixed [116]. Thermal physiology and heat exchange are components within the adaptive model. But even if perfecting heat-exchange model, it would not be sufficient for understanding thermal comfort; contextual factors are also needed. The adaptive model does not fit easily into the current ways of expressing standards for thermal comfort. Its focus is entirely different and will lead to differently expressed standards.

Two kinds of thermal comfort models for the healthy elderly are also all the research for the thermal comfort models of the elderly so far. The difference of thermal comfort models between young and old people lies in their differences in psychological factors such as hot and cold tolerance, thermal sensitivity and so on. The model weakens the explanation of the mechanism and uses data-driven technology. Considering the physiological mechanism, psychological and social factors may be the development direction of establishing a thermal comfort model for the elderly. From the perspective of population, young people are the main subjects of the study, a small number of scholars study the elderly, and thermal comfort model of children has been in the beginning [117], so the topic of thermal comfort model of different age groups is worthy of in-depth discussion.

With the emergence of personal ventilation, radiant ceiling, under floor air distribution and so on [105], energy can be saved. But these environments create a non-uniform environment caused by local stimuli. The research on thermal comfort in this part of the non-uniform environment is still in the beginning of the research, and the prediction accuracy of the thermal comfort model for the non-uniform environment needs to be improved. Therefore, this is also the hotspot of thermal comfort model research in the future.

In terms of the model combined with machine learning, the number of articles published has increased exponentially in the past four years, and its essence is to use the data itself to improve the accuracy of prediction. Judging from the articles published now, the prediction accuracy has been improved greatly as claimed by the authors, but further validation by using more data will show the superiority of the method. Nevertheless, data-driven model brings new opportunities to the development of thermal comfort model, which is promising for interdisciplinary researches in the future.

4. Conclusions

The study of thermal comfort model is one of the most valuable contents in the field of human thermal comfort. It provides a method for predicting and evaluating the state of human thermal comfort, and a basis to set the building environment. The development of human thermal comfort model follows the process from simple to complex, from abstract to concrete, and from whole body to local details.

There are mainly three basic human thermal comfort models of: PMV model, two-node model, and multi-node model. The later models are developed based on the three models. There are corresponding developments in PMV model and Two-node model, but the development of multi-node model is still lacking. The thermal comfort model of human body derives a variety of models for different building environment. For outdoor applications, according to its unique thermal environment, people's psychological state and other parameters, the outdoor thermal comfort model has more than 20 indices, but most models are based on physiological and psychological levels. The thermal comfort model of sleep environment is still in its early stage of research, and many mechanism explanations need to be explored. The development of thermal comfort model according to different sleep stages is an opportunity for sleep thermal comfort model in the future.

The thermal comfort model also had a certain differentiation for different people. The main research still focused on young people, a small number of scholars studied the thermal comfort of the elderly, and even fewer scholars study the thermal comfort of children. In terms of models, there are only two thermal comfort models for the elderly, so the thermal comfort model for the elderly need to be developed. The thermal comfort model for children is still lacking, the thermal comfort model of different race groups has gradually emerged in the development, and the thermal comfort model of Chinese gives a good example. Adaptive models develop quickly, aiming at different types of buildings is still the direction of adaptive models.

In recent years, many models were developed through machine learning approaches, which provides more research ideas on model development. The research in the past 50 years is more focused on the formulation of the thermal comfort standard of the different population. Under the trend of big data, a research opportunity exists to establish thermal comfort model of individuals. Combining data with efficient prediction algorithm, data-driven models can make accurate and efficient prediction of individual thermal comfort, which will also make the thermal comfort model more practical and have more life-oriented applications.

Declaration of Competing Interest

The authors declare that they have no conflict of interest.

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Research involving Human Participants

All protocols were approved by the university's ethics committee and conformed to the guidelines contained within the Declaration of Helsinki.

Informed consent

Informed consent was obtained from all individual participants included in this study.

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