Evolution and performance analysis of adaptive thermal comfort models – a comprehensive literature review

Article

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Abstract

Thermal comfort is fundamental to indoor environmental design and operation as well as indoor thermal environment evaluation. This paper has reviewed the historic evolution of thermal comfort research during the last century using a systematic approach and a particular focus on adaptive thermal comfort studies. A large number of published articles as well as standards and guides were collected and screened based on a rigorous search method to ensure the literature database was both focused and complete. A further evaluation of representative prediction models has been conducted by applying the models to a large database and comparing the differences in their performance. Based on the review analysis, three representative thermal environment assessment approaches were classified as the heat balance approach, the adaptive regression-based approach and the adaptive heat balance approach. The strengths and constraints of each approach were analyzed. Comparisons of different models in the adaptive heat balance approach were conducted using the ASHRAE databases I&II. Thermal comfort theory and approaches have been developed which underpin standards and guidelines in building and engineering system design, operation and evaluation though there are pros and cons of different methods. The heat balance approach features the detailed parameters of design criteria of indoor thermal environments. The adaptive regression-based approach played an important role in raising awareness of adaptive capacities and paved the way towards first implementations into standardization. The adaptive heat balance approach combines the heat balance and the adaptive regression approaches and leads towards future improvements in adaptive comfort modelling. It demonstrates very good performance and its inclusive approach offers potential for further breakthroughs in reducing the limitations of the existing methods.

Keywords: Thermal comfort; Comfort theory; PMV; Adaptive thermal comfort; Performance criteria; Literature survey

1. Introduction

Thermal comfort is fundamental to indoor environmental design and operation as well as indoor thermal environment evaluation. According to the ISO standard 7730 definition [1], thermal comfort is the "*condition of mind which expresses satisfaction with the thermal environment*". Two types of thermal comfort approaches have been intensively studied and debated by researchers over the past decades. The Predicted Mean Vote (PMV) and Percentage People Dissatisfied (PPD) indices developed by Fanger [2] are used worldwide to predict and assess indoor thermal comfort in buildings. The indices are based on laboratory studies and underpinned by the theory of heat balance between the human body and metabolic heat production reflecting human responses to the thermal environment in terms of the physics and physiology of heat transfer. The steady-state heat balance model indicates that thermal sensation is closely related to the thermal load on the effect mechanisms of the human thermoregulatory system. This approach is robust as it enables HVAC engineers to design an indoor environment by determining indoor thermal design parameters including air temperature, humidity and air speed for heating and cooling load calculation as well as radiant temperature for the design of radiant heating and cooling systems.

Driven by the need to tackle the energy crisis and findings from field studies showing deviations in thermal perception from prediction, the adaptive thermal comfort concept made a tremendous contribution to thermal comfort research. The classic adaptive thermal comfort model is based on field studies and aims to explain discrepancies between the predicted thermal sensation using PMV-PPD indices and the actual thermal sensation in free-running indoor climates by considering additional human adaptive factors. The classic adaptive approach is mainly regression models establishing the indoor thermal comfort temperature as a function of outdoor air temperatures. Since 1978 several empirical equations (regression models) for indoor thermal comfort temperature have been developed in the context of different building types and climate conditions [3]. This classic adaptive approach has significantly contributed to the understanding of human adaptive capacity and is very much beneficial to the development of low-energy buildings.

Both classic heat balance and regression-based adaptive approaches became foundations for global thermal comfort standards and guidance, such as ISO 7730 [1], ASHRAE 55 [4], EN 15251 (now EN 16798 [5]) [6], and CIBSE Guide A [7]. These standards and guidance define the PMV-PPD indices as the principle of determining thermal environments of buildings with space cooling or heating, while suggesting the use of the adaptive regression-based approach in naturally ventilated buildings. There exists a long-time debate of the two distinct approaches. de Dear stated *the adaptive and heat balance approaches to modelling thermal comfort are complementary rather than contradictory. At some level, the static heat balance model can be considered as being partially adaptive in the behavioural sense since it accounts for clothing, activity level and indoor climatic parameters which can be adjusted by the occupants* [8]. Several researchers attempted to bridge the gap between the heat balance approach and the adaptive regression-based approach, which include the nPMV model [9], ePMV model [10], aPMV model [11], and ATHB model [12]. There is a great need to carry out an in-depth study to understand the features of these developed models and identify the pros and cons of their implementations in real practice.

The aim of this paper is to provide an overview of the development progress of thermal comfort research and focused views on adaptive thermal comfort models through a comprehensive literature review and quantitative analysis.

The structure of this paper is as follows: Section 2 conducts a preliminary investigation into the overview of adaptive thermal comfort research. Sections 3 and 4 describe the historic development of the heat balance approach and the adaptive regression-based approach, respectively. Section 5 reviews the adaptive heat balance approach developed in recent years. Section 6 introduces how these thermal comfort models are incorporated into national and international standards. Section 7 compares the predictive performance of traditional and newly developed thermal comfort models. Discussion and conclusions are presented in Section 8 and Section 9.

2. Bibliometric view of adaptive approaches

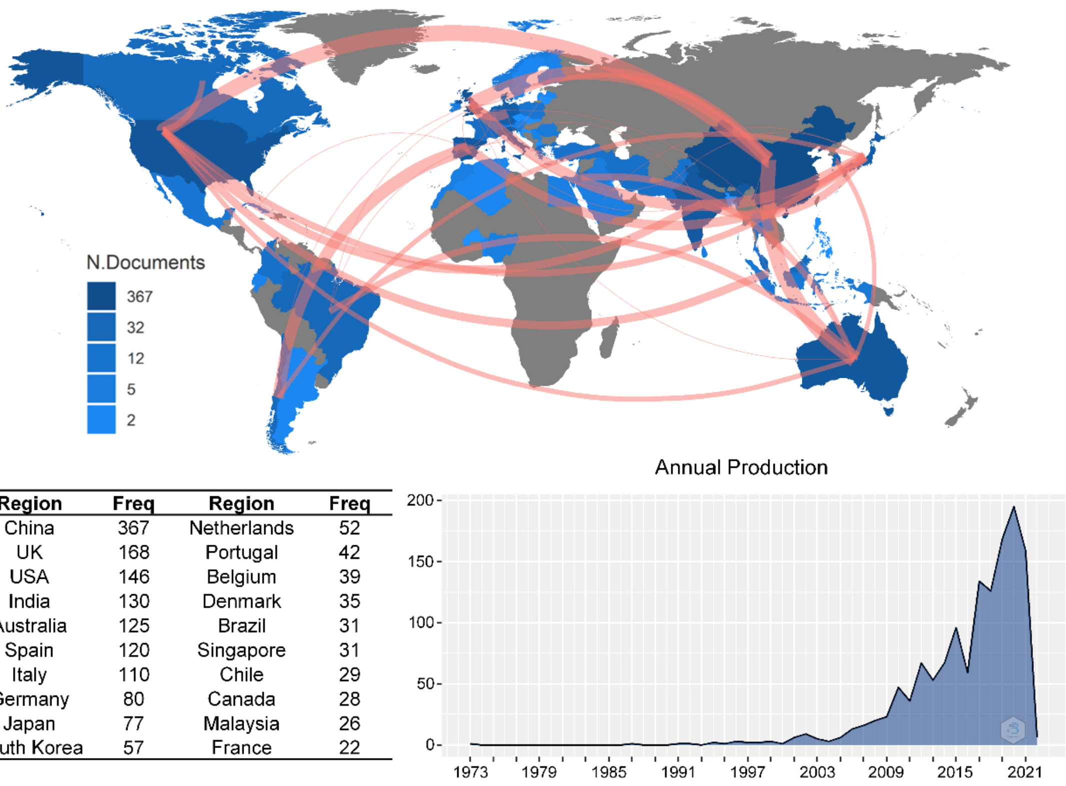
2.1 Data selection

In the selection process, we searched two A&I (abstract and index) databases, Web of Science and Scopus, because they cover most publications in science fields [13]. The search was conducted in the title, keywords, and abstract with the terms "*adaptive*" AND "*thermal comfort*" AND "*model*" AND NOT "*urban*" AND NOT "*street*" AND NOT "*material*" AND NOT "*sleep*" to better exclude distractions from urban climate or street, phrase change material, and sleep conditions. The Web of Science and Scopus returned 892 and 738 results, respectively. After removing the duplicates, 1333 documents were left in the database for further evaluation and analysis as shown in **Table 1**.

Table 1. Key information about collected publications (Search date: Nov 22, 2021)

Period	Timespan	Sources (Journals, Books, etc.)	Documents	References	Author's Keywords	Authors
Early Stage	Before 2010	58	166	3980	223	307
Recent Stage	2011-2022	255	1167	34052	1592	2188
Increase Rate	-	340%	603%	756%	614%	613%

Fig. 1 visualizes the scientific production and international collaboration on a map. It is obvious that the USA, UK, Australia, and China are major centers that generate numerous collaborations with other countries all over the world. The most significant collaborations exist between China-Australia, China-USA, and China-UK (thicker red lines).



Region	Freq	Region	Freq
China	367	Netherlands	52
UK	168	Portugal	42
USA	146	Belgium	39
India	130	Denmark	35
Australia	125	Brazil	31
Spain	120	Singapore	31
Italy	110	Chile	29
Germany	80	Canada	28
Japan	77	Malaysia	26
South Korea	57	France	22

Fig. 1. Scientific production and international collaboration map (Intensity of blue color: number of publications; thickness of red line: number of collaborative publications)

2.2 Bibliometric analysis of adaptive approaches for thermal comfort

The overwhelming volume of new information, scientific publications, conceptual developments and data has brought challenges for accumulating knowledge and collecting evidence through previous research papers [14]. For example, the search for "*thermal comfort*" in Google Scholar will return over 810,000 results. Therefore, this paper used bibliometric tool R package *bibliometrix* v3.1 developed by Aria and Cuccurullo [15] to present the "*big picture*" of how 1333 documents in the previous section reveal the causes of adaptive thermal comfort model evolutionary movements, for instance, the impact due to economic, social activities and green and sustainability movement. Specifically, the Louvain method [16] was used as the clustering algorithm in the co-occurrence network, which measures the density of links within communities and between communities. Thematic analysis [17] was employed to evaluate theme movements over time based on the co-occurrence frequency of relevant keywords in the bibliographic collection. The higher the frequency of co-occurrence of two keywords, the closer their relationship is.

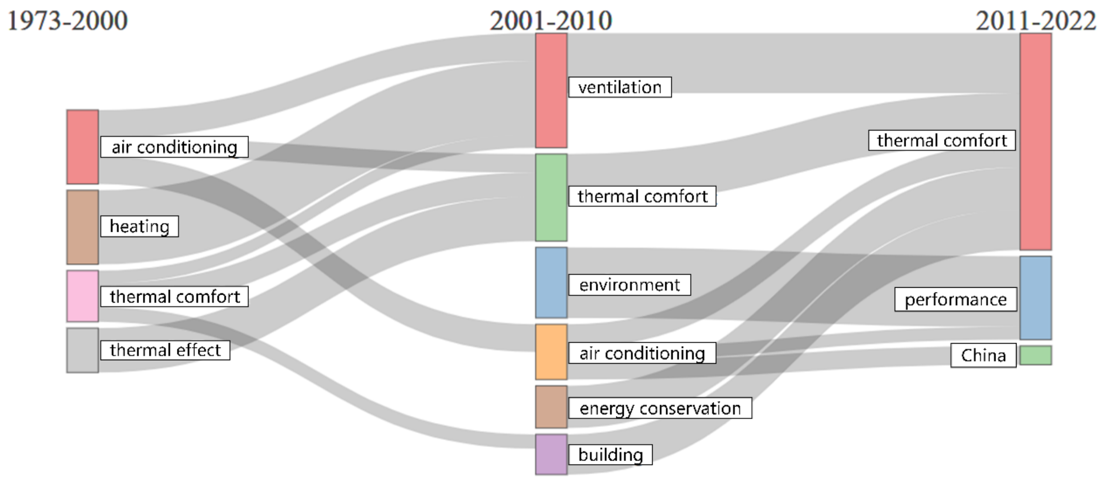


Fig. 2. Thematic evolution of adaptive thermal comfort across three time slices

Fig. 2 presents the clustering results of the bibliometric analysis across three time slices (1973-2000, 2001-2010, and 2011-2022) in *Sankey diagram* to show how various themes were connected and developed through each time slice using the *weighted inclusion index* [17]. The corresponding information about each cluster in **Fig.2** can be found in **Table 2**, which takes into account the occurrences per time slice of each keyword appearing in a theme [18]. From period 1973-2000 to period 2001-2010, the relevant keywords generated by Louvain method are relatively simple and few. However, the migration of each cluster from 2001-2010 to 2011-2022 contains concepts from other disciplines and exhibits more specific methods for better modelling adaptive thermal comfort, such as climate change/model, architectural design, energy-saving, thermal performance, personal control, occupant behaviors, etc. This implies that in recent years, economic and social activities and green building/sustainability/energy efficiency movements have played a greater role in the field of adaptive thermal comfort. The adaptive thermal comfort concept itself was developing into a more mature stage.

Bibliometrics analysis, on the other hand, only processes the authors, abstracts, keywords, citations, and other information in publications using mathematical and statistical models run by computers, with no in-depth human analysis of the full text. As a result, some undesirable outputs may be produced. To strengthen this review, the following sections will go over the specifics of relevant publications, with a focus on the evolution of adaptive thermal comfort models.

Table 2. Thematic evolution of adaptive thermal comfort publications

From cluster—time period	**To cluster—time period**	**Keywords plus**[a]	**Weighted Inclusion Index**[b]
Air conditioning--1973-2000	Air conditioning--2001-2010	Air conditioning	0.38
Air conditioning--1973-2000	Thermal comfort--2001-2010	Computer simulation	0.25
Air conditioning--1973-2000	Ventilation--2001-2010	**Ventilation**	0.38
Heating--1973-2000	Ventilation--2001-2010	Heating	1
Thermal comfort--1973-2000	Air conditioning--2001-2010	Standard	0.1
Thermal comfort--1973-2000	Building--2001-2010	Building; climatology	0.19
Thermal comfort--1973-2000	Environment--2001-2010	Climate	0.04
Thermal comfort--1973-2000	Thermal comfort--2001-2010	Thermal comfort; mathematical model; climate control	0.33
Thermal comfort--1973-2000	Ventilation--2001-2010	**Adaptive model**; atmospheric temperature; survey	0.17
Thermal effect--1973-2000	Thermal comfort--2001-2010	Thermal effect	0.6
Air conditioning--2001-2010	China--2011-2022	Standard; human; humidity; article; male; physiology; thermoregulation	0.25
Air conditioning--2001-2010	Performance--2011-2022	**Adaptation**; sensation; methodology; microclimate; **personal control**; school; air movement; heat	0.17
Air conditioning--2001-2010	Thermal comfort--2011-2022	Air conditioning; field survey; papaya mosaic virus; housing; air; **adaptive behaviour**	0.32
Building--2001-2010	China--2011-2022	**China**	0.03
Building--2001-2010	Performance--2011-2022	Indoor climate; genetic algorithm	0.04
Building--2001-2010	Thermal comfort--2011-2022	Building; indoor air; air temperature; energy use; modeling; temperature effect; indoor environment; cooling; **clothing insulation**; cooling system; **thermal insulation**; **architectural design**; **India**; numerical model; space heating; **thermal adaptation**	0.54
Energy conservation--2001-2010	Thermal comfort--2011-2022	**Energy conservation**; **adaptive comfort model**; **occupant behaviours**; **adaptive comfort**; air quality; indoor air pollution; indoor air quality; residential building; regression analysis	0.57

Environment--2001-2010	Performance--2011-2022	Environment; climate; model; energy; temperature; standards; comfort; performance; design; simulation; buildings; PMV; hot; index; **thermal performance**; climate-change; energy-consumption; impact; field; perception; productivity; quality; urban; vegetation; air-conditioned buildings; city; classrooms; residential buildings; air-temperature; areas; coatings	0.95
Thermal comfort--2001-2010	Performance--2011-2022	Optimization; health; built environment	0.04
Thermal comfort--2001-2010	Thermal comfort--2011-2022	Thermal comfort; **adaptive thermal comfort**; office building; **energy utilization**; **adaptive control system**; computer simulation; climate change; building simulation; **energy efficiency**; neural network; structural design; artificial neural network; **energy saving**; **adaptive control**; algorithm; human thermal comfort; **adaptive modeling**; building performance; energy consumption; energy management; forecasting	0.68
Ventilation--2001-2010	Performance--2011-2022	Europe	0.01
Ventilation--2001-2010	Thermal comfort--2011-2022	**Ventilation**; **adaptive model**; **natural ventilation**; field study; comfort temperature; survey; thermal sensation; thermal environment; heating; atmospheric temperature; climate model; indoor thermal comfort; predicted mean vote; naturally ventilated building; **behavioural research**; neutral temperature; school building; indoor air temperature; **sustainable development**; adaptive approach; air-conditioned building; **ASHRAE standard**; **building code**	0.81

Keywords plus[a]: during the evolution period, migrated from one cluster to another;

Weighted inclusion index[b]: based on the frequency of keyword plus presented in the new cluster, the percentage of keyword plus migrated from one cluster to another [17].

3. Classic steady-state heat balance models

3.1 Brief review before 1970

The first single temperature index that can predict one's comfort and discomfort was the effective temperature (ET), developed by Houghten and Yaglou (1923) [19] at the ASHVE Pittsburgh research laboratories. It is represented by a set of equal comfort lines on a psychrometric chart which combines the effects of dry bulb temperature and humidity at still air conditions. To include the effects of radiant heat and air movement, Vernon (1932) [20] modified the ET index by substituting globe temperature and air velocity measured by a black globe and a hot kata-thermometer. This corrected effective temperature was further developed by Bedford (1946) [21] into a CET nomogram which is a psychrometric chart including ET/CET values.

Developed by Belding and Hatch (1955) [22], the heat stress index (HSI) is defined as the ratio of evaporative heat loss required to maintain the body temperature, to the maximum evaporative capacity of the climate. Lee and Henschel (1963) [23] pointed out that the original HSI was based on the reactions of nude subjects and ignored the effects of clothing in quantitative expressions. They also found that although the HSI explicitly explained the physiological effects of stress and heat gain on living systems, it paid less attention to the concept of "*strain*" which is considered as the changes of living systems resulting from that stress. Therefore, they modified the original HSI into the relative strain index (RSI) with further consideration of radiative temperature and clothing insulation.

More detailed reviews about similar indices before the 1970s can be found in [24][25]. These conventional indices all try to connect physical environments to the human physiological response in a quantitative way, but they are mostly restricted to finding values in a psychrometric chart or suffered from limited combinations of input parameters, thus bringing obstacles for generalizing.

3.2 SET index

Developed by Houghton and Yaglou for ASHVE in 1923, the first single temperature scale ET (effective temperature) has been widely used until 1967 as a psychophysical temperature scale [19] [26]. However, Yaglou [27] found that the ET index could overestimate the effect of humidity in lower temperature environments. Minard [28] also recognized that web bulb temperature was a better predictor of heat tolerance. Gagge [29] claimed that the original ET index was derived from the subjects with a clothing level at 1 clo, which was higher than modern everyday clothing. To resolve the above shortcomings, Gagge in 1971 proposed a new effective temperature (ET*) under the condition of "*clothing: 0.6 clo, metabolic rate: 1 met, air movement <= 0.2 m/s, exposure time: 1 hour*" with the definition of "*the hypothetical dry bulb temperature of an isothermal environment at 50% RH in which a human subject would have the same skin wettedness (w) and heat exchange (H_{sk}) at the skin surface as in the actual test environment*" [29].

As the ET* index depends on certain combinations of clothing and activity level, it is impossible to draw a universal ET* chart. To better overcome this shortcoming, Gagge [30] developed the index into SET* that added the supplement of "*standardized for activity concerned*" to the original ET* definition. The SET* index predicts the physiological response of the human body like vasoconstriction and vasodilation of a skin layer, and sweat secretion for evaporative cooling by means of evaluating skin temperature, skin wettedness, and blood flow rate [30]. More detailed descriptions of ET* and SET* indices can be found in [29] and [30]. Gagge [31] later directly related the SET* index to the magnitude of discomfort and discovered a clear linear relationship, indicating the possibility of linking SET* index to thermal sensation. The ASHRAE Standard 55-2010 [32] reintroduced the SET* index (ASHRAE 55 refers it as SET model) as a calculation basis for determining the cooling effect of elevated airspeeds (0.15 to 3 m/s) on compensating hot sensations in warm environments. This is mainly because the SET* index provides quantitative considerations on the physiological response of the human body from air movement, such as evaporative cooling of sweat.

3.3 PMV index

Developed by Fanger in 1970, the PMV index considers the physical and physiological parameters and treats human thermal comfort as a consequence of the heat balance between the human body and the surrounding environment. In his approach, thermal neutrality is the most desirable state when heat generated inside the human body equals the heat dissipated to the environment [2]. Its mathematical expression has been described in standard ISO 7730 [1] and ASHRAE 55 [33], and the output is a value between -3 to +3 representing thermal sensations from cold to hot.

The PMV index has been challenged over the last two decades as the deviation of the prediction accuracy in a so-called 'real environment' observed in field studies [12] [34]. The interpretation of the discrepancies varies from case to case. These included the unavailability of accurate values of input parameters [35]; misapplication in individuals or a small group [36]; limitations of extending its application to different groups of people [2]; neglect of adaptive elements such as behavior, expectation, culture, climates [37] and so on.

4 Adaptive regression models

To a certain extent, the PMV index can provide theoretical explanations of physical and physiological interaction with human thermal perception. But in real environments, pure steady-state conditions are rarely encountered due to the thermal interaction between the building structure, occupancy, climate, HVAC operation and people's changing activity levels [38]. It is also argued that the complicated PMV index in practice often predict worse than simple indices, such as temperature alone [9]. To overcome the above-described shortcomings, the concept of the adaptive regression model was proposed to treat occupants as active participants to maintain thermal preferences instead of being passive recipients of thermal environments [37].

4.1 Adaptive concept

The fundamental assumption of the adaptive principle is "*if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort*" [39]. This principle can be further distinguished into three categories [37]: behavioral, physiological and psychological.

(1) The **behavioral** adaptation can be easily observed in daily life which can be sub-classified into personal (e.g., changing clothes), technical (e.g., turn on/off a fan or air conditioner), and cultural responses (e.g., having a siesta). For clothing adjustment of occupants, ISO 7730 [1] recommend the value of 0.5 clo and 1 clo in summer and winter, respectively. Liu [40] even discovered that residents in China's hot summer and cold winter regions could actively restore thermal comfort by adjusting their clothing levels to 0.26 clo in summer and 1.3 clo in winter, which are wider ranges than the standard recommendation. Schiavon and Lee [41] and Schweiker and Wagner [12] also presented more dynamic models of clothing adaptation using outdoor temperature as the independent variable.

(2) The **physiological** adaptation regards the thermal regulation of the human body. It is believed that the human thermal regulation system behaves in a highly non-linear manner and contains multiple sensors, outputs, and feedback loops [42]. The adaptation of this category can be divided into genetic adaptation (from generation to generation) and physiological accommodation (within one generation) [37]. The specific physiological accommodations include instant reactions of the body to the actual thermal condition, such as vasoconstriction and vasodilation to regulate blood flow in moderate conditions, and sweating and shivering in extreme hot and cold sides [43]. Current studies on this topic usually focus on exposing human subjects to artificially controlled climate chambers instead of real environments [44].

(3) The **psychological** adaptation is related to past experience and expectations, which is the least researched among the three adaptive mechanisms. The human mind has a thermal memory of environments across many timescales – seconds, minutes, hours, days and years [45]. For example, even under similar indoor environments, the neutral temperature of people in autumn is usually higher than

that in spring because of previous hot and cold thermal experiences in summer and winter [46]. The opportunity of indoor climate control also plays a positive role in lowering people's thermal expectations and broadening the comfort zone [37].

4.2 Historical development of the classic adaptive regression model

In 1964, Webb set up the adaptive thinking that a linear regression equation could explain people's migratory thermal sensations in different cities by studying subjects from Baghdad, Roorkee and Singapore [47]. Later in 1973, Nicol and Humphreys [48] proposed a theoretical framework for a self-regulation system to explain the adaptive mechanisms of how occupants adjust clothing, metabolic rate and the thermal environment itself, which focuses more on active reaction instead of the physiological response of the human body. In 1978, Humphreys firstly set out the regression-based adaptive relation derived from a meta-analysis using over 30 field surveys between 1930 and 1975 with more than 200,000 records to quantitively promote the adaptive principle [49]. He found a significant difference in occupants' thermal neutrality in free-running and heated-or-cooled buildings. The relationship between indoor preferred temperature and monthly mean outdoor temperature was found to be linear in free-running buildings while curvilinear in heated-or-cooled buildings [3].

Given the fact that occupants prefer variations in indoor conditions when outdoor temperature changes, the "*adaptive model*" was later established to connect this relationship by developing a linear regression expressing the relationship of comfort temperature T_{comf} and outdoor reference temperature T_{out} [50]. The comfort temperature is usually determined by the Griffiths method [51] when the sample size is small.

The Griffiths method fully employed the survey data outside the thermal neutrality by approaching these temperature values with the help of occupants' thermal sensitivity (G value). For instance, when G is 0.5 $°C^{-1}$, and one occupant vote "*slightly warm*" (+1 in 7 vote scale) when the indoor temperature is 28 °C, the specific comfort temperature for this person at that moment is assumed to be 26 °C. McCartney and Nicol [52] established the adaptive regression model in smart controls and thermal comfort (SCATs) project for European thermal comfort standards. However, Rupp *et al*. [53] recently questioned whether the G value should always be taken as a constant. After analyzing over 11,500 data covering various building types and climate zones, they found the G value could differ from 0.174 to 0.568 $°C^{-1}$ and suggested that "*sensitivity is actually a variable, not a constant*".

The original outdoor temperature T_{out} suggested by Humphreys [3] was monthly mean outdoor temperature in the 1970s, but meteorological data on a month scale will inevitably neglect the active adaptation of occupants within a week, or even within one day. Humphreys *et al*. [54] later created the "*running mean temperature*" for T_{out} which calculates a weighted-mean from the last day and the previous days with decreasing weighing factors to emphasize more on recent days. ASHRAE 55 standard uses "*prevailing mean outdoor air temperature*" as T_{out} for its adaptive regression in the 2013 version [4] instead of monthly mean outdoor temperature in its 2010 version [32] ; which is similar to the concept of running mean temperature.

4.3 Application worldwide

Since the publication of the adaptive principles, researchers worldwide have adopted this method to develop specific linear expressions, as shown in Appendix A, which covered different countries, climates, building types and occupants, such as for Pakistan [55] [56], Iran [57], China [58] [59] [60] [61] [62] [63], Tunisia [64], Japan [65] [66], India [67] [68] [69], Spain [70], Australia [71] [72], Qatar [73], Brazil [74], the UK [75], Colombia [76], Mexico [77]; mixed-mode buildings [78] [79], hospitals [80], shelters [81], dormitories [82], prefab construction site offices (PCSO) [83], workshops [84]; children in primary schools [85], females [69], older residents [86], etc. These studies have promoted the spread and validity of the adaptive regression-based approach and have meanwhile further confirmed the fact that the heat balance approach faced serious bias in real practice where uniform and steady-state environments rarely happen, especially in non-HVAC buildings.

A summary of relevant adaptive regression models and their coefficients are shown in **Fig. 3** and **Fig. 4**. It is clear that most linear regression lines fall within the boundaries recommended in ASHRAE 55. The coefficient a (slope of adaptive regression model) of NV buildings is generally higher than MM and HVAC buildings, indicating that the NV mode can help people develop a wider comfort range. People in residential buildings also showed greater tolerance (higher value of coefficient a) to thermal environments compared with office environments, meaning that people have more freedom to adjust their clothing insulation level or fully take control of their surrounding environments at home. In general, researchers worldwide can hardly generate one consistent regression line, indicating that regression-based adaptive models are very sensitive to location, climate, and even specific buildings.

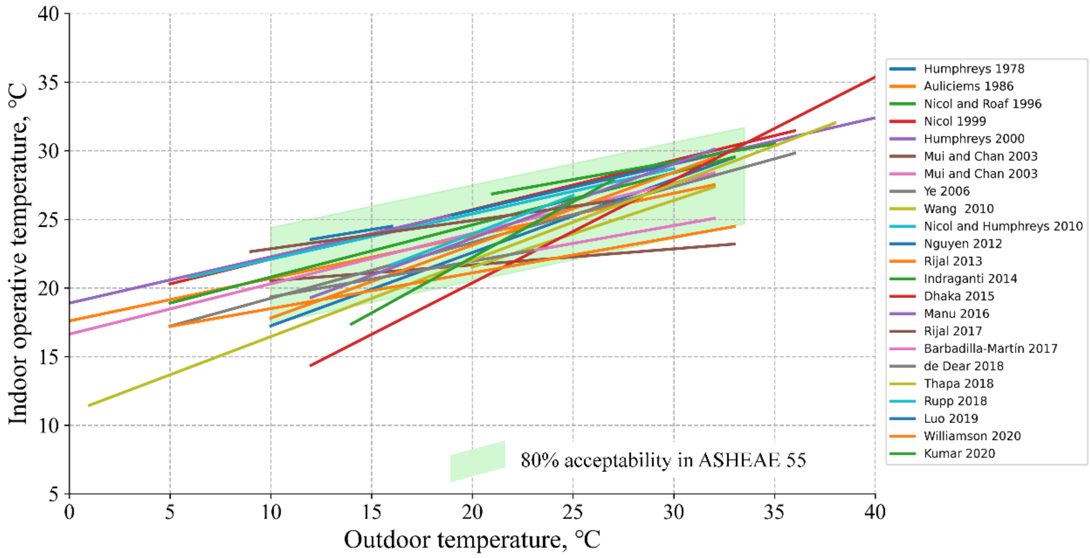
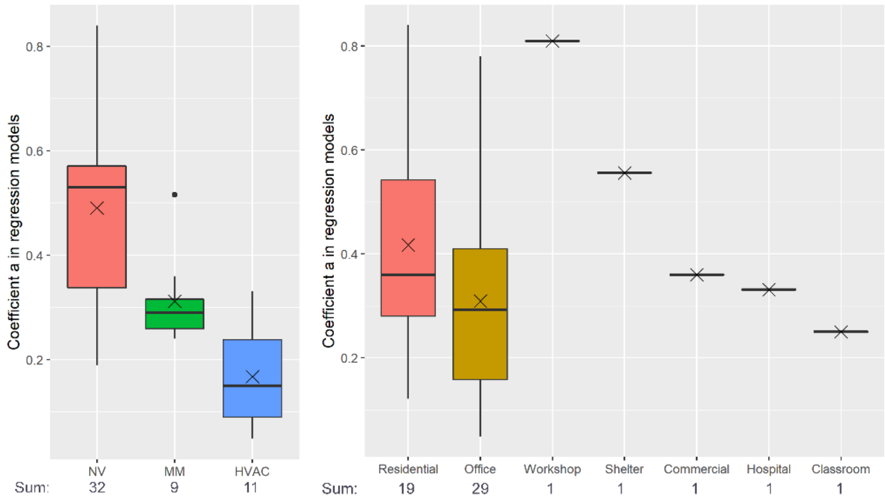


Fig. 3. Adaptive regression models built in different climates and countries



(a) Classified by operation mode (b) Classified by building type

Fig. 4. The coefficient a in adaptive regression models from studies worldwide (more details can be found in appendix A)

5. Adaptive heat balance models

Both laboratory-based classic heat balance model and field-study-based adaptive regression model have been well developed and accepted in thermal comfort standards and relevant research communities. They have their own pros and cons in real applications as mentioned above: the heat balance approach considers environmental and physiological parameters but pays insufficient attention to human adaptation in practice, whereas the adaptive regression approach only regards outdoor temperature as its sole input, providing less evidence for indoor environmental design. The adaptive heat balance approach, which emerged as the third type, aimed at bringing these two classic approaches together and filling the gap. **Fig. 5**. shows the development of this third approach.

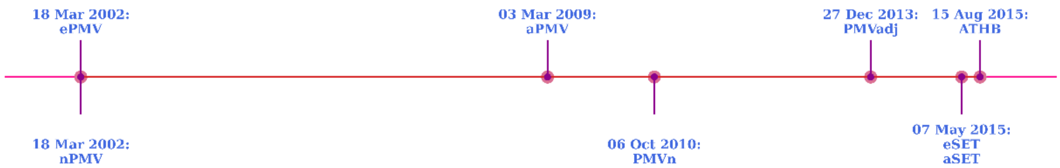


Fig. 5. Chronology of the adaptive heat balance approach

5.1 nPMV

Humphreys and Nicol [9] presented the nPMV model aimed at reducing the biases of using the original PMV index form in ISO 7730 to evaluate thermal comfort in order to avoid it being potentially "*seriously misleading*". This nPMV model added a regression equation (including calculations of operative temperature, relative humidity, metabolic rate, clothing, and outdoor air temperature) to the PMV index, and its validations based on 16762 samples from the RP-884 database revealed a significant reduction in predictive biases in both NV and HVAC buildings.

The calculation process of nPMV considered the outdoor air temperature which was not included in the original PMV index. The data used for generating the nPMV model were mainly from office buildings, so its verification in other types of buildings could further improve the applicability of the nPMV model.

5.2 ePMV

Fanger and Toftum [10] developed the ePMV model by introducing an expectancy factor "*e*" based on the popularity of air-conditioned buildings and duration of warm exposure in the local area meanwhile lowering the metabolic rate, the PMV's one physiological input, to improve the prediction accuracy for NV buildings in warm climates. This model was generated through 3200 observations from four cities (Bangkok, Brisbane, Athens and Singapore) in warm climates, and its prediction showed good agreement with observed values.

5.3 aPMV

In order to shrink the discrepancies of PMV predictions and actual thermal sensation of occupants in NV buildings, Yao *et al*. [11] applied the cybernetics concept to PMV index for better explaining the adaptive mechanism and proposed the aPMV model which incorporates physiological, psychological and behavioral adaptations using the adaptive coefficient λ.

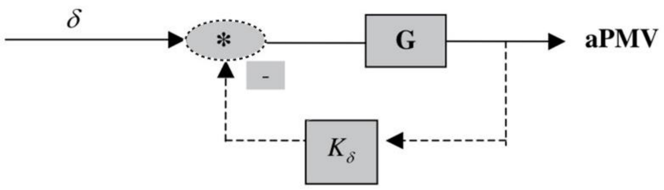


Fig. 6. Model diagram of aPMV [11]

The aPMV model assumes the physiological, psychological and behavioral adaptation of occupants as "*adaptive feedback*" to their thermal sensation, as K_δ is shown in **Fig. 6**. The G in **Fig. 6** represents the original process for calculating PMV, where the λ equals K_δ/G. The detailed deductive and solving process of coefficient λ in the aPMV model can be found in [11]. **Fig. 7** shows the relationship between PMV (x-axis) and aPMV (y-axis). When λ equals 0, aPMV is the same as the PMV index representing no adaptation, as shown by the blue line. When λ does not equal 0, the aPMV model will differ from the PMV index and can be able to fill the gap between predicted and actual thermal sensation in a non-steady environment. The positive λ value on the right side indicates the subjective adaptation in warm or hot environments (red and yellow lines); meanwhile, the negative λ value on the left represents the adaptation in cool or cold environments (purple and green lines). A higher absolute value of λ means larger effects of subjective adaptation. Therefore, these flexible λ values in the aPMV model can relax the deviation of the PMV index in the hot side (PMV>0) and cold side (PMV<0), and make it possible for the heat balance theory to be more appropriately applied in real practice instead of well-controlled environments.

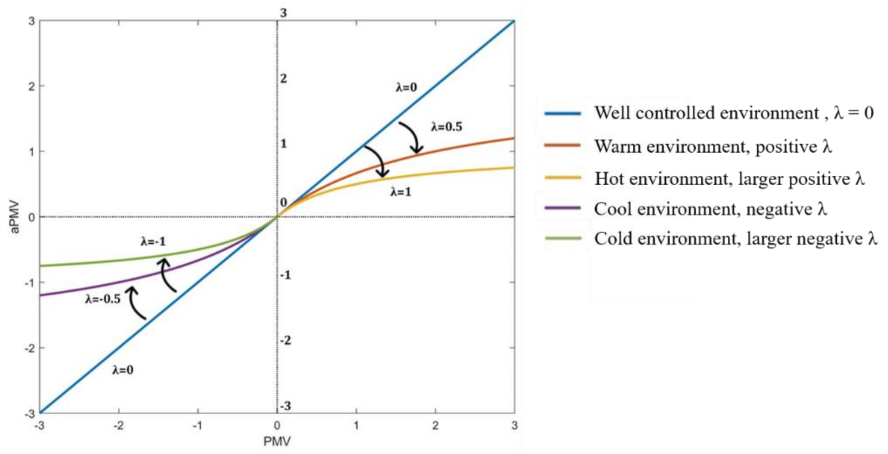


Fig. 7. Relationships between PMV and aPMV

Since the first publication of aPMV model in 2009, over 500 papers have cited it and around 50 papers have directly applied this method to evaluate indoor thermal environments. Good agreements of the aPMV prediction with actual observations have been found in [40], [87], [88]. **Table 3** and **Fig. 8** summarize the aPMV research with customized λ values carried out by different researchers worldwide, which have so far been highly dominated by Asians. In **Fig. 8**, the absolute values of negative λ are generally higher than positive λ, indicating the asymmetry of thermal sensations in cold and hot conditions, and people can adapt more in cold environments. This is in line with the findings from Yao *et al*. [89] who investigated thermal comfort in naturally ventilated classrooms and Li *et al*. [90] who analyzed the global ASHRAE database: the actual dissatisfaction rate in the cold side is lower than in the hot side which is contradictory to Fanger's symmetric PPD curve.

Table 3. Summary of aPMV research with customized coefficient λ

Building type	Source	Location	λ value	Main findings
Residential	Singh *et al*. 2011 [91]	Three Climatic zones, India	12 λ values ranged from -1.68 to 0.44	aPMV model with customized λ value can successfully explain the deviation between PMV and TSV in four seasons data.
	Ren *et al*. 2015 [92]	Turfan, China	-0.48, 0.62	Local residents had greater heat tolerance in hot environments than recommendations in China's standard.
	Song *et al*. 2015 [93]	Guangzhou, China	-0.37, -0.06, 0.64, 1.07	Residents in hot and humid climates showed greater tolerance to thermal environments than cold and dry environments.
	Yu *et al*. 2017 [87]	Tibetan, China	-0.34	Residents actively wore heavy clothes and drank butter-sweet tea to protect themselves from the cold in winter.
	Liu *et al*. 2017 [40]	Chonqqing, Chengdu, Wuhan, Nanjing, Hangzhou, Changsha, China,	-0.49, 0.21	Analysis from a larger sample survey (11,524 subjects) showed good consistency with China's standard.
	Cheng *et al*. 2018 [88]	Tibetan, China	-0.32	The observed neutral temperature of local residents in winter was about 5 °C lower than PMV predicted, and the aPMV model with customized λ presented more accurate predictions.

Office	Chen *et al.* 2020 [94]	Hanghzou, China	-1.38, 0.08	Local residents better tolerated cold environments compared with hot environments.
	Kim *et al.* 2015 [95]	Seoul, South Korea	-5.76, -1.40	The aPMV model showed good prediction performance only when PMV ranged from -1.5 to +1.5.
	Ming *et al.* 2020 [96]	Chongqing, China	-0.49, 0.21	The aPMV model presented close prediction values to TSV both in cooling and transition seasons.
Classroom	Wang *et al.* 2017 [97]	Shaanxi, Gansu, Qinghai, China	-0.42, 0.28; -0.52, 0.22; -0.53, 0.30	Students in field studies were less sensitive to temperature change than PMV predicted, and the aPMV model was more suitable for subjective thermal evaluation.
	Liu *et al.* 2019 [98]	Tianjin, China	0.25, 0.57	The aPMV model successfully predicted the thermal comfort of students in a cold climate while the ePMV model did not as its original modification focused on a warm climate.
Activity center in the university	Li *et al.* 2019 [99]	Beijing, China	-0.131, 0.064	The aPMV model with customized λ value can suitably predict thermal comfort when people remained in the "*motion state*" and "*stationary state*" in the activity center.
Cotton textile factory	Yang *et al.* 2015 [100]	Henan, China	-0.1187, 0.2189	Experienced workers in a hot and humid factory showed better tolerance to extreme thermal environments compared with new interns.
Bus terminal	Cardoso *et al.* 2018 [101]	Porto, Portugal	-1.02, 0.77	Passengers in a transient state did not require strict thermal environments.
Railway station	Liu *et al.* 2016 [102]	Cangzhou, Dezhou, China	0.40, 0.55	Increased waiting time for passengers could lead to a higher expectation of thermal environments.

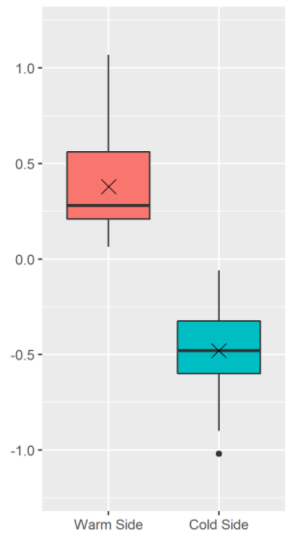


Fig. 8. Customized λ values of reviewed papers

5.4 PMVn

As the adaptive regression model did not consider humidity issues, Orosa and Oliveira [103] presented the PMVn model with the calculative process of adding partial vapor pressure to take advantage of both the PMV index and adaptive regression model. They verified the PMVn model in 25 Spanish office buildings in the summer and found its accuracy better compared with the original PMV index and adaptive regression model.

The PMVn model was designed to take advantage of both the PMV index and adaptive regression model. However, the key factor of the adaptive regression model, namely outdoor air temperature, was not employed. The requirements for using the PMVn model are also stringent, including a dry temperature of less than 25 °C, clothing insulation of around 0.5 clo, and valid PMVn output of between -0.4 and 0.8, which may limit its application to severe environments.

5.5 PMVadj

As the PMV index is suggested to be used when the air speed is below 0.2 m/s, for higher air speed the Elevated Air Speed (EAS) model can be used to maximize the acceptable operative temperature [33]. Schiavon *et al*. [104] proposed the PMVadj model to improve the accuracy of the original EAS model with better ways of utilizing the SET index. The PMVadj model was adopted in the 2013 version of ASHRAE 55 to evaluate the cooling effects of airspeed when it is greater than 0.2 m/s [4].

5.6 eSET and aSET

To better explain the mechanism of thermal adaptation, Gao *et al*. [105] introduced two factors to modify the SET index with processes similar to the ePMV and aPMV models. In their aSET model, the coefficient λ ranges from 0.029 to 0.167, which differs from the recommended λ value (0.21) for this climate region in China's thermal comfort standard when using the aPMV model for evaluation [106]. This could be caused by the lower adaptive level of the local people, as well as the differences in mechanisms and sensitivities between the original PMV and SET indices. Anyway, Gao's attempt reveals a potential way of fully utilizing the new heat balance approach alongside the PMV index.

5.7 $ATHB_{pmv}$ and $ATHB_{pts}$

Schweiker and Wagner [12] proposed the adaptive thermal heat balance model (ATHB) to explain the adaptive process by bridging the adaptive regression model and heat balance model with the help of modifying PMV's inputs. Their approach was based on theoretical thoughts from physiological, neurological and other theories together with results from scientific studies. They suggested modifying the clothing insulation level by means of incorporating outdoor air temperature to represent behavioral adaptation, whereas modifying the metabolic rate by combining the effects of outdoor air temperature, indoor air temperature and obtained perceived control level to represent physiological, variable psychological and constant psychological adaptations, respectively.

The ATHB model presents a highly original way to link the heat balance model to the outdoor climate by permitting the analysis of each of the three adaptive mechanisms individually. One remarkable update of the ATHB model is that it quantifies people's psychological adaptations based on the obtained perceived control level, and this concept was developed into the ATHB model using the coefficient PSYCH which is a conversion factor based on heart rate measurements. [12]. The PSYCH was "*related to the mean of obtained perceived control votes of a group of occupants*". When PSYCH is below zero, it means that occupants have fewer opportunities for psychological adaptation [107]. The PSYCH value in a four-person office is inferred as 0.071 in Schweiker and Wagner's work, and further mathematical descriptions of the ATHB model can be found in [12].

The model has been validated with a good performance, first against the PMV index and adaptive regression model on nearly 1,200 data points from Germany and around 13,000 data points from the ASHRAE RP-884 database [12], and then against PMV, SET, and other indices on nearly 3,100 questionnaires collected in several field studies in Karlsruhe and Stuttgart, Germany [107].

5.8 Summary of model features

Table 4 below summarizes the above seven adaptive heat balance models. All the models require the original inputs from the PMV index, whereas nPMV and ATHB, like the adaptive regression model, include outdoor air temperature as a new input. The ePMV, aPMV and eSET/aSET models attempt to quantify people's adaptive approach by introducing new factors "*e*" and "*λ*", while ATHB explains the adaptive approach by modifying two PMV inputs "*clo*" and "*met*" based on coefficients for individual adaptive mechanisms.

After searching for papers that cited the above seven models in Scopus and Web of Science, over two thousand non-overlapping documents were discovered. These documents demonstrate that papers citing nPMV and eSET/aSET tend to concentrate more on the adaptive approach, whereas papers citing aPMV and ATHB are particularly interested in the topic of sensation vote. The ePMV focused the research attention on the dynamic indoor environment and PMVn drew attention to seasonal field surveys. Because the ASHRAE 55 standard recommends PMVadj for evaluating the cooling effects of air movements, some papers related to PMVadj focus on developing actual software products, such as the CBE Thermal Comfort Tool developed by the University of California Berkeley [108], an educational tool for learning thermal comfort control [109], etc.

Table 4. Comparison of adaptive heat balance models

Model (released time)	**Required inputs**			**Considering SET**	**Adaptation approach**			**Considering three adaptive mechanisms individually**	**Method**	**Cited times**
	Inputs from PMV	**T_{out}**	**New factor**		**Behavioral**	**Physiological**	**Psychological**			
nPMV (2002) [9]	Y	Y							Statistical revision by outdoor air temperature	544
ePMV (2002) [10]	Y		Y				Y		Quantify thermal expectation	660
aPMV (2009) [11]	Y		Y		Y	Y	Y		Reveal feedback loop of thermal adaptation	554
PMVn (2011) [103]	Y								Statistical revision focusing on humidity	57
PMVadj (2014) [104]	Y			Y					Integrate SET to PMV to evaluate the cooling effect of air movement	76
eSET/aSET (2015) [105]	Y		Y	Y	Y	Y	Y		Replace PMV with SET in ePMV and aPMV	61
ATHB (2015) [12]	Y	Y		Y	Y	Y	Y	Y	Modify PMV inputs "*clo*" and "*met*"	96

Note: The citing information was derived from non-overlapping search results of two A&I databases Scopus and Web of Science on April 19, 2021.

6. Implementation in standards

6.1 PMV index

The PMV index has been widely used in national and international standards and guidance ASHRAE 55 [4], EN 15251 (new version EN 16798 [5]) [6], ISO 7730 [1], CIBSE Guide A [7] and GB/T 50785 [110] as shown in **Table 5**. The EN 15251 and ISO 7730 share similar acceptable ranges for PMV (±0.2, ±0.5 and ±0.7) and PPD (6%, 10% and 15%) for each category (I, II and III), EN 16798 [5] expanded category IV to include the range of ±1, while ASHRAE 55 and CIBSE Guide A recommend the category I of PMV-PPD indices with limits of ±0.5 and 10%, and this is the same level of categories II for EN 15251 and ISO 7730. The GB/T 50785 recommends two categories for using the PMV-PPD indices (category I is ±0.5 and category II is ±1.0), with category II presenting the highest PMV range among the listed standards and guidance, which is the same as category IV in EN 16798.

Table 5. Upper and lower limits of PMV-PPD indices in thermal comfort standards and guidance

Standard	PMV				PPD			
	Category I	**Category II**	**Category III**	**Category IV**	**Category I**	**Category II**	**Category III**	**Category IV**
ASHRAE 55	-0.5 ~ +0.5				< 10%			
EN 15251	-0.2 ~ +0.2	-0.5 ~ +0.5	-0.7 ~ +0.7		< 6%	< 10%	< 15%	
EN 16798	-0.2 ~ +0.2	-0.5 ~ +0.5	-0.7 ~ +0.7	-1.0 ~ +1.0	< 6%	< 10%	< 15%	<25%
ISO 7730	-0.2 ~ +0.2	-0.5 ~ +0.5	-0.7 ~ +0.7		< 6%	< 10%	< 15%	
CIBSE Guide A	-0.5 ~ +0.5				< 10%			
GB/T 50785	-0.5 ~ +0.5	-1.0 ~ +1.0			< 10%	< 25%		

6.2 Adaptive regression models

Thermal comfort standards [4] [6] [7] specify the adaptive regression model to evaluate indoor conditions of buildings without mechanical cooling or heating. Although the y-axis "*operative temperature*" in the adaptive regression model is calculated using air temperature, radiant temperature, and air velocity, the calculation process has been simplified according to *ASHRAE Handbook-Fundamentals* [111]. Several other important factors influencing thermal comfort, such as humidity, activity level, and clothing insulation are also considered under assumptions. This imaginary operative temperature lacks clear guidance in terms of indoor environmental parameter design without further detailed boundary conditions provided. This may impact the application of such a model in some regions. The comparisons of the lower and upper boundaries are listed in **Fig. 9** and **Table 6**, revealing the following:

- EN 15251 [6] permits the highest indoor operative temperature, some temperatures of category II and III are beyond 30 ℃. Its replacement version EN 16798 reduced the lower limits of all three categories I, II and III by 1°C, and the starting temperature of the lower limit was changed from 15°C to 10°C, encouraging a wider range of comfort zones for naturally ventilated buildings.
- ASHRAE 55 [4] generally allows lower temperature limits, its lower temperature limit for 80%

acceptability is equal to category III in EN 15251, while the upper temperature limit for 80% acceptability is similar to category I in EN 15251.

- The upper boundary of the input outdoor air temperature for the adaptive regression model in the UK CIBSE Guide A [7] is only about 25 ℃, which is lower than the recommended values of 30-35 ℃ in other standards. It could have been adjusted by features of local climate as the Guide states that "*in the UK the running mean outdoor temperature rarely exceeds 20 °C*".
- The gradients of adaptive regression models (0.77-0.91) in the Chinese standard GB/T 50785 [110] are much higher than the values in other standards (0.31-0.33). This reveals that the acceptable operative temperatures in free-running buildings are broader and more dependent on outdoor temperature, indicating that people in China have a higher tolerance to thermal environments.

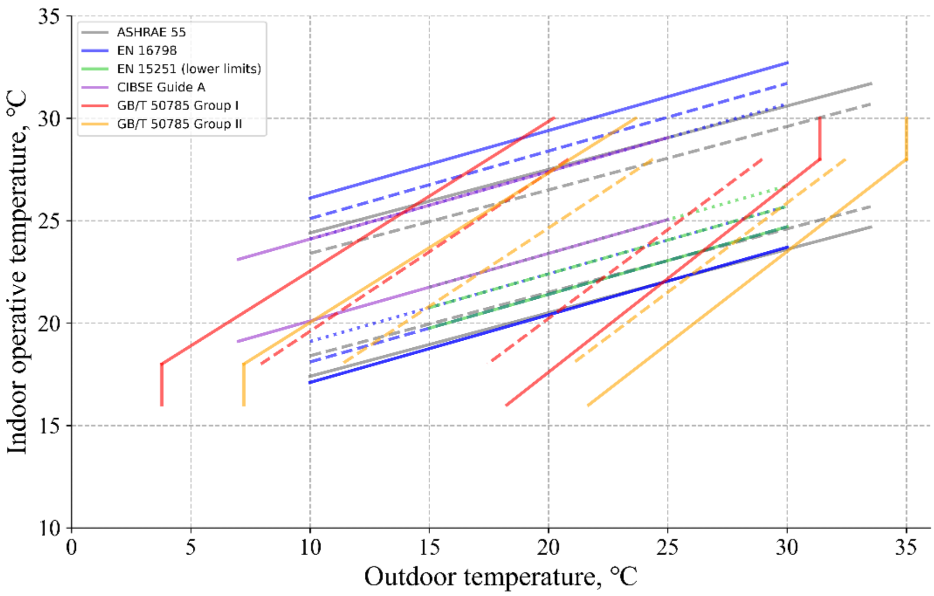


Fig. 9. Adaptive regression models for buildings without mechanical cooling or heating

Table 6. Conditions for the adaptive regression models in buildings without mechanical cooling or heating

Standard	**Category**	**T_{op} upper limit, °C**	**T_{op} lower limit, °C**	**Outdoor temperature range, °C**
ASHRAE 55	90% acceptability	$0.31 * \overline{t_{pma(out)}} + 20.3$	$0.31 * \overline{t_{pma(out)}} + 15.3$	10-33.5
	80% acceptability	$0.31 * \overline{t_{pma(out)}} + 21.3$	$0.31 * \overline{t_{pma(out)}} + 14.3$	10-33.5
EN 15251	I	$0.33 * \Theta_{rm} + 20.8$	$0.33 * \Theta_{rm} + 16.8$	10-30 upper, 15-30 lower
	II	$0.33 * \Theta_{rm} + 21.8$	$0.33 * \Theta_{rm} + 15.8$	10-30 upper, 15-30 lower
	III	$0.33 * \Theta_{rm} + 22.8$	$0.33 * \Theta_{rm} + 14.8$	10-30 upper, 15-30 lower
EN 16798	I	$0.33 * \Theta_{rm} + 20.8$	$0.33 * \Theta_{rm} + 15.8$	10-30 upper, 10-30 lower
	II	$0.33 * \Theta_{rm} + 21.8$	$0.33 * \Theta_{rm} + 14.8$	10-30 upper, 10-30 lower

	III	0.33 * Θ_{rm} + 22.8	0.33 * Θ_{rm} + 13.8	10-30 upper, 10-30 lower
CIBSE Guide A	-	0.33 * Θ_{rm} + 20.8	0.33 * Θ_{rm} + 16.8	7.5-25
Chinese GB/T 50785	Group 1[a]-I	0.77 * t_{rm} + 12	0.87 * t_{rm} + 2.8	7.8-29
	Group 1[a]-II	0.73 * t_{rm} + 15.2	0.91 * t_{rm} – 0.5	3.7-31.3
	Group 2[b]-I	0.77 * trm + 9.3	0.87 * t_{rm} – 0.3	11.3-32.5
	Group 2[b]-II	0.73 * t_{rm} + 12.7	0.91 * t_{rm} – 3.7	7.2-34.8

$\overline{t_{pma(out)}}$: the average of the mean daily outdoor temperatures over no fewer than seven and no more than 30 sequential days prior to the day in question.

Θ_{rm}: exponentially weighted running mean of the daily mean outdoor air temperature.

t_{rm}: exponentially weighted running mean of the daily mean outdoor air temperature during seven days prior to the day in question.
[a] Chinese climate group 1 with Severe Cold, and Cold zones.
[b] Chinese climate group 2 with Hot Summer and Cold Winter, Hot Summer and Warm Winter, and Mild zones.

6.3 Adaptive PMV model

The aPMV model has been stipulated in the current Chinese national standard GB/T 50785-2012 [110] for evaluating the thermal environments of buildings without mechanical cooling or heating. The recommended λ values and boundary limits of the aPMV model are shown in **Table 7** and **Table 8**.

Table 7. Values of λ for the five climate zones in different building types in the Chinese National Standard GB/T 50785-2012 [110]

Building climate zone		**Residential buildings, shops, hotels, and offices**	**Education buildings**
SC and cold zones	*PMV*≥0	0.24	0.21
	PMV＜0	-0.50	-0.29
HSCW, HSWW, and mild zones	*PMV*≥0	0.21	0.17
	PMV＜0	-0.49	-0.28

SC: Sever Cold; HSCW: Hot Summer and Cold Winter; HSWW: Hot Summer and Warm Winter.

Table 8. Grade of thermal environment in buildings without mechanical cooling or heating [110]

Grade	**aPMV**
I	-0.5≤aPMV≤0.5
II	-1≤aPMV<-0.5, or 0.5<aPMV≤1
III	aPMV<-1, or aPMV>1

6.4 Comparison of three approaches in standards

To evaluate the thermal environment of HVAC buildings, all international and national standards employ the calculation method based on the PMV index. For buildings without mechanical cooling or heating, most standards use the graphic method for evaluation based on linear regression, with an exception of GB/T 50785 [110], which provides both a calculation method (aPMV model) and a graphic method (regression-based), as shown in **Table 9**.

Table 9. Comparison between three approaches in standards and guidance

	Heat balance approach	**Adaptive regression-based approach**	**The adaptive heat balance approach**
Model name	PMV	Adaptive regression model	aPMV
Evaluation method	Calculation	Graphic	Calculation
Application context	HVAC buildings	Buildings without mechanical cooling or heating	Buildings without mechanical cooling or heating

Embedded standards	ASHRAE 55 [4], EN 15251 [6], ISO 7730 [1], CIBSE Guide A [7], GB/T 50785 [110]	ASHRAE 55 [4], EN 15251 [6], ISO 7730 [1], CIBSE Guide A [7], GB/T 50785 [110]	GB/T 50785 [110]
Inputs	T_{air}, $T_{radiant}$, RH, v_{air}, clo, met,	Various, generally T_{rm}	T_{air}, $T_{radiant}$, RH, v_{air}, clo, met, λ
Outputs	PMV	$T_{neutral}$ or T_{op}	aPMV
Theoretical basis	Heat balance of human body	Adaptive approach	Heat balance of human body, adaptive approach, adaptive feedback
Empirical basis	Lab studies	Field studies	Field and lab studies
Adaptive mechanisms considered	None	Physiological, behavioral, psychological	Physiological, behavioral, psychological
Modelling of adaptive mechanisms	Not applicable	Lumped	Individual

7. Comparisons of thermal comfort models

Despite the fact that previous adaptive PMV models have been published for years, their predictive performances have not been systematically compared together except by Schweiker and Wagner who compared these models earlier on based on German data and the ASHRAE database I [107]. Therefore, this section employs an open-access database to compare previous thermal comfort models: PMV, PTS (linear transformation of SET), PMVadj, aPMV, aPTS, ePMV, $ATHB_{pmv}$ and $ATHB_{pts}$.

7.1 Data preparation

This paper used the ASHRAE Global database as the uniform data resource to show the differences in the predictive results for different thermal comfort models. The ASHRAE Global Thermal Comfort Database I was established by de Dear in 1998 through project RP-884 to examine adaptive comfort theory and propose a variable temperature model [37]. This database provided data support for determining an acceptable operative temperature range in naturally ventilated buildings [33].

Later in 2014, the ASHRAE Database II project was launched under the leadership of the University of California at Berkeley's Center for the Built Environment and the University of Sydney's Indoor Environmental Quality (IEQ) Laboratory. This project systematically collected and harmonized raw data from thermal comfort field studies worldwide during the last two decades since the establishment of the ASHRAE Database I [112]. Both ASHRAE Databases I and II are now available online (http://www.comfortdatabase.com and https://datadryad.org/stash/dataset/doi:10.6078/D1F671 [112]) for users to download and conduct specific analyses.

This section employs data from ASHRAE Databases I and II to compare the results of thermal comfort models in previous sections. Due to the required input parameters for the models in this analysis, any data that do not simultaneously contain thermal sensation, air temperature, mean radiant temperature, relative humidity, air velocity, metabolic rate, clothing level, and outdoor air temperature have been removed. For data lacking radiant temperature but having both globe and air temperatures, the conversion method suggested in ISO 7726 [113] was used to calculate values of mean radiant temperature. Consequently, for this exemplary comparative analysis, data from six countries in three representative climates has been selected: hot semi-arid (India), humid subtropical (Australia and China), and temperate oceanic (Australia, France, Sweden and UK). A total of 9,662 original data points is available from the ASHRAE database. In order to assure the quality of the data selected for the comparative analysis of models, the Boxplot Outlier Rule [114], which has been proven a good method of data screening [115], has been applied and 1,825 data outliers discarded. The final sample size for analysis was 7,837 with details shown in **Table 10**, **Table 11**, and **Fig. 10**.

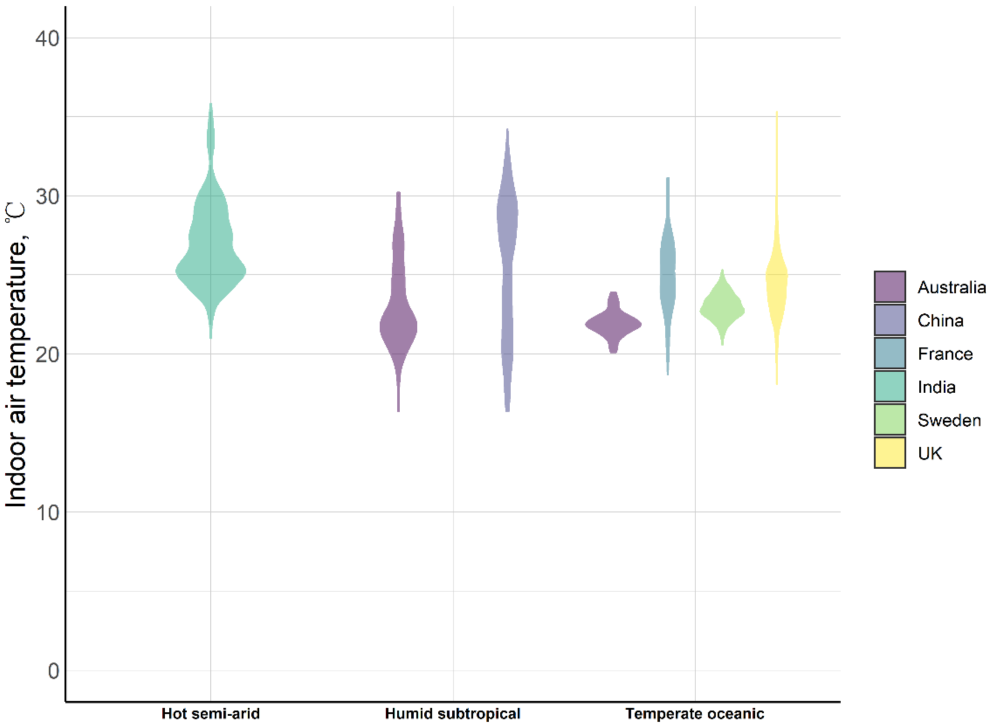
Table 10. Sample size of selected data from ASHRAE database

Koeppen-Geiger classification	Country	City	Total sum	Air conditioning	Natural ventilation	Mixed mode
Hot semi-arid	India	Ahmedabad Hyderabad	4169	133	324	3712
Humid subtropical	Australia	Wollongong	365			365
Temperate oceanic	China	Guangzhou Yueyang	1873		810	1063
	Australia	Goulburn	49			49
	France	Lyon	200	11	125	64
	Sweden	Gothenburg Halmstad Malmo	470	409		61
	UK	London	711	267	285	159
total			7837	820 (10.46%)	1544 (19.7%)	5473 (69.84%)

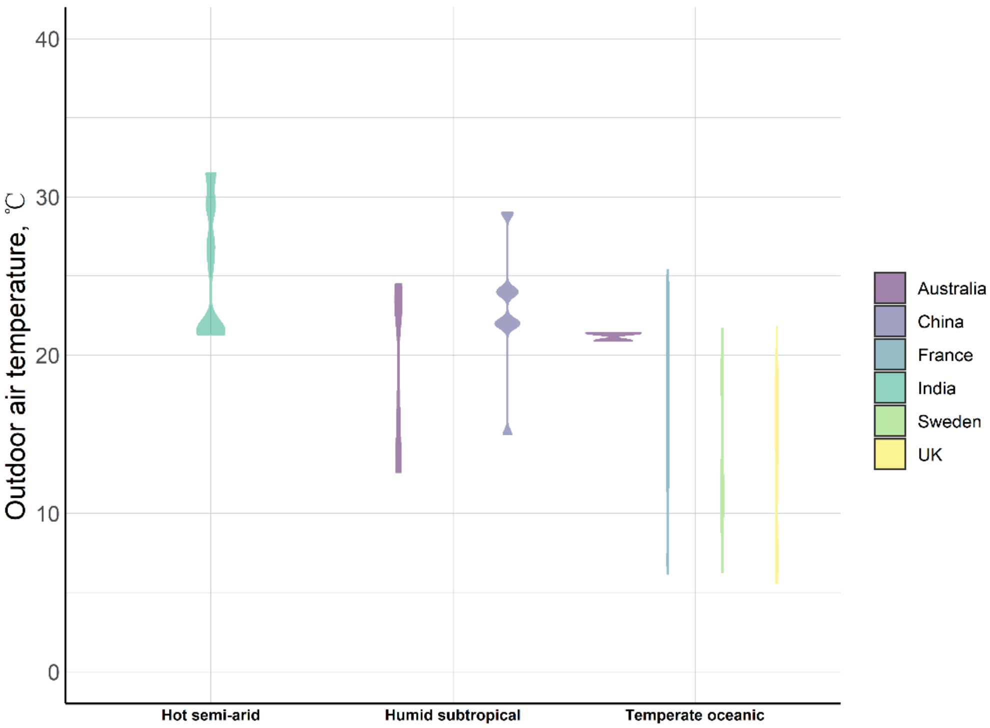
Table 11. Descriptive statistics of Variables in selected data required for the model comparison

Parameter	Hot semi-arid				Humid subtropical				Temperate oceanic			
	Min	Median	Mean	Max	Min	Median	Mean	Max	Min	Median	Mean	Max
TSV	-3	0	0.06	3	-3	0	0.1	3	-3	0	0.27	3
Ta	21	26.4	26.89	35.8	16.4	25.7	25.19	34.2	18.1	23.7	23.97	35.3
Tr	18.86	25.98	26.53	35.5	17	26.3	25.89	35.4	17.7	24.3	24.56	34.6
RH	18	45.7	45.7	86.8	20	59.8	58.96	85.9	22.7	44.8	43.72	68.7
Vel	0	0.04	0.08	0.48	0	0.16	0.18	0.48	0	0.06	0.07	0.48
Met	1	1	1.06	2.1	0.7	1.2	1.24	2.1	0.8	1.2	1.37	2.8
Clo	0.38	0.68	0.7	1.64	0.04	0.49	0.61	2.87	0.18	0.69	0.7	2.42
Tout	21.3	21.6	25.22	31.5	12.6	22	22.33	29	5.6	14.2	13.95	25.4

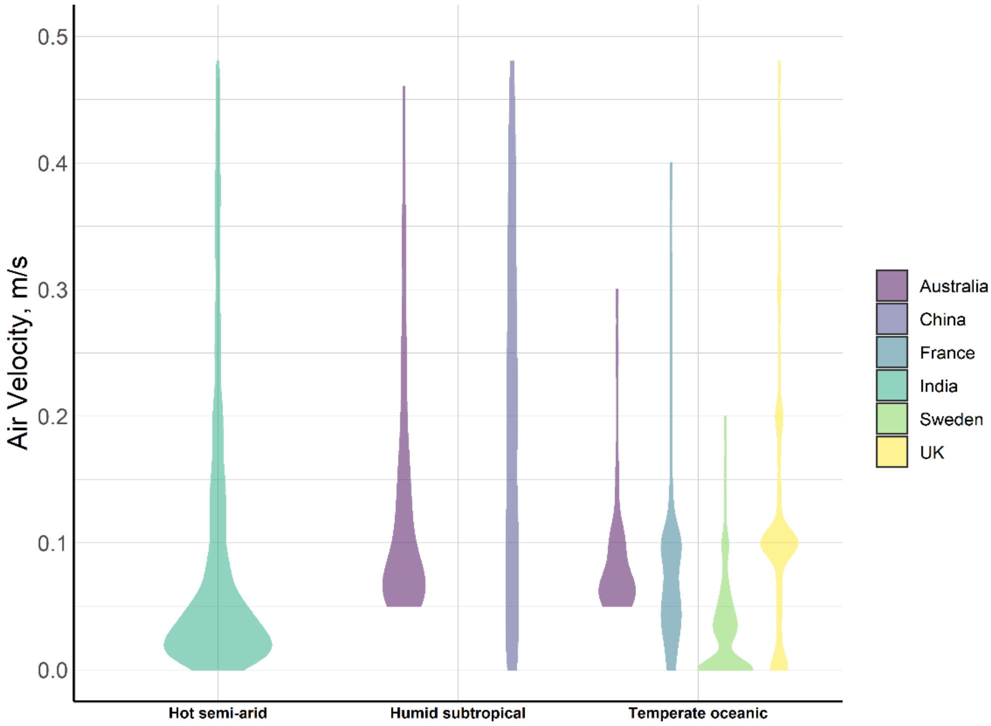
TSV: thermal sensation vote; Ta: air temperature, ℃; Tr: radiant temperature, ℃; RH: relative humidity, %; Vel: air velocity, m/s; Met: metabolic rate, met; Clo: clothing level, clo; Tout: outdoor air temperature, ℃.



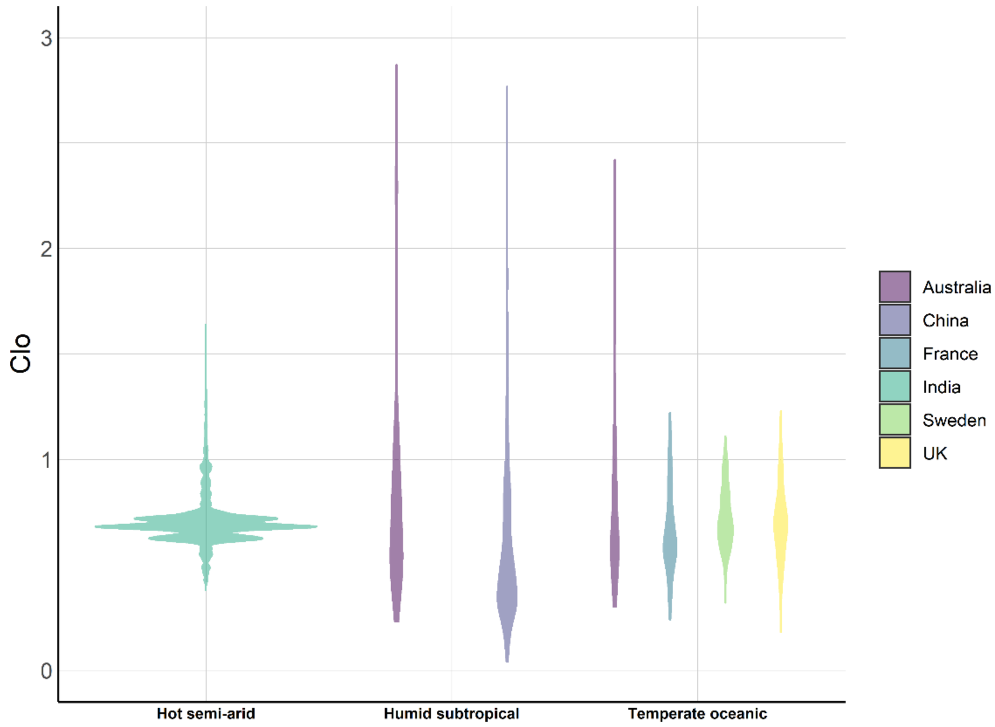
(a) Indoor air temperature



(b) Outdoor air temperature



(c) Air velocity

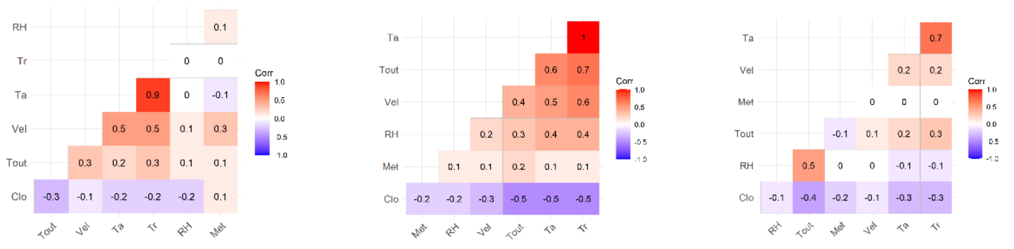


(d) Clothing level

Fig. 10. Variable distribution of selected data grouped by climate and country

Fig. 11 shows the correlation between different physical variables. The clothing value is negatively correlated with outdoor and indoor temperature, indicating that occupants can actively take off clothes when the ambient temperature is high. However, the correlation coefficient between clothing value (Clo) and temperature (Ta: indoor air temperature; Tr: indoor radiant temperature; and Tout: outdoor air temperature) in the hot semi-arid climate (-0.2~-0.3) is lower than that in the humid subtropical climate (-0.5) and temperate oceanic climate (-0.3~-0.4). Combined with **Fig. 10 (d)**, people in the hot semi-arid climate are from India, and their cultural customs may require them to consistently wear certain garments which makes their clothing level remain at a relatively high level. This circumstance reduces the opportunity for clothing adjustments.

The air velocity (Vel) is positively related to indoor air temperature (Ta) and radiant temperature (Tr), but the correlation coefficient in the hot semi-arid climate (0.5) and humid subtropical climate (0.5~0.6) is higher than it in the temperate oceanic climate (0.2). This could be caused by the unpopularity of fan use or the relatively low indoor temperature in the temperate oceanic climate.



(a) Hot semi-arid (b) Humid subtropical (c) Temperate oceanic

Fig. 11. The correlation coefficients between different physical variables

7.2 Calculation process of thermal comfort models

There are eight models to be discussed in this section, including five PMV-related models: PMV, PMV_{adj}, ePMV, aPMV and $ATHB_{pmv}$; and three SET-related models: PTS, aPTS and $ATHB_{pts}$. The PMV and SET calculations have been successfully validated with "*Appendix B Values used to generate the comfort envelop*" and "*Table D3 Validation Table for SET Computer Model*" in ASHRAE 55-2017 [33]. The calculation procedure of PMVadj is consistent with "*Appendix D procedure for evaluating cooling effects of elevated air speed using SET*" in ASHRAE 55-2017 [33].

For the ATHB model, the calculation was processed by the Package "*comf*" in R [116]. Because the perceived control levels were not comprehensively collected in the ASHRAE database, the coefficient PSYCH, which was "*related to the mean of obtained perceived control votes of a group of occupants*", has been simplified to zero [107]. For the ePMV model, the expectancy factor *e* is determined by considering the outdoor climate and the popularity of air-conditioned buildings for each local area [10]. For the aPMV and aPTS models, the adaptive coefficient λ is calculated using the least square method described in [11].

The PTS model translates SET value into a range of -3 to +3, and it was calculated according to **Eq. (1)** [30]:

$$PTS = 0.25 * SET - 6.03 \quad (1)$$

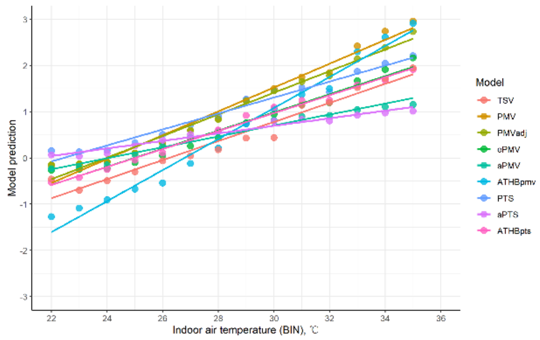
To present results more concisely, the data were divided into 1 ℃ intervals and the corresponding average values of specific predictions in each interval were used for comparing the predictive performance. In case of an abnormal value, any interval with less than 5 surveyed data was removed for the consideration of averaging effects.

Mean bias was chosen for the comparisons of the predictive performance of thermal comfort models. This approach is consistent with the analyses conducted by Humphreys and Nicol [9] and Schweiker and Wagner [107] using the mean bias between the predictive thermal sensation (PSV) and the actual thermal sensation vote (TSV).

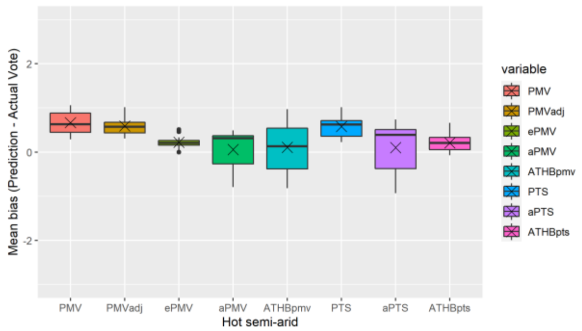
7.3 Predictive performance in different climates

Three climates "*Hot semi-arid*", "*Humid subtropical*", and "*Temperate oceanic*" based on Köppen's climate classification were selected for comparing the predictive performance of different thermal comfort models. These three climates are arranged in descending temperature order: the mean values of outdoor air temperature are 25.22, 22.33, and 13.95 ℃, respectively, while the mean values of indoor air temperature are 26.89, 25.19, and 23.97 ℃.

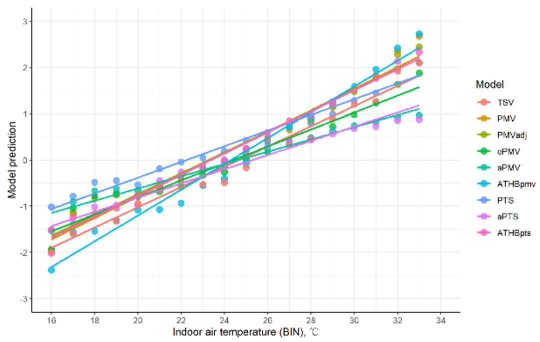
Fig. 12 shows the prediction results of the selected thermal comfort models in three selected climates on ASHRAE 7-point scale. More information about regression lines of model prediction is listed in **Table 12**. As can be seen, the gradients of the fitting line are not constant, a higher gradient predicts that people will have lower adaptability to thermal environments and will more easily feel hot or cold.



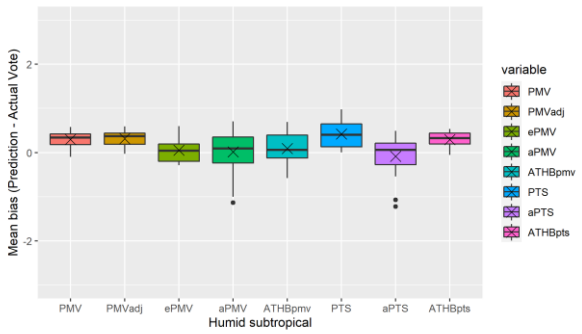
(a) Model predictions in hot semi-arid climate



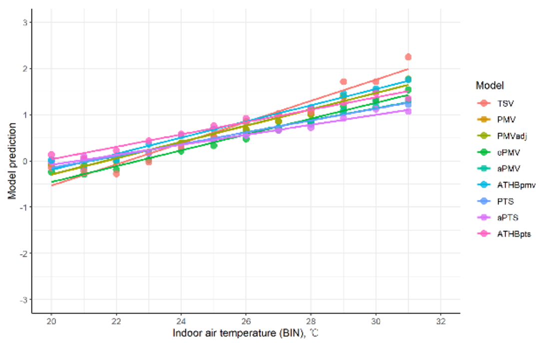
(b) Mean bias in hot semi-arid climate



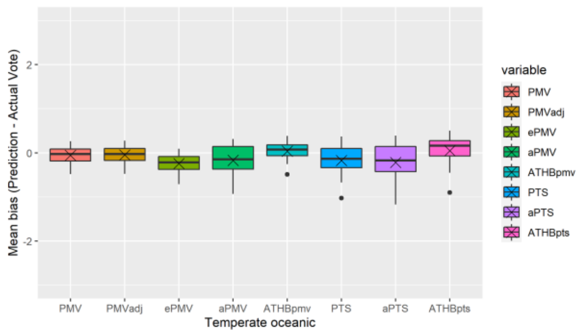
(c) Model predictions in the humid subtropical



(d) Mean bias in the humid subtropical



(e) Model predictions in temperate oceanic



(e) Mean bias in temperate oceanic

Fig. 12. Predictive performance of thermal comfort models in different climates

Table 12. Details of the linear regression of different climates

Type	Hot semi-arid				Humid subtropical				Temperate oceanic			
	Intercept	**Gradient**	**R^2**	**SSE**	**Intercept**	**Gradient**	**R^2**	**SSE**	**Intercept**	**Gradient**	**R^2**	**SSE**
TSV	-5.41	0.21	0.96	0.43	-5.41	0.21	0.96	0.43	-5.12	0.23	0.95	0.41
PMV	-6.22	0.26	0.98	0.37	-6.22	0.26	0.98	0.37	-3.83	0.18	0.98	0.11
PMVadj	-5.61	0.23	0.98	0.22	-5.61	0.23	0.98	0.22	-3.81	0.18	0.98	0.11
ePMV	-4.90	0.20	0.97	0.31	-4.90	0.20	0.97	0.31	-3.89	0.17	0.98	0.11
aPMV	-2.85	0.12	0.96	0.12	-2.85	0.12	0.96	0.12	-2.77	0.13	0.98	0.04
$ATHB_{pmv}$	-9.00	0.34	0.98	0.48	-9.00	0.34	0.98	0.48	-3.71	0.18	0.98	0.10
PTS	-3.87	0.17	0.97	0.20	-3.87	0.17	0.97	0.20	-2.71	0.13	0.98	0.05
aPTS	-1.75	0.08	0.95	0.07	-1.75	0.08	0.95	0.07	-2.25	0.11	0.98	0.04
$ATHB_{pts}$	-4.86	0.21	0.99	0.08	-4.86	0.19	0.99	0.08	-2.64	0.13	0.97	0.08

In hot semi-arid climate **(Fig. 12 (a), (b)**), two conventional heat balance models PMV (brown line) and SET (equivalent to PTS, blue line) both overestimate hot sensation compared with occupants' actual feeling (TSV, red line) when the temperature is over 34 ℃. Meanwhile, the ePMV (green line), aPMV (light green line), and $ATHB_{pts}$ (pink line) show similar results that are more consistent with original TSV values which are also supported by the plot of their mean bias values that are closer to zero representing smaller mean bias.

In humid subtropical climate (**Fig. 12 (c), (d)**), PMV and SET overestimate thermal sensation in surveyed temperature period, but SET lowers this discrepancy when the temperature is high. Similar to hot semi-arid climate, the two PMV-based models PMV_{adj} and $ATHB_{pmv}$ cannot shrink the discrepancy in high temperature periods (over 32 ℃). By contrast, aPMV lowers this discrepancy in hot environments. The mean bias plot also shows that ePMV and aPMV perform best with a closer distance to zero and a small mean bias. The mean-value and mid-value of mean bias of ePMV, aPMV and $ATHB_{pmv}$ models are nearly the same.

In temperate oceanic climates (**Fig. 12 (e), (f)**), the thermal comfort models perform almost equally well. The ePMV underestimates occupants' thermal feelings in the entire temperature range. The mean bias plot indicates that only $ATHB_{pts}$ is a little further from zero points than the other models.

7.4 Predictive performance in different countries

To examine how country factor influences people's adaptive levels in similar outdoor climates, we tried to separate the data to different countries within the same Koeppen climate. However, according to data from previous sections, the hot semi-arid climate has only one country, India, and the temperate oceanic climate has too few samples (only 49 data in Goulburn city in Australia). Therefore, the humid subtropical climate was chosen and further broken down into country level (Guangzhou city and Yueyang city in China, Wollongong city in Australia) to allow detailed analysis. The indoor air temperatures were binned into 1 ℃ wide intervals. The related record overview is shown in **Fig. 13**. It is clear that China's indoor temperatures (data sum: 1873) were generally much higher and spanned a wider range than Australia's (data sum: 365). The information about regression lines of model prediction is listed in **Table 13**.

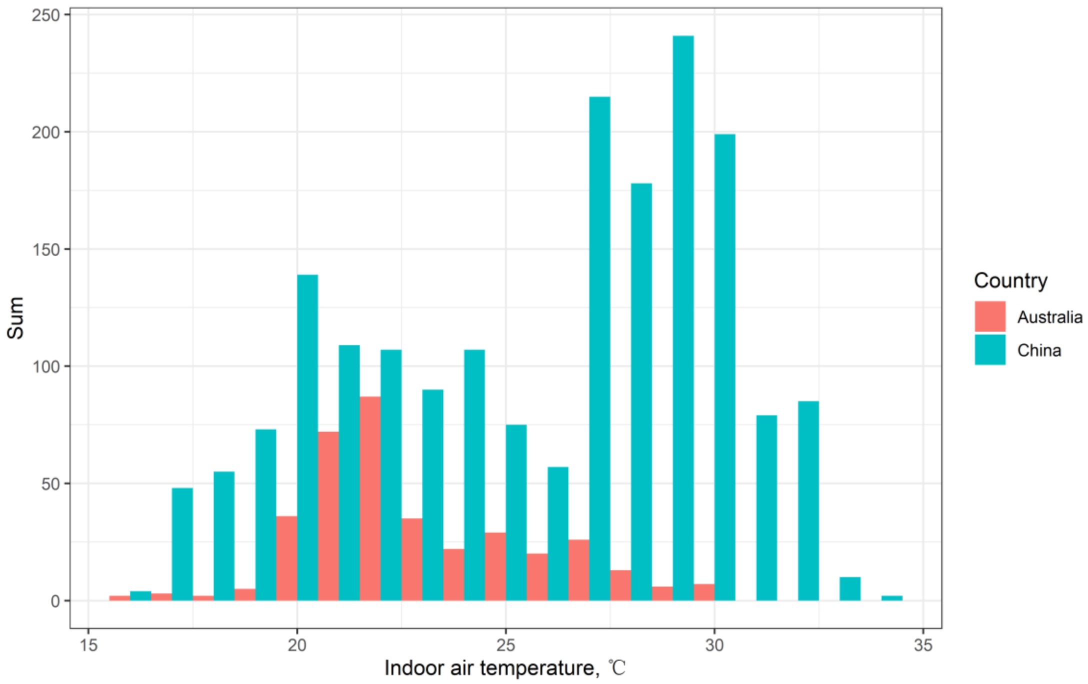
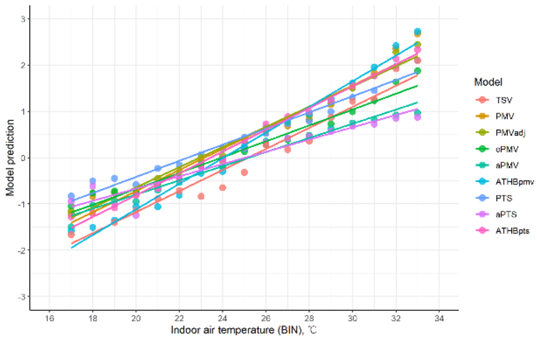
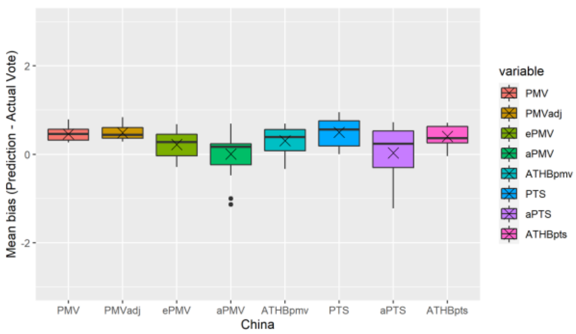


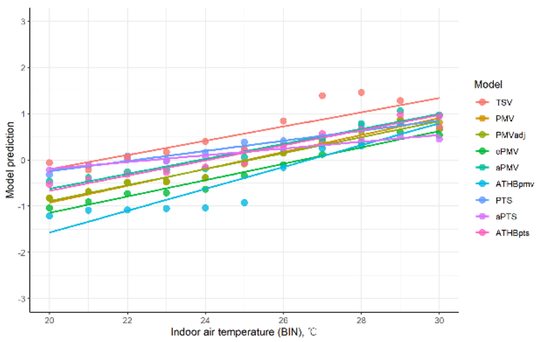
Fig. 13. Distribution of Indoor air temperature data in China and Australia



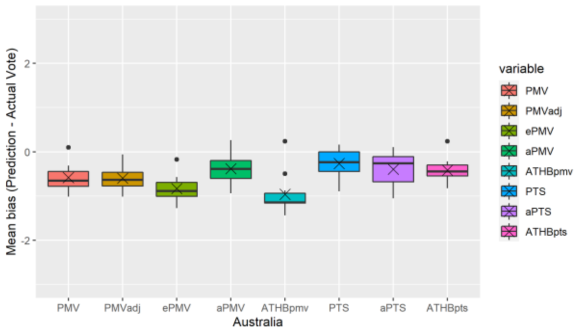
(a) Model predictions in China



(b) Box plots in China



(c) Model predictions in Australia



(d) Box plots in Australia

Fig. 14. Predictive results of thermal comfort models in different climates

Table 13. Details of linear regression for different countries

Type	China				Australia			
	intercept	gradient	R^2	SSE	intercept	gradient	R^2	SSE
TSV	-5.73	0.23	0.96	0.99	-3.28	0.15	0.71	1.04
PMV	-5.29	0.23	0.97	0.77	-4.59	0.18	0.97	0.12
PMVadj	-5.01	0.22	0.98	0.43	-4.35	0.17	0.96	0.14
ePMV	-4.10	0.17	0.97	0.42	-4.68	0.18	0.97	0.12
aPMV	-3.86	0.15	0.97	0.32	-3.87	0.16	0.94	0.19
$ATHB_{pmv}$	-6.66	0.28	0.98	0.52	-6.30	0.24	0.89	0.79
PTS	-3.90	0.17	0.97	0.38	-2.44	0.11	0.94	0.08
aPTS	-3.32	0.13	0.91	0.68	-1.65	0.07	0.96	0.02
$ATHB_{pts}$	-5.52	0.24	0.99	0.17	-3.95	0.16	0.95	0.14

For the fitting curve from China (**Fig. 14 (a), (b)**), almost all the thermal comfort models exhibit higher sensation predictions than occupants' actual feelings, and aPMV and aPTS present two closest fitting curves to TSV with better mean bias. This could be caused by most of the data (1796 out of 1873) being from Guangzhou City where a high temperature level remains during the entire year and cooling needs dominate. People there could have acclimated themselves to hot environments, but this physiological accommodation has not been fully intervened into thermal comfort models. Although ePMV could make the mean bias a little lower and approach more to zero points, its effects are limited. The adaptive coefficient λ used in aPMV and aPTS models using feedback control theory contributes to explaining occupants' acclimation to local environments and shows better predictive results than other models. Also, aPMV was originally derived from Chinese data.

For the fitting curve from Australia (**Fig. 14 (c), (d)**), an opposite trend from China emerges: most models predict lower sensation values than occupants' actual feelings. The gradients of most linear fitting curves in Australia (8/9) are below 0.2, while most gradients in China (5/9) are above 0.2, indicating that people in Australia may have a lower degree of adaptation. Three SET-based models (PTS, aPTS and $ATHB_{pts}$) and aPMV show obvious improvements with better mean bias compared with other PMV-based models.

Due to the methodology of the data cleaning process, previous comparisons on humid and tropical climates only covered cities from China and Australia, and it discovered a clear discrepancy between the adaptive degree of occupants in these two countries. Many important studies from such climates in South East Asia, e.g., Singapore, Malaysia, and Indonesia, have highlighted the specific adaptive approaches of local occupants for thermal comfort. Karyono [117] examined 11 studies from South East Asia (from 1937 to 1993) and concluded that the neutral temperature was between 25 and 30 ℃, which was 1 to 6 ℃ higher than ISO and ASHRAE recommendations. Recent field studies from Aisyah *et al.* [118] in 2016 also confirmed this finding in the South East Asia region, with the exception of Malaysia, which exhibited a trend of lower neutral temperature than standard recommendations. According to their study, the most common adaptive approach (47.5% votes) in investigated buildings was switching AC, which may encourage occupants to seek a cool thermal environment. Studies from Japan with similar climates revealed that occupants in HVAC buildings had a descending neutral temperature: 27.1 ℃ in 2012 [119], 26.5 ℃ in 2014 [120], and 25.8 ℃ in 2016 [118]. de Dear [121] conducted two separate studies in Singapore, one in HVAC offices and one in NV residential buildings, and discovered that the comfort temperature in HVAC offices is 24.2 °C, which is 4.3 °C lower than it is in NV residential buildings. However, one-third of the occupants in these offices were experiencing a cool sensation, which is neither healthy nor energy efficient.

In contrast, Feriadi and Wong [122] investigated thermal comfort of occupants in Indonesian residential buildings and found that the most popular adaptive strategies were: opening windows (78%), drinking or changing clothes (70% to 60%), taking a bath or going to a cooler place (29%), and using air conditioning (AC) (only 3%). The low percentage of AC usage was due to the cost concern of installation and energy bills. The neutral temperature of local occupants was about 29.2 °C. However, their results showed that 63% of the persons still voted "*prefer to be cooler*" even when they voted "*neutral*" in thermal sensation. Therefore, appropriate parametrization of adaptive approaches in the thermal comfort model has the potential to better represent occupants' actual thermal experience and expectations in specific climates or contexts, which is currently lacking in both the climate-based PMV index and the regression-based adaptive model in standards.

7.5 Summary of model comparisons

The thermal comfort models have been compared through the mean bias between the predicted and observed thermal sensation votes, as summarized in **Table 14.** In hot semi-arid and humid subtropical climates, the original PMV and SET indices both overestimate thermal sensations, whereas the ePMV, aPMV and $ATHB_{pts}$ models all predict closer to the actual mean votes, while in temperate oceanic climate, the PMV and SET indices have very small bias.

According to the results from China and Australia, both PMV and SET indices overestimated sensations in China but underestimate sensations in Australia. The adaptive PMV-based models are generally effective in reducing overestimation in China, but ineffective in reducing underestimation in Australia. Furthermore, for Australian data, the adaptive SET-based models generally perform better than the adaptive PMV-based models.

Table 14. Deviations of the modified models comparing with the PMV/SET indices

Category		PMV	PMV-based				PTS (SET)	SET-based	
			PMVadj	ePMV	aPMV	$ATHB_{pmv}$		aPTS	$ATHB_{pts}$
Climate	Hot semi-arid	↑ (red)	**	***	***	**	↑ (red)	**	***
	Humid subtropical	↑ (red) ↑ (blue)	*	***	***	***	↑ (red)	***	**
	Temperate oceanic		**	*	*	*		*	*

Note: ↑ (red): overestimate hot sensation; ↓ (red): underestimate hot sensation; ↑ (blue): overestimate cold sensation; ↓ (blue): underestimate cold sensation; ***: big reduction degree of mean bias: **: modest reduction degree of mean bias; *: small reduction degree of mean bias.

The predict results shown above partly confirm and partly contradict the validation results presented by Schweiker and Wagner [107] and Schweiker [116]. While their evaluations based on German field data (Cfb classification) show lower mean bias values for the two ATHB-models, the analysis presented here does not show such clear trends. It is noteworthy, that the ATHB approach is performing in the same magnitude or better than original models despite that its coefficients have been exemplarily derived so far only based on a limited number of subjects from a German climatic context. In addition, some ATHB inputs, such as the psychological adaptation indicated by the obtained perceived control level, had to be neglected for the analysis presented here due to original questionnaire in RP-884 projects lacked such questionnaire. In summary, from the above comparison of thermal comfort models, it is hard to say which one performs the best. Therefore, it is helpful to adequately analyze the application conditions or specific characteristics of these thermal comfort models and their suitability in different contexts. This section partly employed data from ASHRAE database and only covers limited sample features. The performance of different models can vary if the data sources are different. It is expected to enrich the ASHRAE database covering more regions. A more comprehensive analysis of this topic is expected in the future.

8. Discussion

8.1 Debate of PMV index and classic adaptive regression model

Since its establishment, the PMV index has been adapted into several international and national standards and guidelines for evaluating the design of HVAC systems in buildings. The use of the PMV index necessitates that its inputs fall within certain scopes; for example, ASHRAE 55 requires that air speeds should be less than 0.2 m/s when using the PMV index. The classic adaptive regression model links indoor comfort temperature to outdoor climate based on statistical regressions without further considering the interactions of physical and physiological parameters that can directly affect people's thermal sensation. Although some adaptive regression models use operative temperature as the y-axis to account for radiant temperature and air speed, this method has several simplifications and cannot explain the complex physiological response of the human body to real thermal environments. Studies worldwide using the adaptive regression models also yielded varying regression results (**Fig. 3**), suggesting that the core mechanism of thermal adaptations has not been fully revealed by statistical methods based solely on linear regressions. Therefore, Instead of being irreconcilable, the PMV index and adaptive regression model could be complementary [37].

8.2 Position of adaptive PMV models

The PMV index is regarded as a significant milestone in thermal comfort research by establishing an empirical relationship between physical environments and subjective thermal sensation. The advantages of the model are that it considers the specific indoor environmental parameters such as air temperature, radiant temperature, air velocity, and relative humidity, as well as personal factors including the metabolic rate and clothing level. These features are essential for building and engineering system design. However, it has some limitations when applied in the non-steady-state conditions in real environments [9] and neglecting some of human's adaptive capacities. To fill this gap, the adaptive heat balance approach tried to explain thermal comfort further by considering both thermal regulatory responses and subject adaptations: ePMV uses the expectancy factor "*e*" to quantify thermal expectation in a hot climate; aPMV employs the adaptive coefficient "λ" to reveal the feedback loop to thermal perception; ATHB adapts the inputs "*clothing level*" and "*metabolic rate*" of PMV and SET indices by introducing the parameter of outdoor temperature and new coefficients to account for the three adaptive mechanisms individually. These emerging adaptive heat balance models showed various predictive performances when using specific data from different climates or countries, as discussed in section 7. Mostly, they provided a higher level of agreement with TSV than the PMV index. As their applicability varies with the change of characteristics of the source data, further verifications of reliability and establishing process are still needed. Since heat balance models concentrate on steady-state environments and adaptive regression models can only provide a regression recommendation for dynamic environments, these adaptive heat balance models can bridge the gaps between the two classic approaches by combining their advantages. They contain the same indoor climate parameters as the PMV index does which is essential for building and system design and extending the PMV index to the non-steady environments considering all adaptive mechanisms. They also overcome the limitations of classic regression models lacking human physiological thermal regulation mechanism.

8.3 Thermal comfort models in standards and Guides

Thermal comfort standards and guidance ASHRAE 55 [4], EN 15251 [6], ISO 7730 [1], CIBSE Guide A [7], and GB/T 50785 [110] specify PMV ranges with different categories for specific comfort levels. Due to the uncertainty and difficulty of measuring clothing and activity level in real environments, these two PMV inputs are usually assumed to be fixed values and the PMV ranges are converted to temperature ranges. Therefore, these specifications hypothesize that the narrower PMV (temperature) band is much preferable to the building occupants. However, Arens *et al*. [123] examined the acceptability of three classes of temperature range based on ASHRAE RP-884, European SCATs database and Berkeley City Center (BCC) databases. They found that category I with tightly controlled indoor temperature did not provide higher acceptability than categories II and III. This way of utilizing PMV may lead to a low occupants' satisfactory degree and high energy cost.

Compared with the PMV index, the adaptive regression-based approach in thermal comfort standards suffered completely the opposite limitations. The idea of a regression-based approach has contributed significantly to thermal comfort research, but its mathematical expression in standards only employs one input: outdoor temperature. No matter how this input has been evaluated or amended, it cannot reveal the physiological mechanism of human thermal response and the influence of indoor physical conditions on occupants at a theoretical level. Fanger queried the adaptive chart at a Windsor conference: "*I have two problems with this graph ... the vertical axis and the horizontal axis*" [124]. The basic principle of determining the adaptive regression model in standards is mainly based on statistical analysis with the inevitable weakness: focus on correlation rather than causation. Although the majority of the factors that influence adaptation (clothing, activity, expectation, history, personal control) have been well studied, we do not understand how they come together to influence personal perception. This will still leave the core of adaptive mechanisms unresolved.

The developed adaptive PMV models could provide the opportunity for better evaluating thermal comfort by considering the advantages of both PMV index and adaptive regression models. Their basis is the heat balance model whilst using additional factors to quantify the adaptive degree of occupants. The Chinese standard GB/T 50785 [110] has further attempted to use the aPMV model as a supplement to the adaptive regression-based approach for evaluating thermal environments in NV buildings.

8.4 Building characteristics

Thermal comfort standards and guidance recommended the PMV index and adaptive regression models to be applied in HVAC and NV buildings respectively, but they pay less attention to mixed mode (MM) buildings. It is based on one hypothesis that HVAC environments are usually steady and those building occupants seldom adjust their clothing or activity. However, Parkinson *et al*. [125] analyzed 60,321 records in the ASHRAE global database and found that the changing neutral temperature of occupants with different indoor air temperatures not only happened in NV buildings but also in HVAC and MM buildings, indicating that the fixed and narrow PMV range may not well represent the thermal comfort boundaries in practice.

As standard-based projects (RP-884 [126], SCATs [52]) were mostly conducted in office buildings, their applicability in other building types still requires further verifications. de Dear *et al*. [71] found the acceptable temperature range for Sydney residents falls 2 to 3 K on the cool side of ASHRAE 55 adaptive regression model, meanwhile with a 2 K wider range in general. This decrease is caused by the high tolerance of occupants at home and ASHRAE 55 adaptive regression model is mostly based on data from offices. Li *et al*. [90] and Wang *et al*. [127] also discovered that occupants of residential buildings can accept a much larger temperature variation than in offices or classrooms. One reason could be that people at home can directly modify their environment with a higher degree of adaptive opportunities, such as adjusting clothing levels at a wider range [128]. Therefore, occupants in a specific type of building will present unique thermal responses regarding the environmental context. These characteristics need a better way of parameterization in thermal comfort models.

The adaptive heat balance models have the potential of parameterizing characteristics of different buildings. For example, the aPMV model has been applied in the college activity center, factory, bus and railway stations using customized values for the coefficient λ to quantify the adaptive degree of people. These λ values could indicate people's comfort level during "*motion state*" and "*stationary state*" in the activity center [99], effects of past working experience on thermal feelings of senior and young employees in the factory [100], and different expectation patterns of passengers during waiting or transient periods [101] [102].

8.5 Adaptive heat balance models for sustainable building design and operation

Tightly controlled conditions without consideration of occupants' specific preferences and level of adaptation can lead to unnecessary energy consumption as well as thermal discomfort [123]. Simple application of a traditional PMV index or regression-based adaptive model designed for a general population can hardly address all requirements of sustainable building design and operation. The evolution in thermal comfort research reveals that a more flexible and robust theoretical foundation is urgently needed to support the transition from a steady to a dynamic view, and from a building-focused to a human-oriented perspective.

To achieve carbon neutrality, future buildings will need to improve occupants' comfort, despite local climate fluctuations, by focusing more on passive solutions, such as harvesting on-site environmental resources to obtain energy for heating, cooling, lighting, and electricity before relying on mechanical and infrastructural sources [129]. Thereby, the adaptive thermal comfort concept can make a significant contribution to the sustainability of buildings. The adaptive heat balance models presented above simultaneously consider the level of adaption and physical and personal input parameters and achieve an improved performance within a wide climatic context. The acquisition of data required for model processing could be assisted by a fast-developing technology, such as portable or wearable devices that can collect and transmit personalized data conveniently [130]. Such data will enable future model developments to account for the varied mechanisms of human adaptation to the thermal environment due to a variety of factors such as climate, culture, economics etc. The exploration of thermal adaptation in different regions, different types of buildings, and different demographic groups may help establish localized adaptation policies for low energy building design. The thermal comfort research paradigm should be considered moving from a steady to a dynamic addressing human-oriented behavioural sensitivity impacted by other human factors such as culture, economics, age and gender. The research on dynamic thermal comfort theory is in need to provide guidance to energy efficient building design and operation in contribution to carbon neutrality.

8.6 Limitations

Several factors can affect the reproducibility of results from comparing different models. These factors include the data cleaning principle; the data binned interval or start/end point; the database version; the model coefficient selection; the evaluation parameter, etc. The aim of the model comparison presented in this work was to exemplify the differences in the model performance rather than a validation of any model. Beyond the scope of this review was the more comprehensive performance analysis of the latest model developments [131]. Such work is expected in the near future.

9. Conclusions

Thermal comfort research deals with the complex relationship between indoor environmental conditions and human thermal perception which spans several disciplines including physiology, psychology, human behavioral studies, social sciences, engineering, and architecture disciplines. Since the last century researchers have approached this challenge from different perspectives and numerous prediction models have emerged and evolved to contribute to theory and knowledge in this area. Thermal comfort theory and approaches have been developed which underpin standards and guidelines in building and engineering system design, operation and evaluation though there are pros and cons of different methods. Guidance for building and engineering design based on the existing theory and up-to-date research outcomes are since ever been desired to meet the growing demand of the sustainable design requirement. This paper has reviewed the historic evolution of thermal comfort research during the last century using a systematic approach and a particular focus on adaptive thermal comfort studies. A large number of published articles as well as standards and guides were collected and screened based on a rigorous search method to ensure the literature database was both focused and complete. A further evaluation of representative prediction models has been conducted by applying the models to a large database and comparing the differences in their performance. The main findings from this comprehensive analysis of the literature and analysis of models can be summarized as follows:

- Thermal comfort research has been moved forward during the last century, particularly in the last two decades, towards more complex dynamic conditions. The main approaches used to predict thermal comfort can be classified in three categories namely: 1) the heat balance approach, which is mainly based on laboratory studies; 2) the adaptive regression-based model, which is mainly based on field studies and 3) the adaptive heat balance approach which extends the well-established theory from laboratory studies by taking into account adaptive concepts and results from field studies.
- There is a clear trend for research activities in this area to move from the heat balance approach towards a dynamic thermal environment based field studies in the real world in the past two decades. The key feature of the heat balance approach is that it is fundamental to building and engineering system design for creating a comfortable indoor thermal environment as the detailed indoor environmental design parameters are included in this approach. However, the bias of this approach is that it pays less attention to the potential of human adaptation such as behavioral, physiological and psychological adaptations, which leads to prediction deviation in the real buildings.
- The adaptive regression-based approach emphasizes human adaptation and considers the variations of outdoor temperature. The advantage of this approach is that it highlights the capacity of human adaptation benefiting a low-energy building design and operation. However, it is missing the inclusion of the environmental and personal variables of the heat balance approach affecting thermal perception which might be the hurdle for its application in building and engineering system design.
- The emerging adaptive heat balance approach aims to bridge the gap between the two classic approaches. It incorporates features of both heat balance and regression-based approaches maintaining thermal design criteria in more detail while extending its application to a wider range of building types and operational conditions. Comparisons of results using different adaptive heat balance models show a promising way forward to increase predictive performance.
- In recent years, adaptive thermal comfort studies have played a positive role in the sustainability of buildings. The exploration of thermal adaptation in different regions, different types of buildings, and different demographic groups is encouraged in future studies. This may help to establish localized adaptation policies for low energy building design. Research into end-users' centric adaptive thermal comfort in a dynamic environment can be explored to provide optimized energy-efficient energy system control in future studies.

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Appendix

Appendix A. Adaptive comfort models based on the linear algorithm

Author	Year	Building type	Operation mode	Model	Main findings
Humphreys [3]	1978	Residential, office & classroom	NV	$T_n = 0.534\ T_{out} + 11.9$	Outdoor air temperature is a valuable parameter for estimating indoor thermal conditions.
Humphreys [132]	1981	Residential, office & classroom	NV	$T_{comf} = 0.55\ T_{out} + 14.1$	Mean indoor temperature is highly correlated to the comfort temperature.
Auliciems and de Dear [133]	1986	Office	NV	$T_n = 0.31\ T_{out} + 17.6$	PMV is less useful for predicting thermal sensations in NV. Air cooling in Australia is not efficient enough.
Nicol and Roaf [55]	1996	Office	NV	$T_{comf} = 0.38\ T_{out} + 17.0$	Occupants in Pakistan show large variations in desired indoor temperature.
Nicol *et al*. [56]	1999	Commercial	MM	$T_{comf} = 0.36\ T_{out} + 18.5$	The air conditioner is not as popular as the fan in Pakistan. Occupants rarely find discomfort at the indoor temperature between 20 and 30 ℃.
Humphreys and Nicol [134]	2000	Office	NV	$T_{comf} = 0.54\ T_{a(out)} + 13.5$	A rise in winter neutral temperature is found over the decades.
Heidari and Sharples [57]	2002	Residential & office	NV	Short-term study (home)：$T_{comf} = 0.36\ T_{out} + 17.3$ Long-term study (office)：$T_{comf} = 0.292\ T_{out} + 18.1$	Neutral temperatures in Iran are 26.7 to 28.4 ℃ in summer and 20.8 to 21.2 ℃ in winter.
Mui and Chan [58]	2003	Office	HVAC	$T_n = 0.158\ T_{out} + 18.303$	Using the adaptive model in Hong Kong can lead to 7% energy saving.
Nicol [135]	2004	Office	NV	$T_n = 0.534\ T_{out} + 12.9$	PMV does not adequately describe comfortable conditions in tropical climates. Fans can enlarge an additional 2 ℃ to the boundaries of the comfortable temperature range.
Bouden and Ghrab [64]	2005	Residential & office	NV	$T_{comf} = 0.68\ T_{out} + 6.88$	Occupants in Tunisia and North Africa show high tolerance to hot environments
Ye *et al*. [59]	2006	Residential	NV	$T_n = 0.42\ T_{out} + 15.12$	The acceptable indoor temperature in NV buildings in Shanghai, China is between 14.7 to 29.8 ℃.
Rijal *et al*. [78]	2009	Office	MM	Europe transverse Database: $T_{comf} = 0.316T_{rm} + 19.2$ Europe longitudinal Database: $T_{comf} = 0.308T_{rm} + 18.1$ Pakistan transverse Database: $T_{comf} = 0.516T_{rm} + 15.4$	Occupants in MM buildings perform similarly to NV buildings and rely less on HVAC systems.
Wang *et al*. [60]	2010	Residential	NV	$T_{comf} = 0.486\ T_{out} + 11.802$	The preferred indoor temperature in Harbin, China from the cold climate is between 24 to 28 ℃.

Nicol and Humphreys [136]	2010	Office	NV	T_{comf}=0.33T_{rm}+18.8	Introduce the data and method in determining adaptive model in European standard EN15251.
Li *et al*. [61]	2011	Residential	MM	T_n=0.29 T_{out} +15.0	The acceptable temperature range for residents in Yangtze River Valley in China is 16.3 to 28.1 ℃.
Nicol *et al*. [137]	2012	Office	HVAC	T_{comf}=0.09T_{rm}+22.6	Introduce the theory of the adaptive comfort model and the design process of using adaptive comfort model strategies.
Nguyen *et al*. [138]	2012	-	NV	T_{comf}=0.341 T_{out} +18.83	The preferred indoor temperature in south-east Asia is between 26 and 34 ℃.
Rijal *et al*. [65]	2013	Residential	MM	NV: T_{comf}=0.531T_{rm}+12.5 AC: T_{comf}=0.297T_{rm}+18.8 HT: T_{comf}=0.307T_{rm}+16.5	The neutral temperatures for residents in Gifu region of Japan are 18.9, 22.7 and 27.1 ℃ during heating, naturally ventilated and cooling modes respectively.
Ge *et al*. [62]	2014	Residential	NV	T_n=0.691 T_{out} +12.91	Discuss passive design strategies based on an adaptive model built in Guangzhou of China.
Indraganti *et al*. [79]	2014	Office	HVAC & NV	NV: T_{comf}=0.26T_{rm}+21.4 AC: T_{comf}=0.15T_{rm}+22.1	The neutral temperatures in offices in Chennai and Hyderabad of India are 26.4 and 28 ℃ during cooling and naturally ventilated modes respectively.
Yau and Chew [80]	2014	Hospital	HVAC	T_n = 0.3314 T_{out} +14.858	The acceptable temperature range for hospital workers in Malaysia is 23.3 to26.5 ℃.
Yang *et al*. [63]	2015	Residential	-	Severe cold：T_n =0.121 $\overline{T_{pma}}$ +21.489（16.3< T_n <26.2） Cold：T_n =0.271$\overline{T_{pma}}$ +20.014（15.8< T_n <29.1) Hot summer and cold winter：T_n =0.32 $\overline{T_{pma}}$ +16.862 (16.5< T_n <27.8) Hot summer and warm winter：T_n =0.554 $\overline{T_{pma}}$ +10.578（16.2< T_n <28.3）	The energy-saving potentials using adaptive models for Beijing, Shanghai and Guangzhou are 5%, 6.5% and 8% respectively.
Dhaka *et al*. [67]	2015	Residential & office	NV	T_{comf}=0.75 T_{out} +5.37	The neutral temperatures in office from India are 25.6, 27 and 29.4 ℃ during winter, moderate and summer seasons.
Humphreys et al. [139]	2015	Office (most data)	NV	T_{comf}=0.53T_{rm}+13.8	Discuss how adaptive model is developed.
Haddad *et al*. [85]	2016	Classroom	NV	T_{comf}=0.25T_{rm}+19.14	Schoolchildren are more sensitive to temperature change compared with adults.
Manu *et al*. [68]	2016	Office	HVAC, MM & NV	NV: T_{comf}=0.54T_{rm}+12.83 MM: T_{comf}=0.28T_{rm}+17.87	The neutral temperature in offices from India varies from 19.6 to 28.5 ℃ for outdoor running mean temperature ranging from 12.5 to 31 ℃.

Rijal *et al*. [66]	2017	Office	HVAC & MM	NV: T_{comf}=0.206T_{rm}+20.8 AC: T_{comf}=0.065T_{rm}+23.9	Neutral temperatures in offices from Tokyo and Yokohama of Japan are 20 and 28 ℃ during heating and cooling modes.
Barbadilla-Martín *et al*. [70]	2017	Office	MM	T_{comf}=0.24T_{rm}+19.3	A hybrid adaptive model is proposed for both NV and HVAC office buildings in Spain with a neutral temperature of around 23.6 ℃.
de Dear *et al*. [71]	2018	Residential	MM	T_n=0.26$\overline{T_{pma}}$+16.75	The acceptable temperature range for Sydney residents falls 2 to 3 K on the cool side of ASHRAE 55 adaptive comfort model.
Thapa *et al*. [81]	2018	Temporary shelters	NV	T_{comf}=0.556 T_{out} +10.9	The comfortable temperature range in temporary shelters after the earthquake from Nepal is between 15 and 28.6 ℃.
Indraganti and Boussaa [73]	2018	Office	HVAC	T_{comf}=0.049T_{rm}+22.5	The neutral temperature in Qatar is 24.8 ℃.
Rupp *et al*. [74]	2018	Office	MM	NV: T_{comf}=0.56$\overline{T_{pma}}$+12.74 AC: T_{comf}=0.09$\overline{T_{pma}}$+22.32	Occupants in mixed-mode buildings from southern Brazil show more tolerance to cooler and warmer environments.
Luo *et al*. [75]	2019	Office	MM	T_{comf}=0.24$\overline{T_{pma}}$+20.66	The adaptive model is more acceptable than PMV in mixed-mode buildings in the UK with a neutral temperature of 25.4 ℃.
Wu *et al*. [82]	2019	Residential	NV	T_{comf}=0.19T_{rm}+22.5	The neutral temperature of NV dormitory buildings in Changsha from China is 26.2 ℃.
García *et al*. [76]	2019	Office	NV	T_{comf}=0.41 T_{out} +16.00	Both PMV and adaptive model do not predict well for occupants in NV office from Bogotá of Colombia. The comfortable temperature is 23.47 ℃.
López-Pérez *et al*. [77]	2019	Office	MM	NV: T_{comf}=0.32T_{rm}+18.45 AC: T_{comf}=0.13T_{rm}+22.70	The neutral temperatures of educational buildings in Mexico are 24.7 and 26.9 ℃ during AC and NV modes.
Thapa [69]	2020	Residential	NV	T_{comf}=0.605T_{rm}+10.408	The adaptive model in the cold climate region of India does not comply with ASHRAE 55 standard. The yearly mean comfort temperature of females in this region is 17.88 ℃.
Williamson and Daniel [72]	2020	Residential	-	T_{comf}=0.26$\overline{T_{pma}}$+15.9	Develop a new adaptive model for residential buildings in temperate Australia.
Jiao *et al*. [86]	2020	Residential	NV	Winter: T_{comf}=0.706$\overline{T_{pma}}$+9.375 Summer:T_{comf}=0.418$\overline{T_{pma}}$+15.960 Mid-senson:T_{comf}=0.840$\overline{T_{pma}}$+6.935	The acceptable temperature ranges for older residents in Shanghai of China are 14.1 to 19.4 ℃in winter, 23.8 to 27 ℃in summer, and 20.6 to 31.7 ℃ in mid-season.
Fu *et al*. [83]	2020	Offices	MM	Winter (NV): T_{comf}=0.78$\overline{T_{pma}}$+9.42	The comfortable temperatures in prefab construction site offices (PCSO) are

				Summer (AC): $T_{comf}=0.18\overline{T_{pma}}+22.89$	26.1 and 21.1 ℃.
Kumar *et al*. [84]	2020	Workshop	NV	$T_{comf}=0.81T_{rm}+6.03$	The comfortable temperature range of students at high metabolic rates in a naturally ventilated workshop building from India is between 28 to 32 ℃.

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