Field Studies of PMV and Its Several Extended Models in Real Buildings: A Literature Review

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Abstract

The Predicted Mean Vote (PMV) is widely acknowledged as the quintessential model for assessing thermal comfort in indoor environments on a global scale. Its empirical validation has sparked debates regarding the applicability and dependability of the model within real-world building contexts. This paper initially presents the fundamental principles of the PMV model, encompassing its mathematical formulation, influential variables, and criteria for thermal comfort assessment. Subsequently, a comprehensive classification and review of the PMV model is conducted with respect to office buildings, residential spaces, educational institutions, healthcare facilities, fitness centers, religious structures, and commercial complexes. Finally, detailed descriptions of several extended PMV models (*e*PMV, *a*PMV, and *n*PMV) are provided. This paper aims to assist architectural designers and HVAC system operators in navigating the intricate and diverse landscape of standards related to thermal environments. The ultimate goal is to enhance indoor environmental quality and energy efficiency.

Keywords

Field studies; Predicted Mean Vote(PMV); thermal comfort; extended PMV models.

1. INTRODUCTION

Thermal comfort is a pivotal focus in the examination of the built environment, with its origins dating back to Blagden and his team's assessment of thermal tolerance[1,2]. Gaggeand Fangerdefined thermal comfort as a state of contentment in which individuals do not perceive themselves as either hot or cold relative to their environment, they experience a neutral thermal sensation in this state of comfort[3,4].Widely recognized international standards ISO 7730 (2005)and ASHRAE (2004) defined it as the mentalcondition in which satisfaction with the thermal environmentis expressed[5,6].The formulation of these two standards is grounded in the study of the predicted mean vote (PMV) model.

The PMV thermal comfort evaluation model was proposed by Fanger and his colleagues in the late 1960s,based on the human thermal comfort equation and the thermal sensation voting results of 1396 American and Danish subjects in an artificial climate chamber. It is utilized to assess how much a specific environment's thermal comfort deviates from that of a "thermal neutral" environment[4].And it is widely applied in thermal comfort design and field evaluation[7,8].

For over the past half a century , numerous researchers across various regions have embraced the PMV modelas an internationally recognized, thequintessential, and the extensively utilized thermal comfort evaluation indicator[9].Generally effective within built environments equipped with HVAC systems owing to their ability to produce near-neutral thermal sensations. However, intricateinteractions involving building envelopes, external weather conditions, window opening and HVAC systemoften render energy equilibrium between occupants and indoor climates unstable. In many field studies, researchers collected real data from the built environment, compared the predicted thermal sensation with actual occupant feedback and found that the predicted value of PMV model based on human thermal balance is significantly different from the real feelings of people in the actual building environment[9-12], underscoring an urgent imperative for comprehensive theoretical and practical investigations into refining our understanding of this influential framework.

In order to enhance the precision of PMV model and broaden its applicability, several extended PMV models have beenproposed, such as the extended predicted mean vote(ePMV) [13],adaptive predicted mean vote(aPMV) [14]and new predicted mean vote(nPMV) [15].These three modified models have exerted significant influence and have been widely utilized in various studies. For instance,aPMV has been employed by the Chinese standard GB 50785-2012 for assessing free-running environments. Therefore, these three modified models can serve asas representatives of the adjustment model.

At present, the existing review articles mainly focus on the direction of thermal comfort, thermal adaptation,etc.[1,8,11,15],there are no comprehensive review articles on the PMV model in real buildings. Therefore, this paper conducts a thorough review of field studies on PMV in real buildings over the past decades to better understand the progress of PMV research and its accurate application. It categorizes and reviews literature based on building types to identify similarities and differences, discusses the limitations of the PMV model, and explores the influence of other factors. The scope includes both air-conditioned and free-running buildings.

This paper is structured into five sections. Section 2 introduces the methodology of literature retrieval, while section 3 presents the foundation of the PMV model, encompassing its equation, influencing factors, and standards for thermal comfort evaluation. Section 4 categorizes and reviews the application of the PMV model from a building type perspective. In section 5, several extended PMV models are summarized.

2. LITERATURE SEARCH METHOD

This study adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines[16], employing a method that integrates keywords and conducts research across scientific information databases, followed by targeted screening to refine the retrieved literature

The Web of Science was utilized as the primary literature database for this study, and keywords such as predicted mean vote (PMV), thermal comfort, thermal adaptation, building, and field study were employed to conduct a systematic literature search. We utilized Boolean operators such as “AND” and “OR” to amalgamate the "predicted mean vote" with keywords pertaining to various building types in order to retrieve the most pertinent research.The Web of Science database was selected for this review due to its extensive coverage, multidisciplinary nature, core journal citation index inclusion, encompassing a wide array of globally recognized and high-impact academic journals. It is also widely adopted by researchers as the primary database.Theresults of keyword combination search strategy in Web of Science can be found in Table 1:

Table 1. Results of search strategy.

Search Strategy	Keywords and Combinations	Results
Database:Web of Science Search in:Topic	predicted mean vote OR PMV, AND thermal comfort OR thermal adaptation,AND field study AND building	349 articles

A literature search identified 349 pertinent publications, which were subsequently subjected to further scrutiny for the purposes of this study. The screening criteria are detailed in Table 2.

Table 2. Criteria for inclusion and exclusion.

Inclusion Criteria	Exclusion Criteria
Papers in English.	Reviews.
Articles published from 2005 to 2024.	Conference papers.
Field studies of PMV.	Papers in other languages.
Papers focusing on the correlation between PMV and field study buildings.	Papers were published without abstracts, failing to provide complete basic information.
(i.e. : Comparison of PMV with TSV or AMV)	Papers in thermal comfort, although not based on a field study.

According to the aforementioned criteria, a total of 47 publications were identified. The selection and collection process is illustrated in Fig. 1.

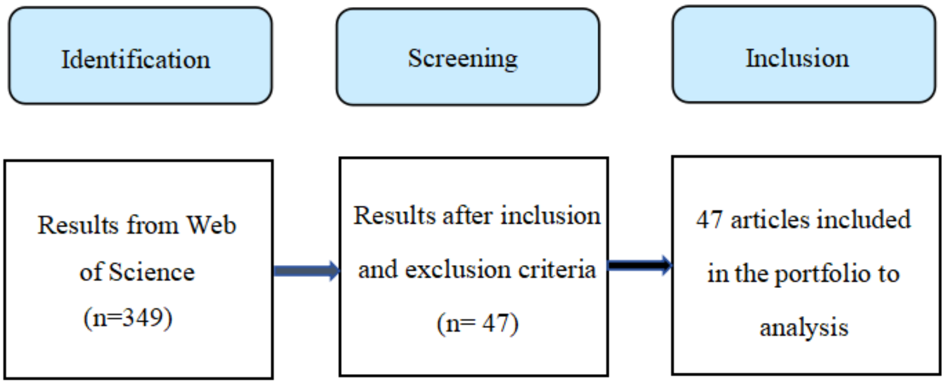

Figure 1. Process of selection and compilation for review

3. BASIS OF THE PMV MODEL

Thermal comfort refers to the integrated perception of the body's thermal state. The PMV model then quantifies this perception through the human body heat balance equation to assess the level of comfort experienced by individuals.

3.1. The equation of PMV model

The PMV model is calculated using the comfort equation for human body heat exchange [4]. It represents a heat balance model that considers the human body as a holistic entity. This model is valuable for predicting responses in steady-state air-conditioned environments but does not account for transient responses. The PMV is linked to the disparity between the actual heat transfer from a human body in a given environment and the required heat transfer for optimal comfort during specific activities, as expressed by the following equation[17]:

$$
\begin{aligned}
&PMV = [0.303 \bullet e^{(-0.036 \cdot \dot{M})} + 0.028] \\
&\bullet \{(\dot{M} - \dot{W}) - 3.05 \bullet 10^{-3} \bullet [5733 - 6.99(\dot{M} - \dot{W}) - p_a] \\
&\bullet 0.42[(\dot{M} - \dot{W}) - 58.15] - 1.7 \bullet 10^{-5} \bullet \dot{M} \bullet (5867 - p_a) - 0.0014 \bullet \dot{M} \\
&\bullet (34 - T_{db}) - 3.96 \bullet 10^{-8} \bullet f_{cl} \bullet [(T_{cl} + 273)^4 - (T_{MR} + 273)^4] \\
&- f_{cl} \bullet h_c \bullet (T_{cl} - T_{db})\}
\end{aligned}
\tag{1}
$$

Where: $\dot{M}$: metabolic heat rate, W /m²

$\dot{W}$:rate of mechanical work (or effective mechanical power) [W /m²],

T_{cl}:clothing surface temperature,°C

h_c:convective heat transfer coefficient,°C

f_{cl}:ratio of clothed surface area, m²

p_a: water vapor pressure, kPa

T_{db}:airtemperature,°C

T_{MR}:radiation temperature,°C

Among the terms present in the PMV equation,T_{cl}, representing clothing surface temperature, and the convective heat transfer coefficient $h_c$can be determined through iterative solution of the implicit equation. Owing to the complexity arising from numerous parameters in the PMV equation, its computation process typically involves computer-aided or graphical methods as detailed in section 3.4.

3.2. Factorsaffecting PMV

The body's heat balance is influenced by two primary groups of factors, ambient parameters and personal parameters. Ambient parameters encompass air temperature, radiation temperature, relative humidity, air velocity, while personal parameters include clothing thermal resistance and activity. In the 1960s to 1970s, Fangerformulated a mathematical model related to thermal comfort using these six parameters. While previous researchers proposed numerous influencing factors, Fanger selected only the key factors, incorporating not only physical environmental elements but also human physiological parameters [4]. These six parameters impact the PMV value in calculations as depicted in Fig. 2.

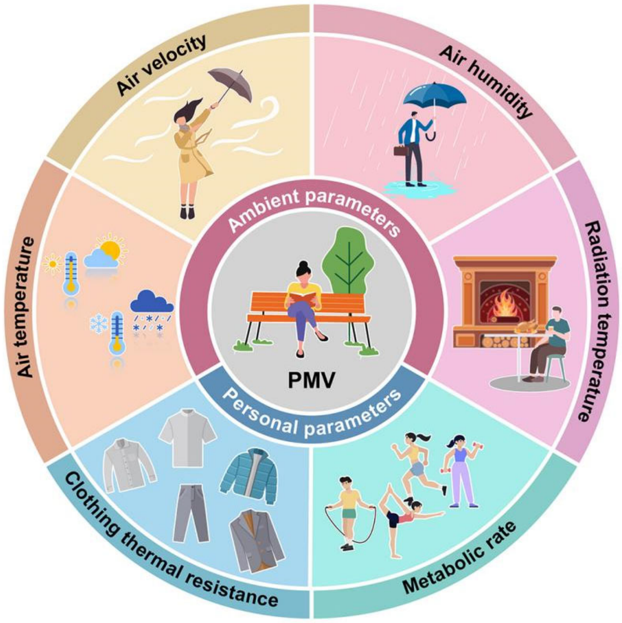

Figure 2. Six parametersaffecting PMV.

Among the ambient parameters, air temperature exerts the most significant influence. An increase in air temperature leads to a sharp rise in PMV (Fig. 3) [18]. Relative humidity has a lesser impact on PMV compared to air temperature. As humidity levels rise, their effect on thermal sensation of the human body becomes more pronounced. Nicol noted that while humidity does affect comfortable temperatures in tropical regions, its impact is minimal and challenging to quantify [19]. Radiant temperature also plays a crucial role, particularly in hot and humid areas, making it difficult for conventional indoor temperature and humidity control to ensure indoor comfort. Yang and Su [20] addressed the effects of radiant temperature and air velocity on PMVbased thermal comfort through experimental studies.Increased indoor air velocity has been shown to enhance thermal comfort[21, 22]. This represents a promising avenue for achieving energy savings.

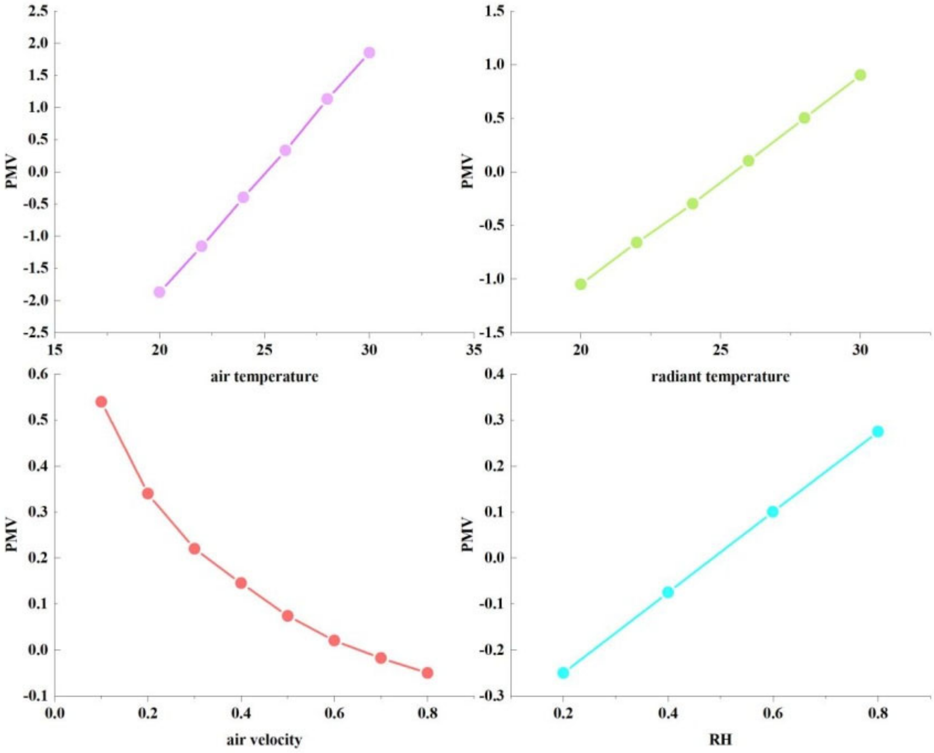

Figure 3. The influence of ambient parameters on PMV[18]

Both clothing thermal resistance and metabolic rate exert significant influences on PMV in personal parameters. However, in residential buildings, occupants typically engage in sedentary activities with a constant metabolic rate. Can and Ibrahim[23] conducted an experimental study comparing the thermal comfort of different clothing resistances in a controlled environment. The distribution of PMV values for both suit dresses and summer clothes closely align with the acceptable limits outlined by ASHRAE Standards. A thermal environment can provide comfort to individuals wearing either suit dresses (Icl=1.0 clo) or summer clothes (Icl=0.5clo). The appropriate selection of clothing is among the most critical factors for ensuring comfort, while also enabling energy consumption minimization.

3.3. Standards for thermal comfort

In the field of thermal comfort, three widely recognized international standards are frequently utilized: American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) standard-55 [6,24-26], the International Organization for Standardization (ISO) standard-7730 [5,27,28], and the European standard EN15251 [29]:

The ASHRAEStandard-55 exclusively deals with thermal comfort in indoor environments. Its scope is not limited to any specific building type, making it applicable to both residential and commercial buildings, as well as new or existing structures. Furthermore, it can be extended to occupied spaces such as vehicles (e.g., cars, trains, planes, and ships)[6]. The standard defines conditions that are acceptable to the majority of occupants exposed to the same environment within a space. The term "majority" is based on an 80% overall acceptability threshold, while specific dissatisfaction limits vary for different sources of local discomfort.

The PMV model employs the ASHRAE-55 standards 7-point scaleto quantify individuals thermal sensation (+3 hot, +2 warm, +1 slightly warm, 0 neutral, －1 slightly cool, －2 cool, －3 cold),as depicted in Fig.4 [30]:

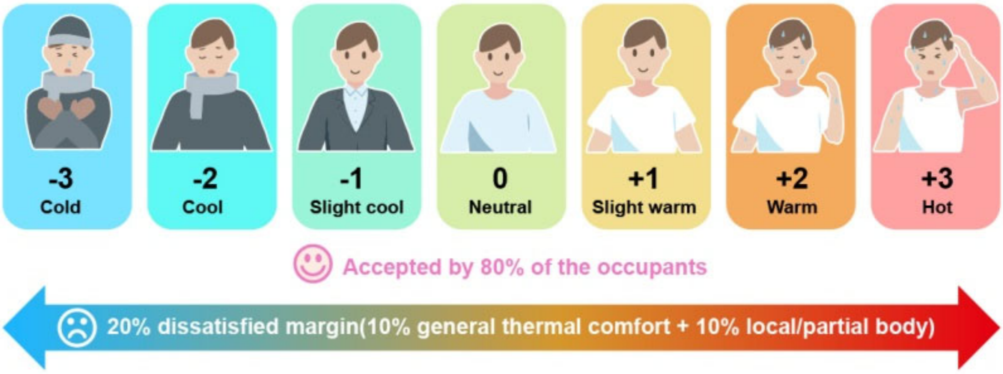

Figure 4. Thermal comfort definition from PMV acknowledged in ASHAR standard

The PMV index represents the thermal sensation experienced by the majority of individuals in a given environment. However, due to biological variations among people, the indicator may not accurately reflect everyone's perception. Therefore, Fanger proposed an associated index, Predicted Percentage Dissatisfied (PPD), to assess dissatisfaction with the thermal environment. The relationship between these two indicators is as follows [4]:

$$PPD = 100 - 95 \cdot \exp(-a_P \cdot PMV^4 - b_P \cdot PMV^2) \tag{2}$$

where $a_P = 0.03353$ and $b_P = 0.2179$.

The Predicted Percentage Dissatisfaction (PPD) serves as an indicator that quantifies the level of thermal comfort by expressing the percentage of individuals experiencing thermal dissatisfaction, and is directly determined by PMV.According to ASHRAE Standard 55–2010, the recommended acceptable PMV range for thermal comfort is $-0.5 < PMV < +0.5$, corresponding to $PPD < 10\%$ within an indoor environment.

ISO7730 standard: Since the formulation of the ISO7730-1984 standard, a series of ISO7730 standards have been developed, including ISO7730-1984[28], ISO7730-1994[29], and ISO7730-2005[5]. These standards are based on the PMV-PPD thermal comfort model proposed by Professor Fanger, and the evaluation indexes have remained largely unchanged. Additionally,the three different comfort categories A-C are proposed in ISO 7730:2005(Shown as Table 3).

Table 3. Categories of the thermal environment[5].

Thermal comfort standard	Recommended values
ASHRAE Standard 55	80% citeria(PPD≤20%;-0.85<PMV<+0.85)
	90% citeria(PPD≤10%;-0.5<PMV<+0.5)
	Category
ISO 7730	A(PPD<6%;-0.2<PMV<+0.2)
	B(PPD<10%;-0.5<PMV<+0.5)
	C(PPD<15%;-0.7<PMV<+0.7)
EN15251	I(PPD<6%;-0.2<PMV<+0.2)
	Ⅱ (PPD<10%;-0.5<PMV<+0.5)
	Ⅲ(PPD<15%;-0.7<PMV<+0.7)
GB50785-2012	(PPD<10%;-0.5<PMV<+0.5)

The PMV-PPD model is a widely utilized design tool integrated into thermal comfort standards, suggesting its applicability across various building types (such as schools, commercial spaces, hospitals , etc.) and climates. However, the accuracy of PMV-PPD model in predicting thermal comfort has been questioned through field studies in real buildings [9, 31] as well as in laboratory studies [10, 32, 33]. The Fig.5 is shown that different researchers have found a relationship between PMV and PPD that differs from the one described by Fanger[9].

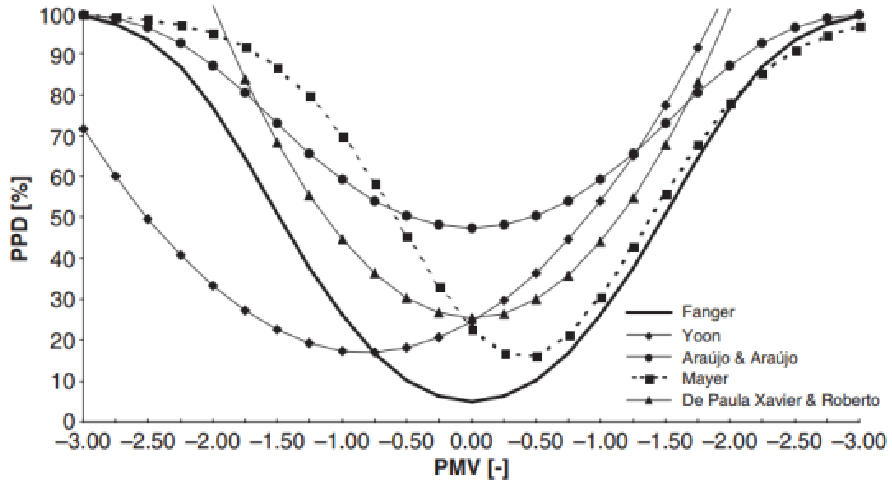

Figure 5. The relationship curve between PMV and PPD by other researchers[9]

European standard EN15251:The European Standard EN15251 [29], titled Indoor environmental input parameters for the design and assessment of energy performance of buildings, addresses indoor air quality, thermal environment, lighting, and acoustics. It is part of a suite of standards formulated by CEN to support the European Performance of Buildings Directive (EPBD), which aims to reduce the energy load of the built environment in Europe [34]. EN15251 utilizes data from the more recent European SCATs project, making it more directly applicable to Europe as befits a European standard.

4. FIELD INVESTIGATIONS OF THE PMV MODEL IN REAL BUILDING ENVIRONMENTS

4.1. PMVmodel in office buildings

The thermal comfort within office buildings has a direct impact on the operational efficiency and job satisfaction of employees. PMV models offer an effective means to evaluate indoor thermal comfort, enabling designers and managers to cultivate a more conducive work environment and enhance employee motivation and productivity.

The references [4, 9, 35-37] provide justification for the enhanced predictability of PMV in air-conditioned environments, particularly within office buildings. Appendix 1 compiles findings from studies comparing actual thermal sensation data collected in field settings with PMV indices in office buildings.Based on references [22, 38, 39], it is evident that PMV tends to overestimate the thermal sensation of occupants, indicating a substantial disparity between PMV and actual thermal perception. Conversely, as supported by references [40-43], it becomes apparent that the PMV model underestimates individuals' adaptability to relatively high temperatures. Notably, within the same office building, PMV may concurrently underestimate or overestimate thermal comfort depending on the season. This phenomenon could be attributed to variations in neutral temperature across different regions or diverse air conditioning modes leading to distinct thermal comfort and adaptive behaviors among occupants.

If the temperature falls outside the neutral zone, a "scissors difference" between TSV and PMV[44-46] emerges. Bin et al[45] also noted that this "scissors difference" is present not only in non-air-conditioned environments during summer, but also in air-conditioned environments.

Due to human adaptive behavior, individuals in naturally ventilated environments exhibit greater tolerance towards their thermal surroundings. The PMV model's predictions in such settings tend to overestimate thermal sensation at high temperatures and underestimate it at low temperatures[19, 47, 48].

4.2. PMV model in residential buildings

Extensive research on the indoor thermal comfort of residential buildings has been conducted by scholars from India and China, as evidenced in Appendix 2. As a country with diverse climates, Indian scholars have focused on the adaptability of the thermal environment in different regions and seasons, exploring methods to achieve a comfortable indoor environment under varying climatic conditions. Field studies conducted during the summer and monsoon seasons in Hyderabad, India, on naturally ventilated residential buildings have consistently shown that PMV exceeds TSV [49-51]. Similar conclusions have also been reached by scholars in Indonesia and China [52,53].

Some researches have indicated a weak correlation between the thermal sensation vote (TSV) and PMV in residential buildings [51, 54-56]. Becker et al.[54] conducted field studies on thermal comfort in 189 dwellings during winter and 205 dwellings during summer in Israel, both with and without HVAC systems. The results showed that the TSV value was significantly higher than the PMV value. This discrepancy was attributed to inconsistencies with the PMV Model, which generally underestimates actual thermal sensation. A similar conclusion was drawn from a field study of dormitory buildings in China and India [51, 56].

Chinese scholars have also investigated residential thermal comfort in various climate zones, encompassing both urban and rural areas[57], and have similarly observed a "scissors difference" as described in reference [45]. Shen et al.[58] noted that the predicted PMV results vary across different seasons.

The PMV model not only enables the prediction of thermal comfort in indoor environments, but also facilitates the selection of the most suitable type, capacity, and operational mode for air conditioning systems by designers to achieve a balance between comfort and energy efficiency

4.3. PMV model in schools

Schools, particularly classrooms, are crucial environments for teaching activities, and the indoor thermal comfort significantly impacts the effectiveness of instruction. Almeida et al. [59] conducted a study in Portugal, collecting 32 measurements and 490 questionnaires from 10 educational spaces including classrooms and libraries across different educational levels. The overall comfort was assessed using the PMV index and EN 15251 adaptive model. The study revealed that adjusting metabolic rate is essential when employing PMV analysis methods, with the child's body surface area identified as an effective correction factor. Discrepancies were observed between calculated PMV values and mean thermal sensation reported in questionnaires. Furthermore, comparison with the EN 15251 model indicated greater stringency of the PMV index. A separate investigation into thermal comfort for children (aged 9-11) in non-air-conditioned classrooms at three schools in the Netherlands [60] demonstrated that the PMV model inadequately predicted their thermal sensation, underestimating it by up to 1.5 scale points; children preferred lower temperatures than those predicted by the PMV method. Teli et al.'s findings further supported these conclusions and highlighted that existing thermal comfort standards underestimated children's thermal sensation during summer [61,62].

Children exhibit greater sensitivity to changes in metabolic rate compared to adults, and their preferred temperature was found to be lower than the prediction by the PMV model [63,64]. A comparison of various adjustment methods in the literature for the PMV model indicates that adjusting resting metabolic rate based on surface area and calculating "met" values appear to yield reasonable results for thermal sensation and satisfaction in school-aged children [59,61,62].

In comparison to adults, young children exhibit a reduced capacity for recognizing thermal sensations and tend to feel comfortable in temperatures approximately 3 degrees lower than those preferred by adults[63]. The findings presented in Appendix 3 provide additional evidence that the PMV model significantly underestimates the thermal sensation of students during summer. Consequently, there is a need to develop a new PMV model tailored specifically for children in future studies.

4.4. PMV model in hospitals

The indoor environment of hospitals exerts a significant influence on the operational efficiency of medical personnel and the recovery process of patients. In a tropical climate, Sattayakorn et al. [65] conducted an assessment of two hospitals in Bangkok and observed that the PMV model did not accurately capture thermal comfort for healthcare occupants, particularly medical staff. The acceptable temperature range for patients, visitors, and medical staff was found to be higher than what is suggested by Thai standards. A similar study in Malaysia by Yau et al. [66] evaluated four hospitals and revealed that 49% of occupants were satisfied with the thermal environment; however, Malaysians in hospital settings require a higher comfort temperature compared to ASHRAE 55 regulations. Reference [67] concludes that due to their illness and lower expectations regarding thermal conditions, patients tend to accept wider comfort ranges than others; conversely, medical staff in humid areas prefer cooler temperatures. The substantial deviation between AMV/TSV and PMV strongly suggests that PMV may not be suitable for application in tropical hospitals such as those in Malaysia.

Ma et al. [68] conducted a study to investigate and compare the thermal comfort status of medical staff in four hospitals in Ningbo, China. They evaluated the thermal neutral temperature of medical staff (as shown in Appendix 4), developed an adaptive prediction vote model (aPMV) for medical staff (introduced in section 5.2), and validated its reliability.

In the context of the COVID-19 pandemic, with hospital environments and health professionals receiving significant attention, Pedro et al.[69] conducted a literature review encompassing studies published between 1968 and August 2020. They highlighted that the Fanger index does not accurately represent the thermal sensation experienced by individuals in hospital settings, and emphasized clear distinctions between PMV and TSV.

From Appendix 1 to Appendix 4, it can be inferred that the thermal sensation of occupants varies significantly when considering factors such as building type, location, gender, age, and activity. These findings have been summarized in detail. Fig. 6 illustrates the neutral temperature, comfortable temperature, and operating temperature ranges based on relevant literature.

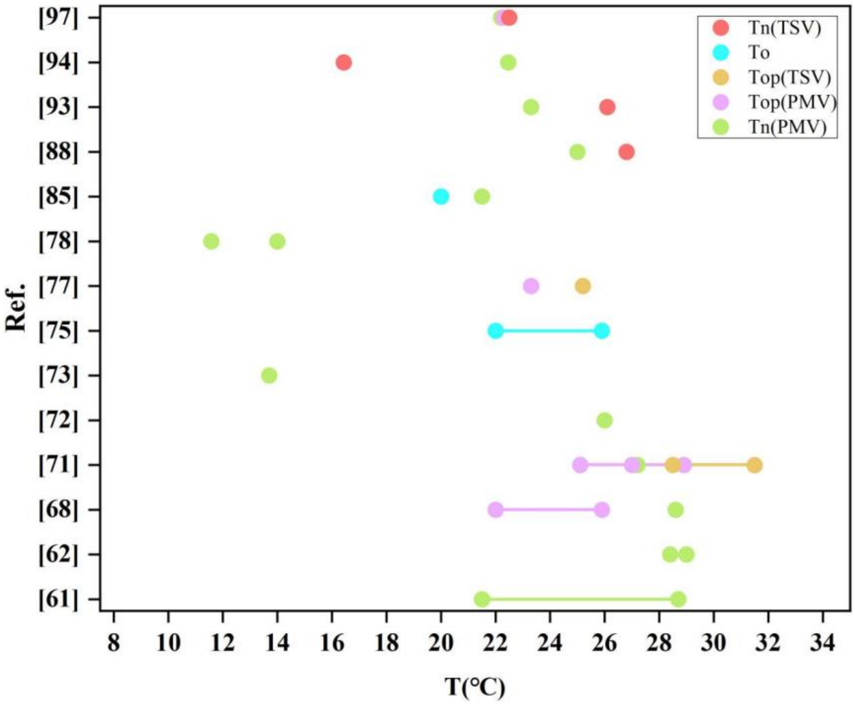

Figure 6. The T_n,T_o,T_{op} in the selected studies

Various factors influencing the accuracy of PMV include occupant clothing, activity level, health status, expectations, preferences, adaptation, and cultural differences. These factors lack specific measurement devices and are estimated only, leading to inaccuracies in predicting thermal sensation. Strict adherence to the PMV model is suitable for building evaluation; however, practical application may call into question the accuracy of PMV under certain conditions.

5. EXTENSION OF PREDICTED MEAN VOTE (PMV) MODEL

The extended models refer to the theoretical indoor thermal comfort evaluation model which integrates steady-state PMV and adaptive model.

5.1. Extended Predicted Mean Vote(ePMV)

In order to expand its applicability to free-running(naturally ventilated)buildings, enhancements were incorporated into the original PMV model. Fanger and Tofum[13] proposed an expectation factor "*e*," estimated to range between 0.5 and 1, in order to adjust the PMV model calculations for warm and humid climates in non-air conditioned buildings under steady-state air conditioning conditions.As expressed by the following equation:

$$PMV\mathrm{e} = \mathrm{e} \times PMV \tag{3}$$

Alfano et al. [70] presented a comprehensive analysis of the humid and thermal comfort conditions in naturally ventilated Italian classrooms during summer and winter, incorporating both objective and subjective measures. By calculating PMV values from objective data and gathering thermal voting responses through questionnaires from a surveyed student sample of over 4,000 individuals, it was found that the students were better able to adapt to warm conditions than originally predicted by Fanger's theory.

In the case of China, Fanger suggested that "*e*" should be 0.7. However, Shen, Duanmulin, and others argue that considering China's extensive territory and complex climate, attention should be paid to the value of "e" when utilized.

5.2. Adaptive Predicted Mean Vote(aPMV)

The term Adaptive Predicted Mean Vote (*a*PMV) refers to the thermal comfort in non-air-conditioned buildings within a warm environment. This model comprises a regression equation that establishes the relationship between indoor neutral temperature and outdoor monthly average temperature [71].

Yao et al. [14] demonstrated the correlation between aPMV and PMV based on Fanger's experimental research in naturally ventilated buildings:

$$aPMV = (PMV^{-1} + \beta)^{-1} \tag{4}$$

The term β, known as the "adaptive coefficient," reflects the adaptive effects of humans. The value of β is -0.125 for cold conditions and 0.293 for warm conditions, slightly larger than the range of 0.029 to 0.167 obtained in [72]. This difference is attributed to relative humidity, which strongly influences the thermal sensation of free-running buildings. However, the "adaptive coefficient" varies among different regions and residents; for instance, it takes on values of -0.34/-0.196 in cooler environments and 0.128/0.334 in warmer environments in [58,73].

5.3. New Predicted Mean Vote (nPMV)

The New Predicted Mean Vote (nPMV) is recommended by Humphreys and Nicol [15] for air-conditioned buildings. This method is also based on the adaptive comfort theory.The equation for nPMV is presented in [19] as follows:

$$nPMV = \gamma \cdot \left\lfloor PMV - f_{PMV\_ASHRAE} \right\rfloor \tag{5}$$

with the coefficient γ = 0.8.

The predictive regression expression of the f_{PMV_ASHRAE} function assesses the correlation between the PMV model and the actual thermal sensation [15]:

$$f_{PMV\_ASHRAE} = -4.03 + 0.0949 \bullet T_{OP} + 0.00584 \bullet RH\% + 1.201 \bullet \dot{M} \bullet I_{cl} + 0.000838 \bullet T_{out}^{2} \tag{6}$$

T_{out} is the outdoor mean air temperature.

The findings of Kim et al. [74] indicated that nPMV has the potential to enhance the accuracy and performance of the original PMV, making a significant contribution to reducing cooling energy consumption in air-conditioned buildings. Wong and Khoo[75] evaluated thermal conditions in naturally ventilated classrooms in Singapore. However, it was found that the nPMV model is not suitable for predicting thermal sensations at lower temperatures (27℃-28℃) or higher temperatures (31℃-32℃).

6. CONCLUSIONS

The purpose of this study was to investigate the validity and accuracy of the PMV model, which necessitated conducting field studies in real buildings. Drawing from nearly 20 years' worth of relevant literature, the findings can be summarized as follows:

Faner's thermal comfort model integrates six factors that influence human thermal comfort, encompassing both personal variables and ambient variables. It derives the PMV index, thereby shifting the focus of thermal comfort research from qualitative to quantitative. This model represents the most comprehensive approach for evaluating the thermal environment to date, making a pioneering contribution to the theory of thermal comfort and indoor thermal environment evaluation in buildings.

Several studies have indicated that the PMV model may not always be suitable or fully appropriate for accurately predicting thermal comfort in certain scenarios. It overlooks certain secondary factors such as building type, body type, age, gender, activity intensity, and the surrounding thermal environment. For instance, in hot, dry, cold or wet areas, one should take into account people's adaptability to local climate and their ability to adjust to environmental conditions when determining the PMV index value for optimal thermal design. This approach ensures a more comfortable thermal environment while also conserving energy.

Fundamentally, the adaptive theory suggests that humans can exert significant influence on thermal comfort, indicating that individuals have the capacity to consciously or unconsciously manipulate their ambient thermal environment by adjusting metabolic rate, posture, and clothing preferences. Therefore, the three typical modified models (*e*PMV, *a*PMV, and *n*PMV) considering thermal adaptationexhibit superior accuracy compared to the PMV model; however, there remains scope for further enhancement.

CREDITAUTHORSHIP CONTRIBUTION STATEMENT

Li Li: Writing – review &editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. Lei Zhang: Visualization, Investigation, Formal analysis. Huijuan Xu: Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization. LijunGao: Visualization, Investigation, Formal analysis, Conceptualization. RongLi: Visualization, Investigation, Formal analysis.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY

Data will be made available on request.

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Appendix 1: Discrepancies between PMV and real thermal sensation in office buildings

Reference (Year)	Samples	Season	Type of ventilation	Country (City)	Standard	Predicted Results		Main Findings (Equation)
						Over estimated	Under estimated	
[38] (2006)	1 office building	summer	NV	China (Shanghai)	ASHRAE-55	×		The upper boundary of the Top is about 29℃.
[59] (2017)	1 office building	summer	VAV AC	Qatar (Doha)	ASHRAE-55	×		There is a large gap between PMV and ATS.
[40] (2020)	88 offices and 7 meeting rooms	summer	AC	Benin (Cotonou)	ISO 7730		×	The comfort interval: 24.7℃-28℃
[41] (2009)	2 office buildings	summer	AC	Belgium (BrusselsLeuven)	ASHRAE-55		×	The number of dissatisfied noted was higher than the 5% from the standard curve in two cases.
[42] (2012)	6 office buildings 18 offices	summer	AC/MV	Singapore China (Hong Kong) (Taiwan) (Hunan)	ISO 7730		×	PMV =0.16 ± 0.31, TSV=1.34 ± 1.28
[43] (2016)	16 office buildings	summer	AC(3) NV(7) MM(6)	India (Chennai) (Ahmedabad) (Delhi) (Bangalore) (Shimla)	ASHRAE-55		×	The predicted feeling is always warmer than the observed. Indians prefer warmer temperatures and are highly adaptability.
[44] (2023)	7 office buildings (3 ECA and 4 NV office buildings)	summer	ECA(3)NV(4)	China (Turpan)	ASHRAE-55	scissors difference		TSV＝0.47Top－13.35 TSV＝0.46Top－13.36
[45] (2008)	1 office building	summer + winter	AC	China (Beijing)	ASHRAE-55	scissors difference		The “scissors difference” between TSV and PMV when the temperature was out of the neutral zone.
[46] (2012)	1 office building	summer + winter + swing season	MM	Australia (Sydney)	ASHRAE-55	scissors difference		Although the PMV value is the same, the thermal sensation is different for different modes.
[47]	2 office buildings	summer	Case 1: MM Case 2: NV	Australia (Sydney)	ASHRAE-55		×	The users of the naturally ventilated building are more tolerant with respect to their thermal environment.
[48]	1505 valid questionnaires	summer + autumn + winter	AC/NV	China (Guangzhou)	—	× overestimated (summer and autumn) underestimated (winter)		The thermal comfort ranges were significantly different in different seasons.

*Please note that TSV (Thermal Sensation Vote), MTSV (Mean Thermal Sensation Vote) ， TPV(Thermal Preference Vote)and AMV (Actual Mean Vote) are the same thing.

Appendix 2: Discrepancies between PMV and real thermal sensation in residential buildings

Reference (Year)	Season	Type of ventilation	Country (City)	Standard	Predicted Results		Main Findings (Equation)
					overestimated	underestimated	
[49](2010)	summer + monsoon season	NV/MV	India (Hyderabad)	ASHRAE-55	×		Comfort band ： 26℃-32.5℃, above the standard (23 ℃-26℃)
[52] (2004)	dry season + rainy season	NV	Indonesia (Jogjakarta)	ASHRAE-55	×		$TSV = 1.33PMV - 1.61$
[53] (2021)	winter	heated Kang + radiators	China (Qingdao)	ASHRAE-55	×		$TSV = -0.93 + 0.07Top$ $PMV = -3.03 + 0.15Top$
[54](2009)	summer + winter	AC/NV/MV	Israel	—		×	The 90% satisfaction level： summer：$Ta=23$℃(AC) $Ta=26$℃(NV) winter：$Ta=21.5$℃(heated) $Ta=19.5$℃(non-heated)
[55](2006)	summer	AC/NV	China (Changsha，Guangzhou，(Shenzhen)	ASHRAE-55		×	$TSV=0.409Top-11.71$ $PMV=0.242Top-5.39$
[56] (2016)	winter + transition season	radiators	China (Harbin)	ASHRAE-55		×	LA：$MTS=0.198Ta-4.249$ $PMV= 0.280Ta-6.432$ EH：$MTS=0.340Ta-7.106$ $PMV= 0.245Ta-5.639$ MH:$MTS=0.176Ta-3.867$ $PMV= 0.244Ta-5.535$ LH:$MTS=0.132Ta-2.798$ $PMV= 0.227Ta-5.332$ ES:$MTS=0.248Ta-5.603$ $PMV= 0.277Ta-6.615$
[51] (2017)	summer	NV	India (Calicut)	ASHRAE-55		×	$PMV=0.746TSV+1.454$ $PMV= 0.852TPV+1.239$
[57] (2009)	winter	NV	China (Changsha)	—	(scissors difference)		Urban residence： $MTSV=0.21Top-2.93$ $PMV=0.17Top-2.42$ Rural residence： $MTSV=0.22Top-2.53$ $PMV=0.46Top-4.16$
[58] (2009)	summer + winter	FR	China (Wenchuan)	ASHRAE-55	× summer	× winter	Winter: $TSV=0.1049Ta-1.7126$ $PMV=0.2112Ta-4.1623$ Summer: $TSV = 0.1612Ta-2.79$ $PMV=0.4021Ta-10.1362$

Appendix 3: Discrepancies between PMV and real thermal sensation in schools

Reference (Year)	age	Season	Type of ventilation	Country (City)	Standard	Predicted Results		Main Findings (Equation)
						overestimated	underestimated	
[59] (2015)	adult	summer + winter	FR	Portugal (Viseu)	EN 15251		×	Metabolic rate needs to be adjusted, using the body surface area as the correction factor.
[60] (2011)	9-11	winter + spring + summer	MV/NV/FR	Netherlands (Eindhoven)	ISO 7730		×	PMV underestimates the mean thermal sensation up to 1.5 scale point.
[61] (2012)	7-11	spring + summer	NV	UK (Southampton)	EN 15251		×	Children are more sensitive to temperature than adults.
[63] (2014)	4-6	spring + summer	NV	Korea (Seoul)	EN 15251		×	PMV = 6.866 Met-9.301 TSV=10.396Met-13.306
[64] (2007)	adult	spring	NV	China (Changsha)	ASHRAE-55	×		TSV＝0.0448Top－0.9628 PMV =0.1162Top－2.8758

Appendix 4: Discrepancies between PMV and real thermal sensation in hospitals

Reference (Year)	Season	Type of ventilation	Country (City)	Standard	Predicted Results		Main Findings (Equation)
					overestimated	underestimated	
[65] (2017)	summer	AC	Thailand (Bangkok)	ASHRAE-55		×	Patient:To=21.8℃－27.9℃, Visitor:To=22.0℃－27.1℃ Medical Staff:To=24.1℃－25.6 ℃
[66] (2009)	summer	AC	Malaysian	ASHRAE-55		×	To=25.3℃－28.2℃
[68] (2023)	summer	AC	China (Ningbo)	ASHRAE-55	–	–	PMV:Tn=21.81℃ TSV：Tn=20.99℃
[67] (2013)	summer	AC	Malaysian	ASHRAE-55	×		PMV=0.982TSV+0.757 TSV=0.487Top-12.96