

EVOLUTION AND ADVANCEMENTS IN THERMAL COMFORT RESEARCH : A NARRATIVE LITERATURE REVIEW

Shivani Senthilkumar^{1*}, Poulomee Ghosh²

¹Research Scholar, NICMAR University, Pune, India – 411045

²School of Real Estate and Facilities Management, NICMAR University, Pune, India – 411045

*Corresponding author's email: shivani.phd2@pune.nicmar.ac.in

Abstract

Introduction: Climate change, heat waves, greenhouse gas emissions, and global warming have become a never-ending cycle, contributing to environmental degradation and causing discomfort to humans and other living beings. To address climate change, research on the thermal comfort of buildings has been conducted and developed since 1946, using both passive and active thermal comfort strategies. To understand the evolution of thermal comfort, this paper aims to establish the progression and principles of thermal comfort research. **Methodology:** A narrative literature review method was adopted to analyze the progress of thermal comfort research. A total of 122 selected articles examined concepts, models, architectural perspectives, standards, and policies related to thermal comfort. **Results and discussion:** Thermal comfort has evolved from the invention of air conditioning to the application of passive thermal comfort strategies in buildings. Thermal comfort research has consistently identified six key parameters that have improved our understanding of indoor thermal comfort. Moreover, the use of innovative technologies in thermal comfort studies can enhance occupant health and well-being. An interdisciplinary approach to thermal comfort research is therefore necessary. **Recommendations:** This study outlines the sequence of thermal comfort research, including innovations in models, simulation, prediction, and emerging challenges. As such, it will help future researchers, developers, and other stakeholders in the built environment to fill gaps and connect past findings with future directions.

Keywords: thermal comfort, chronology of thermal comfort, thermal comfort models, adaptive thermal comfort model.

Introduction

Climate change is a global concern. Human emissions become trapped in the atmosphere and release heat back into the environment. Carbon dioxide — one of the key greenhouse gases responsible for climate change — remains in the atmosphere for 300 to 1,000 years after it is initially produced, causing heat waves (NASA, 2019). As a result, the average global temperature has risen by 0.8°C compared to pre-industrial levels (NASA, 2011). Heat waves are becoming more frequent, severely affecting human survivability, especially in countries like India (Gupta, 2024). This climate scenario increases the demand for thermal comfort (TC) in living spaces, leading to the widespread installation of air conditioners in buildings and further contributing to emissions. It should be noted that approximately 30 % of all CO₂ emissions come from buildings, which accounts for nearly 40 % of global energy use (Lee et al., 2023).

Thermal comfort (TC) refers to the sensation of being hot or cold in a confined environment. It is essentially about how a person feels in a space, whether they perceive it as comfortable or not. Here, comfort is understood primarily in terms of temperature. The definition of TC is “the condition of mind that expresses satisfaction with the thermal environment” (ASHRAE, 2013). Several

other studies have also provided definitions of TC. According to Emeter (2022), TC is a subjectively evaluated mental state that indicates contentment with the thermal environment. In addition to being a person's perception of the thermal atmosphere, TC is also described as a neutral sensation regarding a given thermal environment — that is, the ability to remain sweat-free. TC is a multifaceted phenomenon influenced by mean radiant heat, air velocity, relative humidity, and ambient temperature (Chatzidimitriou and Yannas, 2016). There are six main TC parameters: four environmental factors (air temperature, relative humidity, mean radiant temperature, and air velocity) and two personal factors (clothing insulation and metabolic rate). These parameters are universally recognized and adopted in research and practice.

Research on TC has continually progressed, evolving from the invention of air conditioning (active strategies) to a growing focus on passive strategies, with contemporary emphasis on climate change, energy consumption, and environmental impacts. However, the roots of TC extend back to human evolution, beginning when humans lived in caves. The invention of fire provided warmth during cold nights, marking one of the earliest concerns for TC. This historical perspective illustrates that humans have always sought ways to maintain thermal

satisfaction. Scientists studied TC on warships and gradually shifted their focus to indoor environments. Research advanced further with the introduction of computerization, simulation, and modeling. Modern TC research began in earnest in the 1930s, initially focusing on human metabolic activities (Stoops, 2006).

Typical areas of TC research can be categorized as follows: TC and energy efficiency, indoor environmental quality (IEQ) (Ma et al., 2021; Weng et al., 2023; Zuo et al., 2021), TC measurements (Nishi et al., 2017; Revel et al., 2014), passive strategies (Elshafei et al., 2021; Inusa and Alibaba, 2017; Pitts, 2017; Rana, 2021; Tungnung et al., 2023), active strategies (Gomez-Azpeitia et al., 2012; Han and Chen, 2017; International Energy Agency, 2018), TC bands (Faheem et al., 2023; Pal et al., 2024; Soflaei et al., 2020), adaptive TC (Manu et al., 2016; Rawal et al., 2022), personal TC (Luo et al., 2018), group comfort systems and analysis (Chowdhury et al., 2008; Kumar et al., 2022; Weng et al., 2023; Xie et al., 2014), simulation (Pragati et al., 2023; Thapa et al., 2023), and optimization (Alghamdi et al., 2024; Liu et al., 2024; Senthilkumar and Ayyathurai, 2022). As research has advanced, the complexity and scope of TC studies have also expanded. Understanding the chronological development and diverse areas of TC research is therefore crucial for new researchers. Given the breadth of the literature and the significance of the field, a clear understanding of TC evolution is especially important, particularly regarding its implications in India.

This study aims to identify the chronological progression of TC research, providing a comprehensive overview of its evolution over time. It seeks to explore key themes, trends, and debates within the literature, offering insights into the primary focus areas and

ongoing discussions in the field. Finally, the study aims to highlight gaps and opportunities for future research, equipping researchers with a clearer understanding of TC studies and guiding them in selecting appropriate methodologies by building on existing models and approaches.

Method of Literature Review

This study adopted a narrative literature review approach, which is well-suited to the aim of understanding the chronological progression of TC research. The literature search was conducted using electronic databases such as Scopus, Google Scholar, ScienceDirect, and ProQuest. The timeline for the search was set from 1946 to 2024 (see Fig.1). Such an extensive time range was required to capture the chronology of TC studies. The starting year of 1946 was chosen because the earliest published evidence on Scopus dates from that year. The preliminary screening of papers was based on titles and abstracts. The keyword “thermal comfort” generated 39,847 papers in Scopus. Papers were selected according to three main criteria: 1) to understand the fundamental concepts of TC and its relationship with the environment; 2) to trace the evolution of TC, including its origins, early indicators, and applications in architecture; 3) to examine research domains focused on TC models, simulation and prediction, standards, and policies. Only papers written in English were considered. In total, 122 sources were reviewed for this study, including journal papers, reports, conference proceedings, book chapters, code books, standards, and web resources. Of these, 86 were cited directly.

Chronology of Thermal Comfort Research

The study of TC is inherently interdisciplinary. As discussed earlier, TC concerns the thermal

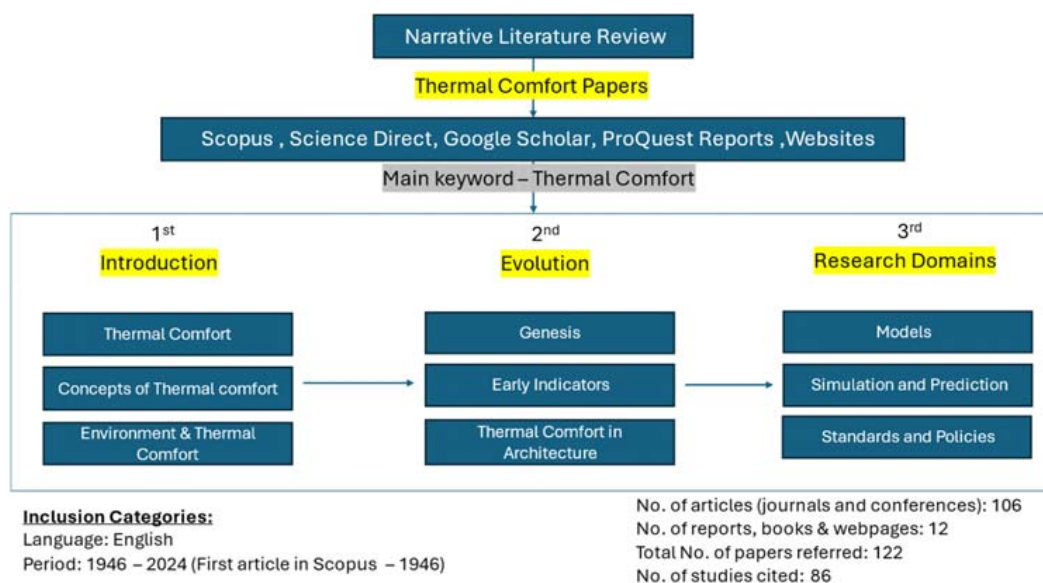


Fig. 1. Flowchart illustrating the literature review process for this study (Source: Author)

satisfaction of building occupants. Early TC research was primarily driven by military needs, focusing on innovations for warships, airplanes, and high-temperature environments. Research then shifted to indoor TC, examining physical, physiological, psychological, social, and cultural interactions, including the influence of human activity, clothing, architecture, and eating habits (Fabbri, 2015). Initially, TC studies concentrated on human physiology and physical factors. Over time, the focus evolved toward adaptive thermal comfort, exploring how people adjust their behavior to maintain comfort indoors. This transition also introduced the concept of space heating, which became a central concern in Western countries, where heating needs were particularly significant (de Dear et al., 2016).

Genesis of Thermal Comfort Research

This section identifies and discusses the key events and milestones in the history of TC research in chronological order.

The earliest stages of TC research focused on human comfort and the physiological effects of the environment. In 1850, American physician John Gorrie invented the first cooling machine, designed for hospitals to treat yellow fever patients. The device operated on a cold-air refrigeration process, emerging from attempts to reduce patient fevers by cooling indoor spaces. Fifty years later, in 1902, Willis Carrier — known as the father of modern air conditioning — developed the first true air conditioner. Carrier's system cooled air by passing it over coils filled with chilled water. Although the earliest air conditioners were large and expensive, the underlying principles remain the basis of today's systems. Early research at this stage primarily emphasized air temperature and air-related parameters. In the 1910s, synthetic air charts were introduced to represent vapor–liquid equilibria in the air. Building on this, Carrier made a major contribution in 1911 by presenting the psychrometric chart, a breakthrough that laid the foundation for modern air conditioning (McDowall, 2006). This chart illustrated the relationships between temperature, humidity, and other air properties, becoming an essential tool for engineers, architects, and HVAC (Heating, Ventilation, and Air Conditioning) specialists. The application of psychrometrics quickly extended beyond building comfort to fields such as meteorology, agriculture, and industrial processes, significantly shaping the design and operation of air conditioning and refrigeration systems (Teitelbaum et al., 2023). At the core of these studies was the investigation of water–air vapor–liquid equilibrium, fundamental to understanding TC and the dynamic interplay between relative humidity and air temperature (Mark Crawford, 2012).

The studies “Determination of the Comfort Zone” and “Determining the Lines of Equal Comfort”, published in 1923 by Houghten and Yaglou, introduced the empirical index of Effective

Temperature (ET). ET for a given space is defined by the dry-bulb temperature of a thermo-equivalent environment with 50 % relative humidity and a specific uniform radiation condition. The term “thermo-equivalent conditions” refers to combinations that produce the same sensation of warmth or coldness (Roy Choudhury et al., 2011).

In 1936, Gagge developed the two-node model, a technique for predicting how the human body responds to temperature changes in its surroundings. This model has applications in thermal ergonomics, occupational health, and HVAC design, and is useful for evaluating human TC. According to the model, the human body is represented as two interacting thermal nodes: the core node, representing internal organs, and the skin node, representing the body's outer layer. This model is particularly important in environments where maintaining optimal temperatures is critical for human safety and comfort (van Hoof, 2008).

Simultaneously, the use of thermal manikins for TC research gained popularity in the 1940s. The United States Army was the first to adopt thermal manikins, subsequently using them to study indoor environments, clothing, and textiles (Simova et al., 2021). Thermal manikins are used to measure the Manikin-Based Equivalent Temperature (MBET), helping to determine tolerable temperatures and evaluate personal comfort systems (Luo et al., 2018; Mustakallio et al., 2017).

By the 1950s and 1960s, research increasingly focused on the impact of discomfort on health, giving rise to the term “Sick Building Syndrome” (Ganji et al., 2023; Nduka et al., 2021; Weng et al., 2023; Zuo et al., 2021). Many studies from this period were published in journals related to medicine, health, textiles, physiology, industrial medicine, toxicology, and industrial hygiene. The first documented building TC research in Scopus dates back to 1954, with a study by A. E. Moore on the thermal properties of concrete floors.

The 1960s and 1970s are often regarded as the golden era of TC research, during which numerous influential studies were conducted. Danish physiologist Ole Fanger focused on the correlation between environmental and physical factors and physiological responses, alongside subjective well-being reported by occupants (van Hoof, 2008). Building on this work, Fanger developed models such as the Predicted Mean Vote (PMV) to predict TC for groups of people (van Hoof, 2008). His contributions laid the foundation for adaptive TC research (Fabbri, 2015; Karyono et al., 2020). Later, Richard de Dear proposed an adaptive TC model, which was adopted in the ASHRAE 55 guidelines (Brager and de Dear, 1998).

Early Indicators of Thermal Comfort

In the 1950s, researchers including Constantine P. Yaglou and David Minard made a significant

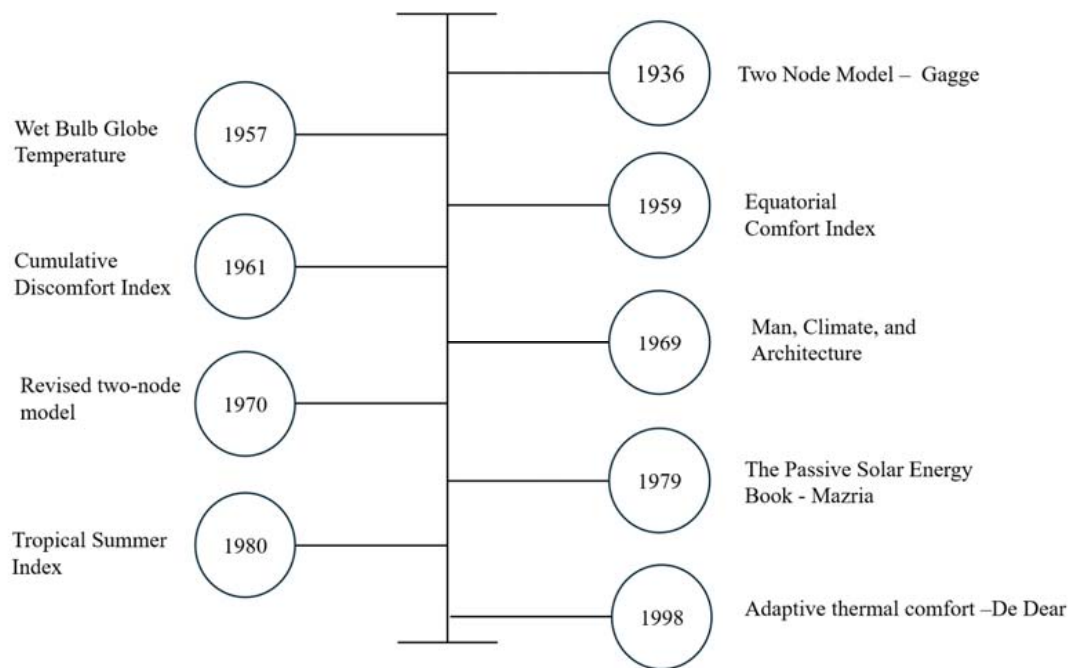


Fig. 2. Key milestones in the development of TC research (Source: Author)

contribution to the development of TC research (Fig. 2, Table). They introduced the Wet Bulb Globe Temperature (WBGT), a comprehensive index for assessing thermal discomfort that accounts for temperature, humidity, wind speed, and solar radiation. The WBGT is widely used to prevent heat-related illnesses and ensure safety in hot environments (Hensen Centnerová, 2018). Two other notable indices were subsequently developed: the Equatorial Comfort Index (ECI) in 1959 and the Cumulative Discomfort Index (CDI) in 1961. The ECI is used to assess TC in hot and humid climates by integrating temperature and humidity into a single measure. The CDI provides a practical method for evaluating the total amount of discomfort a person experiences over time due to environmental factors. It offers a comprehensive assessment of thermal stress by considering both the intensity and duration of exposure, helping to guide interventions and improve comfort and safety in various contexts (Fabbri, 2015). In 1980, researchers at the Central Building Research Institute, Roorkee, India, developed the Tropical Summer Index (TSI). This index measures the degree of tropical climatic characteristics, particularly during the summer, and is calculated using multiple meteorological parameters such as temperature, humidity, and precipitation. The TSI reflects both the severity and frequency of tropical conditions, representing an early effort to adapt TC research to local geographical and climatic conditions (Sharma and Ali, 1986).

Thermal Comfort in Architecture

Over time, TC research increasingly focused on the architectural aspects of buildings. While the use

of vernacular materials and traditional designs was common, there was little documented evidence before the 1960s on the application of passive strategies to achieve TC. In 1963, Victor Olgyay published “Design with Climate”, introducing the concept of bioclimatic architecture, which examined the relationship between building form and climate. Similarly, in 1969, Baruch Givoni’s book “Man, Climate and Architecture” discussed human heat transfer and perspiration, emphasizing strategies to maintain comfort within built environments (Givoni, 1969).

Givoni discusses climate, human comfort, climate zones, architectural design, passive design strategies, building materials, thermal performance, and several case studies in his book. These works inspired Mazria’s 1979 “The Passive Solar Energy Book”, which developed architectural design principles for solar, passive, green, and bioclimatic architecture. Since then, researchers have explored and experimented with passive design strategies in buildings to enhance TC. Passive design strategies investigated include window-to-wall ratio (Abdullah and Alibaba, 2020), building envelope (Sharma and Chani, 2019; Surendran et al., 2023; Wang et al., 2020; Yamamoto, 2023), building insulation (Arumugam and Ramalingam, 2024), materials (Marey et al., 2024; Sen et al., 2014), glazing, building orientation (Kaushal et al., 2023; Sharma and Rakshit, 2017), form and shape, green and cool roofs, etc. (Jia et al., 2024; Kumar and Mahalle, 2016; Pragati et al., 2023). Researchers have also employed computer simulations to analyze and evaluate the performance of these passive strategies.

Key Milestones in TC Research (Source: Author)

Period	Focus	Key Developments	Key Researchers	Significance
Early research	Thermal regulation models	Two-node models	Gagge (1936)	Laid the foundation for understanding and modeling human thermal regulation.
1950s–1960s	Indoor TC, comfort zones	Comprehensive studies on Wet Bulb Globe Temperature (WBGT), Equatorial Comfort Index (ECI) and other thermal comfort indices, and comfort lines	Webb (1959), Yaglou and Minard (1957)	Identified indoor environment indices to measure and understand TC.
1960s–1970s	Developing TC models	Introduction of Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) models to predict group TC	Fanger (1967)	Established a basis for predicting and quantifying TC in built environments.
1980s–present	Adaptive TC	Introduction of adaptive models; recognition of dynamic and personal variations in comfort	Brager and de Dear (1998)	Supported more flexible and energy-efficient building designs; influenced ASHRAE 55 and NBC.
Recent decades & ongoing	Passive and active strategies	Exploration of building orientation, materials, HVAC control, and PCM insulation	Ali et al. (2020), Dili et al. (2010), Elshafei et al. (2021), Figueiredo et al. (2020), Inusa and Alibaba (2017)	Advanced strategies for enhancing TC and energy efficiency in buildings.
Recent decades & ongoing	Simulations and computerization	Use of AI, ML, and genetic algorithms to optimize indoor TC and energy usage	Lu et al. (2019), Pragati et al. (2023), Silva et al. (2016), Soflaei et al. (2020), Xu et al. (2023)	Enhanced precision and control in building automation systems; improved energy efficiency.
1940–ongoing	Thermal manikins	Measurement of equivalent temperatures and evaluation of personal systems	Simova et al. (2021), Zasimova et al. (2023)	Provided accurate, detailed assessments of TC and supported ergonomic designs.
Recent & ongoing	Climate change and TC	Assessing climate change scenarios, mitigation strategies, and weather file usage	Dodoo and Ayarkwa (2019), Ferdyn-Grygierek et al. (2021), Tomrukcu & Ashrafian (2024)	Mitigation strategies for climate change scenarios.

Models of Thermal Comfort

This section discusses the main techniques and models used to measure and evaluate TC. Two widely recognized and universally accepted approaches are Fanger's PMV and PPD model and de Dear's adaptive comfort model.

(i) Fanger's model

Fanger made significant contributions to TC studies. He emphasized the relationship between physical environmental parameters, physiological indicators of occupants, and their subjective experience of well-being. In 1967, he published the paper "Calculation of Thermal Comfort: Introduction of Basic Comfort Equation", proposing a rating scale to assess reported sensations of comfort. In 1970, his book "Thermal Comfort" further highlighted the study of comfort and health in indoor environments. Fanger introduced the Predicted Mean Vote (PMV) to quantify an individual's perception of comfort based on four environmental and two personal factors. The

PMV helps identify a comfort zone on psychrometric charts, setting optimal conditions for shared spaces such as theaters, hospitals, and shopping centers. However, the PMV alone does not indicate whether these conditions are universally acceptable. To address this limitation, Fanger proposed the Predicted Percentage of Dissatisfied (PPD) index, which estimates the proportion of individuals likely to feel discomfort under given conditions, even if the majority find them acceptable. For example, a PMV of -0.3 may appear slightly cold, but the PPD accounts for the 5 % of occupants who may find it unsatisfactory. The PPD–PMV diagram helps determine the percentage of dissatisfied individuals based on variations in the PMV, which depends on factors such as relative humidity, air velocity, temperature, metabolism, and clothing. Extreme PMV values, such as "very cold" or "very hot," exponentially increase dissatisfaction. Additional indicators, including stress indices and local

discomfort measures like heat stress, also reflect dissatisfaction caused by non-uniform environmental conditions. Architect Baruch Givoni introduced the Index of Thermal Stress (ITS) to assess thermal discomfort under such circumstances (Fabbri, 2015).

(ii) Adaptive TC

De Dear's adaptive thermal comfort model has significantly advanced our understanding and application of TC in building design. Unlike static models, it emphasizes the dynamic interaction between occupants and their surroundings by considering human adaptability to temperature variations. De Dear's research, particularly during the late 20th and early 21st centuries, provided robust empirical evidence and theoretical frameworks highlighting the importance of behavioral and contextual factors in TC. In collaboration with Gail Brager, de Dear developed a pioneering theory, presented in their 1998 paper "Developing an Adaptive Model of Thermal Comfort and Preference". This study demonstrated that occupants in naturally ventilated buildings could tolerate a wider range of indoor temperatures than those in mechanically controlled environments.

The model emphasizes the significance of occupants' actions, such as adjusting clothing, opening windows, and acclimating to seasonal temperature changes. According to the adaptive approach, comfort levels should be context-specific and flexible, rather than universally applicable. This approach highlights the dynamic and adaptive nature of human comfort in response to environmental changes. The model predicts comfort based on observed occupant behavior and preferences, demonstrating that people can feel comfortable across a wide range of temperatures. Empirical data from various climates and building types are used to define adaptive comfort ranges. The relationship between outdoor and indoor temperatures is established through regression analysis of the collected field data. The results of the adaptive model are typically presented as a comfort band graph, illustrating the acceptable range of indoor temperatures.

Subsequent research has further validated the applicability and robustness of the adaptive model. Its assumptions have been supported in diverse climate zones, including tropical, temperate, and continental regions. For example, Nicol and Humphreys (2002) observed comparable adaptive responses in European environments. These findings support a more occupant-centered approach to thermal regulation and building design, reducing reliance on HVAC systems and improving energy efficiency. Further adaptations of the model include work by Manu et al. (2016), who developed an adaptive thermal comfort model for air-conditioned, mixed-mode, and naturally ventilated commercial

buildings. The approach was also incorporated into the National Building Code of India (Bureau of Indian Standards, 2016). More recently, Rawal et al. (2022) proposed a thermal comfort model specifically for Indian residential buildings.

Simulation and Prediction

Simulation in the built environment, often referred to as Building Performance Simulation (BPS), is a crucial tool for predicting the energy performance, thermal performance, and daylighting of buildings (Altan et al., 2016). A simulation tool typically requires input data such as climate, building envelope characteristics, lighting, equipment, occupancy patterns, ventilation, heating and cooling systems, fans, and occupant schedules. Based on these inputs, the tool generates outputs projecting building energy use and environmental performance across end-use categories such as cooling, lighting, heating, fans, plugs, and processes. Some simulation software can also estimate energy costs. The potential applications of building simulation include building design, Life Cycle Analysis (LCA), and retrofit assessments. Widely used tools include DesignBuilder, EnergyPlus, TRNSYS, Ecotect, and IES-VE. DesignBuilder, with its integrated EnergyPlus plugin and user-friendly interface, is particularly popular among researchers for rapid adoption. The main advantage of building simulation is its ability to test and compare different design solutions, optimize equipment efficiency, and predict building performance during the design phase. The duration of a simulation depends on the complexity of the building model (Altan et al., 2016).

Recognition of the limitations of older models through large-scale field studies involving actual building occupants has led to a better understanding of thermal interactions and overall satisfaction with the indoor environment, thereby informing improved design and operation of buildings and building services (de Dear et al., 2013). Recently, the use of computer-based technologies in TC research has expanded significantly. In addition to energy simulation, optimization techniques have gained popularity, including genetic algorithms, artificial neural networks (ANNs), and multi-objective optimization algorithms (Han and Chen, 2017; Liu et al., 2024; Sekartaji et al., 2023; Sen et al., 2014; Senthilkumar and Ayyathurai, 2022; Wang, 1990; Xu et al., 2023). These methods have also been applied to evaluate comfort hours and optimize set points in retail spaces in India.

Several studies have explored the use of machine learning (ML) and artificial intelligence (AI) in TC research. Researchers have experimented with AI models to estimate building temperatures based on external temperature and other environmental parameters. Most published studies have focused on model validation (Ngarambe et al., 2020). Additionally,

some studies have applied optimization algorithms, such as genetic and multi-objective algorithms, alongside sensitivity analysis to evaluate passive strategies, including building orientation, insulation, glazing, and materials, and their effects on TC.

Standards and Policies

Globally, standards for TC have evolved to incorporate both static and adaptive models, aiming to create interior spaces that enhance human health and productivity. The most widely recognized standard is ASHRAE Standard 55, developed by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers. This standard integrates both the Predicted Mean Vote (PMV) and Adaptive Comfort Model and has undergone multiple revisions, allowing adjustments of TC parameters according to climate and occupant management (ASHRAE, 2013). Similarly, the ISO 7730 standard of the International Organization for Standardization provides guidelines for calculating TC based on the PMV and PPD indices (ISO, 2005).

The European Standard EN 16798-1, which replaced EN 15251, emphasizes the adaptive approach, allowing for greater temperature variations based on outdoor conditions and occupant behavior, particularly in naturally ventilated buildings. This standard reflects a growing recognition of the need for flexible comfort criteria to accommodate the wide climatic variations across Europe (European Committee for Standardization, 2019).

Due to India's diverse climate zones and increasing emphasis on sustainable building practices, TC standards have received growing attention. The National Building Code of India (NBC) incorporates the adaptive thermal comfort model. The Energy Conservation Building Code (ECBC) promotes energy-efficient building design that accounts for regional climate variations in commercial buildings (BEE, 2017; Bureau of Indian Standards, 2016). In addition to the ECBC, the ECBC-R (Residential), also known as Eco Niwas Samhita (ENS), addresses efficient building design for residential buildings in India. Research from Indian academic institutions, such as the Center for Advanced Research in Building Science and Energy (CARBSE) at CEPT University, has supported the inclusion of the adaptive model in national standards by validating its suitability for Indian climates (Manu et al., 2016; Rawal et al., 2022).

Indian policies such as the Affordable Housing Policy (Pradhan Mantri Awas Yojana) aim to provide housing for all while ensuring comfort for low-income populations. State-level policies, including the Tamil Nadu Affordable Urban Housing and Habitat Policy and the Punjab Affordable Housing Policy, encourage energy-efficient and eco-friendly building practices. Adaptation and sustainability are increasingly prioritized to meet both national and international

requirements for TC. While international standards such as ISO 7730 and ASHRAE 55 provide broad frameworks, Indian standards adopt a more tailored approach, recognizing the country's unique climatic and cultural contexts.

Results and Discussion

According to de Dear et al. (2013), TC in buildings is essential for ensuring occupant well-being. Early researchers focused on the human factors of TC and demonstrated how environmental parameters influence human comfort. These pioneering studies laid the foundation for subsequent key contributions in the field. For example, the two-node models help identify and observe core body responses to environmental conditions and changes. Additionally, researchers developed tools such as the psychrometric chart, which remains a fundamental resource for understanding air-related environmental factors, as it comprehensively represents the interactions between temperature, humidity, and other atmospheric parameters. Following this, indices such as the Wet Bulb Globe Temperature (WBGT), Equatorial Comfort Index (ECI), Cumulative Discomfort Index (CDI), and Tropical Summer Index (TSI) were introduced, further linking TC to environmental parameters. Research on the architectural aspects of TC began in the 1960s with contributions from Givoni and other influential architects, including works such as "Man, Climate and Architecture", "The Passive Solar Energy Book", etc. To this day, research on architectural strategies for TC continues to evolve, driven by varying climatic conditions, climate change scenarios, urban agglomeration, urban heat islands, and other environmental challenges. However, very few studies have examined the cost implications of passive design strategies on TC. Adaptive TC and other TC models have been widely tested and adopted globally to measure TC levels. Standards such as ASHRAE 55 are internationally recognized, while EN 15251 is primarily applied in European contexts. Over time, researchers worldwide have also developed adaptive comfort models tailored to their local climates. Recent studies increasingly rely on simulation and computational tools to investigate TC. Tools such as EnergyPlus and DesignBuilder are commonly used for energy simulations, optimization, and TC modeling. These tools enable researchers to generate optimized results and prioritize desired parameters for TC. Recent research has explored passive strategies, optimization techniques, and energy simulation approaches. However, simulation tools have limitations: they primarily model building systems and environmental factors, while thermophysical, physiological, psychological, and human core responses are often excluded, except for clothing insulation. Emerging research areas include the effects of urban heat islands, personal

comfort systems, real-time mapping using AI and IoT, computational fluid dynamics (CFD), and sleep quality. Despite these advances, significant gaps remain, particularly in defining specific design requirements for different building spaces. Addressing these gaps is essential for optimizing energy use, enhancing environmental conditioning, and developing design guidelines that improve TC while reducing energy consumption across diverse building types.

On the other hand, existing comfort bands and standards often fail to account for regional climatic diversity. For instance, India, with its five distinct climatic zones, lacks an all-encompassing TC band. Consequently, architects, designers, and construction professionals face challenges in creating thermally comfortable environments tailored to local climates. Addressing these knowledge gaps is essential for improving energy efficiency, enhancing occupant satisfaction, and optimizing environmental conditioning in buildings. Given the rapidly evolving challenges posed by global warming, there is an urgent need for comprehensive design standards and adaptive models that integrate localized climatic variations and account for changing occupant behavior patterns. Furthermore, a significant gap exists in understanding TC at the project scale, as most existing studies focus on the unit level. Bridging this gap represents a critical and promising direction for future research.

Conclusion

This paper examines the historical trajectory of TC research, highlighting key milestones, innovations, and directions for future exploration. TC has evolved from the invention of air conditioning to the integration of passive design strategies in buildings. De Dear's adaptive thermal comfort model, now internationally recognized, has been incorporated into major standards such as ASHRAE 55 and the National Building Code of India. Over time, researchers have consistently identified six key parameters. In addition, complementary measures such as the Wet Bulb Globe Temperature (WBGT), the Cumulative Discomfort Index (CDI), and the Tropical Summer Index (TSI) have further advanced our understanding of indoor comfort. These indices provide a more nuanced basis for maintaining

optimal indoor conditions across different settings. The integration of cutting-edge technologies into TC studies presents significant opportunities for enhancing building design and improving occupant well-being. At the same time, there is a growing need to examine the long-term impacts of TC on both health and productivity. Some of the key takeaways of this study are as follows:

- **Evolution of TC research:** Progressing from early physiological investigations to advanced adaptive models, reflecting a growing understanding of human–environment interactions.
- **Passive strategies:** Implementation of design measures such as insulation, building envelope improvements, phase-changing materials (PCM), orientation, window-to-wall ratios, and cool roofs can significantly enhance occupant satisfaction and well-being.
- **Policy context in India:** While policies encourage eco-friendly materials and native landscaping, explicit integration of TC performance into regulations remains limited.
- **Technological advancements:** AI, ML, AR, and IoT are transforming simulation and modeling tools, opening new opportunities for evaluating TC in dynamic and complex contexts.
- **Design guidelines:** There is a pressing need to develop context-specific guidelines that simultaneously improve TC and reduce electricity consumption in buildings.
- **Research gaps:** More integrated approaches combining optimization, simulation modeling, climate change considerations, and region-specific comfort models are required. Moreover, most studies focus on individual houses, whereas project-scale investigations remain underexplored but could yield significant societal benefits.

In conclusion, the critical contribution of this paper lies in summarizing the key areas of TC research that can be adopted in practice, while also providing insights into the chronological evolution of TC studies.

Acknowledgements

The authors would like to express their sincere gratitude to NICMAR University for its continuous support and encouragement throughout this research.

References

- Abdullah, H. K. and Alibaba, H. Z. (2020). Window design of naturally ventilated offices in the Mediterranean climate in terms of CO₂ and thermal comfort performance. *Sustainability*, Vol. 12, Issue 2, 473. DOI: 10.3390/su12020473.
- Alghamdi, S., Tang, W., Kanjanabootra, S., and Alterman, D. (2024). Optimising building energy and comfort predictions with intelligent computational model. *Sustainability*, Vol. 16, Issue 8, 3432. DOI: 10.3390/su16083432.
- Ali, S. F., Sharma, L., Rakshit, D., and Bhattacharjee, B. (2020). Influence of passive design parameters on thermal comfort of an office space in a building in Delhi. *Journal of Architectural Engineering*, Vol. 26, Issue 3, 04020017. DOI: 10.1061/(asce)ae.1943-5568.0000406.
- Altan, H., Padovani, R., and Hashemi, A. (2016). Building performance and simulation. In: Noguchi, M. (ed.). *ZEMCH: Toward the Delivery of Zero Energy Mass Custom Homes*. Springer Tracts in Civil Engineering. Cham: Springer, pp. 311–338. DOI: 10.1007/978-3-319-31967-4_11.
- Arumugam, P. and Ramalingam, V. (2024). Thermal comfort enhancement of office buildings located under warm and humid climate through phase change material and insulation coupled with natural ventilation. *Sustainable Energy Technologies and Assessments*, Vol. 63, 103657. DOI: 10.1016/j.seta.2024.103657.
- ASHRAE (2013). *ANSI/ASHRAE Standard 55-2013. Thermal Environmental Conditions for Human Occupancy*. Atlanta, GA: ASHRAE, 52 p.
- BEE (2017). *Energy Conservation Building Code 2017*. New Delhi: Bureau of Energy Efficiency, 183 p.
- Brager, G. S. and de Dear, R. J. (1998). Thermal adaptation in the built environment: a literature review. *Energy and Buildings*, Vol. 27, Issue 1, pp. 83–96. DOI: 10.1016/S0378-7788(97)00053-4.
- Bureau of Indian Standards (2016). *National Building Code of India 2016 (NBC 2016): Volume 2*.
- Chatzidimitriou, A. and Yannas, S. (2016). Microclimate design for open spaces: ranking urban design effects on pedestrian thermal comfort in summer. *Sustainable Cities and Society*, Vol. 26, pp. 27–47. DOI: 10.1016/j.scs.2016.05.004.
- Chowdhury, A. A., Rasul, M. G., and Khan, M. M. K. (2008). Thermal-comfort analysis and simulation for various low-energy cooling-technologies applied to an office building in a subtropical climate. *Applied Energy*, Vol. 85, Issue 6, pp. 449–462. DOI: 10.1016/j.apenergy.2007.10.001.
- De Dear, R. J., Akimoto, T., Arens, E. A., Brager, G., Candido, C., Cheong, K. W. D., Li, B., Nishihara, N., Sekhar, S. C., Tanabe, S., Toftum, J., Zhang, H., and Zhu, Y. (2013). Progress in thermal comfort research over the last twenty years. *Indoor Air*, Vol. 23, No. 6, pp. 442–461. DOI: 10.1111/ina.12046.
- De Dear, R., Foldvary, V., Zhang, H., Arens, E., Luo, M., Parkinson, T., Du, X., Zhang, W., Chun, C., and Liu, S. (2016). Comfort is in the mind of the beholder: a review of progress in adaptive thermal comfort research over the past two decades. In: *The Fifth International Conference on Human-Environment System*, October 29 – November 2, 2016, Nagoya, Japan.
- Dili, A. S., Naseer, M. A., and Zacharia Varghese, T. (2010). Passive control methods of Kerala traditional architecture for a comfortable indoor environment: comparative investigation during various periods of rainy season. *Building and Environment*, Vol. 45, Issue 10, pp. 2218–2230. DOI: 10.1016/j.buildenv.2010.04.002.
- Dodoo, A. and Ayarkwa, J. (2019). Effects of climate change for thermal comfort and energy performance of residential buildings in a Sub-Saharan African climate. *Buildings*, Vol. 9, Issue 10, 215. DOI: 10.3390/buildings9100215.
- Elshafei, G., Vilcekova, S., Zelenakova, M., and Negm, A. M. (2021). Towards an adaptation of efficient passive design for thermal comfort buildings. *Sustainability*, Vol. 13, Issue 17, 9570. DOI: 10.3390/su13179570.
- Emetere, M. E. (2022). *Numerical methods in environmental data analysis*. Amsterdam, Netherlands; Elsevier, 240 p.
- European Committee for Standardization (2019). *EN 16798-1:2019 (2019). Energy performance of buildings - Ventilation for buildings - Part 1: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics - Module M1-6*. [online] Available at: https://standards.iteh.ai/catalog/standards/cen/b4f68755-2204-4796-854a-56643dfce89/en-16798-1-2019?srsId=AfmBOoqyRO8k7ngNVXq_R_xEb-JJAME8PZbXLcfBK2omvVWzyguGYWOW [Date accessed 07/06/2024].
- Fabbri, K. (2015). Indoor thermal comfort perception: A questionnaire approach focusing on children. In *Indoor Thermal Comfort Perception: A Questionnaire Approach Focusing on Children*. Springer International Publishing. <https://doi.org/10.1007/978-3-319-18651-1>.
- Faheem, M., Bhandari, N., and Tadepalli, S. (2023). Adaptive thermal comfort in naturally ventilated hostels of warm and humid climatic region, Tiruchirappalli, India. *Energy and Built Environment*, Vol. 4, Issue 5, pp. 530–542. DOI: 10.1016/j.enbenv.2022.04.002.
- Fanger, P. O. (1967). Calculation of thermal comfort: introduction of a basic comfort equation. *ASHRAE Transactions*, Vol. 73, Part 2, pp. III4.1–III4.20.

- Ferdyn-Grygierek, J., Sarna, I., and Grygierek, K. (2021). Effects of climate change on thermal comfort and energy demand in a single-family house in Poland. *Buildings*, Vol. 11, Issue 12, 595. DOI: 10.3390/buildings11120595.
- Figueiredo, A., Rebelo, F., Castanho, R. A., Oliveira, R., Lousada, S., Vicente, R., and Ferreira, V. M. (2020). Implementation and challenges of the passive house concept in Portugal: lessons learnt from successful experience. *Sustainability*, Vol. 12, Issue 21, 8761. DOI: 10.3390/su12218761.
- Gagge, A. P. (1936). The linearity criterion as applied to partitional calorimetry. *American Journal of Physiology*, Vol. 116, Issue 3, pp. 656–668. DOI: 10.1152/ajplegacy.1936.116.3.656.
- Ganji, V., Kalpana, M., Madhusudhan, U., John, N. A., and Taranikanti, M. (2023). Impact of air conditioners on sick building syndrome, sickness absenteeism, and lung functions. *Indian Journal of Occupational and Environmental Medicine*, Vol. 27, Issue 1, pp. 26–30. DOI: 10.4103/IJOEM.IJOEM_23_22.
- Givoni, B. (1969). *Man, climate, and architecture* (Cowan J. Henry, Ed.). Elsevier Publishing Company Limited. <https://archive.org/details/manclimatearchit0000unse/page/n7/mode/2up>.
- Gomez-Azpeitia, G., Estrella, K., and Torres, M. (2012). Thermal comfort and health conditions in air-conditioned offices in a warm and sub-humid climate. In: *PLEA2012 - 28th Conference, Opportunities, Limits & Needs Towards an Environmentally Responsible Architecture*, November 7–9, 2012, Lima, Peru.
- Gupta, J. (2024). *In South Asia, heat stress kills without a heatwave*. [online] Available at: <https://www.preventionweb.net/news/south-asia-heat-stress-kills-without-heatwave> [Date accessed 06/05/2024].
- Han, M. and Chen, H. (2017). Effect of external air-conditioner units' heat release modes and positions on energy consumption in large public buildings. *Building and Environment*, Vol. 111, pp. 47–60. DOI: 10.1016/j.buildenv.2016.10.014.
- Hensen Centnerová, L. (2018). *On the history of indoor environment and its relation to health and wellbeing*. [online] Available at: <https://www.rehva.eu/rehva-journal/chapter/on-the-history-of-indoor-environment-and-its-relation-to-health-and-wellbeing> [Date accessed 12/06/2024].
- International Energy Agency (2018). *The future of cooling. Opportunities for energy-efficient air conditioning*. [online] Available at: <https://www.iea.org/reports/the-future-of-cooling> [Date accessed 20/05/2024].
- Inusa, M. and Alibaba, H. Z. (2017). Application of passive cooling techniques in residential buildings: a case study of Northern Nigeria. *International Journal of Engineering Research and Application*, Vol. 7, Issue 1, pp. 24–30. DOI: 10.9790/9622-0701012430.
- ISO (2005). *ISO 7730:2005. Ergonomics of the thermal environment — Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria*. [online] Available at: <https://www.iso.org/standard/39155.html> [Date accessed 06/05/2024].
- Jia, S., Weng, Q., Yoo, C., Xiao, H., and Zhong, Q. (2024). Building energy savings by green roofs and cool roofs in current and future climates. *Npj Urban Sustainability*, Vol. 4, 23. DOI: 10.1038/s42949-024-00159-8.
- Karyono, K., Abdullah, B. M., Cotgrave, A. J., and Bras, A. (2020). The adaptive thermal comfort review from the 1920s, the present, and the future. *Developments in the Built Environment*, Vol. 4, 100032. DOI: 10.1016/j.dibe.2020.100032.
- Kaushal, A. A., Anand, P., and Aithal, B. H. (2023). Assessment of the impact of building orientation on PMV and PPD in naturally ventilated rooms during summers in warm and humid climate of Kharagpur, India. In: *BuildSys 2023 – Proceedings of the 10th ACM International Conference on Systems for Energy-Efficient Buildings, Cities, and Transportation*. New York: Association for Computing Machinery, pp. 528–533. DOI: 10.1145/3600100.3627034.
- Kumar, V. and Mahalle, A. M. (2016). Investigation of the thermal performance of green roof on a mild warm climate. *International Journal of Renewable Energy Research*, Vol. 6, No. 2, pp. 487–493.
- Kumar, S., Sheeja, R., Ajin, M., Chandrasekar, P., Sekar, S., and Sai Krishnan, G. S. (2022). Thermal performance analysis of PCM building for moderate climatic region in Bangalore City, India. *IOP Conference Series: Earth and Environmental Science*, Vol. 1100, 012003. DOI: 10.1088/1755-1315/1100/1/012003.
- Lee, M., Ham, J., Lee, J.-W., and Cho, H. (2023). Analysis of thermal comfort, energy consumption, and CO₂ reduction of indoor space according to the type of local heating under winter rest conditions. *Energy*, Vol. 268, 126722. DOI: 10.1016/J.ENERGY.2023.126722.
- Liu, M., Que, Y., Yang, N., Yan, C., and Liu, Q. (2024). Research on multi-objective optimization design of university student center in China based on low energy consumption and thermal comfort. *Energies*, Vol. 17, Issue 9, 2082. DOI: 10.3390/en17092082.
- Lu, S., Wang, W., Lin, C., and Hameen, E. C. (2019). Data-driven simulation of a thermal comfort-based temperature set-point control with ASHRAE RP884. *Building and Environment*, Vol. 156, pp. 137–146. DOI: 10.1016/j.buildenv.2019.03.010.

- Luo, M., Arens, E., Zhang, H., Ghahramani, A., and Wang, Z. (2018). Thermal comfort evaluated for combinations of energy-efficient personal heating and cooling devices. *Building and Environment*, Vol. 143, pp. 206–216. DOI: 10.1016/j.buildenv.2018.07.008.
- Ma, N., Aviv, D., Guo, H., and Braham, W. W. (2021). Measuring the right factors: a review of variables and models for thermal comfort and indoor air quality. *Renewable and Sustainable Energy Reviews*, Vol. 135, 110436. DOI: 10.1016/j.rser.2020.110436.
- Manu, S., Shukla, Y., Rawal, R., Thomas, L. E., and de Dear, R. (2016). Field studies of thermal comfort across multiple climate zones for the subcontinent: India Model for Adaptive Comfort (IMAC). *Building and Environment*, Vol. 98, pp. 55–70. DOI: 10.1016/j.buildenv.2015.12.019.
- Marey, H., Kozma, G., and Szabó, G. (2024). Green concrete materials selection for achieving circular economy in residential buildings using system dynamics. *Cleaner Materials*, Vol. 11, 100221. DOI: 10.1016/j.clema.2024.100221.
- McDowell, Ian, *Measuring Health: A guide to rating scales and questionnaires*, 3rd edn (New York, 2006; online edn, Oxford Academic, 1 Sept. 2009), <https://doi.org/10.1093/acprof:oso/9780195165678.001.0001> [Date accessed: 16/05/2024].
- Mustakallio, P., Bolashikov, Z., Rezgals, L., Lipczynska, A., Melikov, A., and Kosonen, R. (2017). Thermal environment in a simulated double office room with convective and radiant cooling systems. *Building and Environment*, Vol. 123, pp. 88–100. DOI: 10.1016/j.buildenv.2017.06.029.
- NASA (2011). *Secrets from the past point to rapid climate change in the future*. [online] Available at: <https://science.nasa.gov/earth/climate-change/secrets-from-the-past-point-to-rapid-climate-change-in-the-future/> [Date accessed 29/05/2024].
- NASA (2019). *The atmosphere: getting a handle on carbon dioxide*. [online] Available at: <https://science.nasa.gov/earth/climate-change/greenhouse-gases/the-atmosphere-getting-a-handle-on-carbon-dioxide/> [Date accessed 10/06/2024].
- Nduka, D. O., Oyeyemi, K. D., Olofinnade, O. M., Ede, A. N., and Worgwu, C. (2021). Relationship between indoor environmental quality and sick building syndrome: a case study of selected student's hostels in Southwestern Nigeria. *Cogent Social Sciences*, Vol. 7, Issue 1, 1980280. DOI: 10.1080/23311886.2021.1980280.
- Ngarambe, J., Yun, G. Y., and Santamouris, M. (2020). The use of artificial intelligence (AI) methods in the prediction of thermal comfort in buildings: energy implications of AI-based thermal comfort controls. *Energy and Buildings*, Vol. 211, 109807. DOI: 10.1016/j.enbuild.2020.109807.
- Nicol, J. F., & Humphreys, M. A. (2002). Adaptive thermal comfort and sustainable thermal standards for buildings. *Energy and Buildings*, 34(6), 563–572. [https://doi.org/10.1016/S0378-7788\(02\)00006-3](https://doi.org/10.1016/S0378-7788(02)00006-3).
- Nishi, K., Demura, M., Miura, J., and Oishi, S. (2017). Use of thermal point cloud for thermal comfort measurement and human pose estimation in robotic monitoring. In: *2017 IEEE International Conference on Computer Vision Workshops (ICCVW 2017)*, October 22–29, 2017, Venice, Italy, pp. 1416–1423. DOI: 10.1109/ICCVW.2017.168.
- Pal, C. L., Netam, N., Sanyal, S., and Manish, M. (2024). Exploring thermal comfort in rural houses of Chhattisgarh state, India: a comprehensive survey and adaptive model analysis. *Science and Technology for the Built Environment*, Vol. 30, Issue 5, pp. 523–545. DOI: 10.1080/23744731.2024.2312799.
- Pitts, A. (2017). Passive house and low energy buildings: barriers and opportunities for future development within UK practice. *Sustainability*, Vol. 9, Issue 2, 272. DOI: 10.3390/su9020272.
- Pragati, S., Shanthi Priya, R., Pradeepa, C., and Senthil, R. (2023). Simulation of the energy performance of a building with green roofs and green walls in a tropical climate. *Sustainability*, Vol. 15, Issue 3, 2006. DOI: 10.3390/su15032006.
- Rana, K. (2021). Towards passive design strategies for improving thermal comfort performance in a naturally ventilated residence. *Journal of Sustainable Architecture and Civil Engineering*, Vol. 29, No. 2, pp. 150–174. DOI: 10.5755/j01.sace.29.2.29256.
- Rawal, R., Shukla, Y., Vardhan, V., Asrani, S., Schweiker, M., de Dear, R., Garg, V., Mathur, J., Prakash, S., Diddi, S., Ranjan, S. V., Siddiqui, A. N., and Somani, G. (2022). Adaptive thermal comfort model based on field studies in five climate zones across India. *Building and Environment*, Vol. 219, 109187. DOI: 10.1016/j.buildenv.2022.109187.
- Revel, G. M., Arnesano, M., and Pietroni, F. (2014). Development and validation of a low-cost infrared measurement system for real-time monitoring of indoor thermal comfort. *Measurement Science and Technology*, Vol. 25, No. 8, 085101. DOI: 10.1088/0957-0233/25/8/085101.
- Roy Choudhury, A. K., Majumdar, P. K., and Datta, C. (2011). Factors affecting comfort: human physiology and the role of clothing. In: Song, G. (ed.). *Improving Comfort in Clothing*. Oxford: Woodhead Publishing, pp. 3–60. DOI: 10.1533/9780857090645.1.3.
- Sekartaji, D., Ryu, Y., Novianto, D., Eto, K., and Gao, W. (2023). Energy-use and indoor thermal performance in junior high school building after air-conditioning installation with the private finance initiative. *Buildings*, Vol. 13, Issue 2, 455. DOI: 10.3390/buildings13020455.

- Sen, R., Chattopadhyay, S., and Kandra, S. (2014). Investigation on the performance of alternative walling materials in an affordable housing unit situated in warm humid climate. In: *30th International PLEA Conference*, December 16–18, 2014, Ahmedabad, India.
- Senthilkumar, S. and Ayyathurai, V. (2022). Energy efficiency management and setpoints optimisation strategy in retail store building, India. *Journal of Building Pathology and Rehabilitation*, Vol. 7, Issue 1, 99. DOI: 10.1007/s41024-022-00238-2.
- Sharma, M. R. and Ali, S. (1986). Tropical summer index—a study of thermal comfort of Indian subjects. *Building and Environment*, Vol. 21, Issue 1, pp. 11–24. DOI: 10.1016/0360-1323(86)90004-1.
- Sharma, A. and Chani, P. S. (2019). Adaptive thermal comfort for naturally ventilated buildings through building envelope retrofitting. In: Agrawal, A. and Gupta, R. (eds.). *Revisiting the Role of Architecture for 'Surviving' Development. 53rd International Conference of the Architectural Science Association 2019, Roorkee, India*, Architectural Science Association, pp. 391–400.
- Sharma, P. and Rakshit, D. (2017). Quantitative assessment of orientation impact on heat gain profile of naturally cooled buildings in India. *Advances in Building Energy Research*, Vol. 11, Issue 2, pp. 208–226. DOI: 10.1080/17512549.2016.1215261.
- Silva, A. S., Ghisi, E., and Lamberts, R. (2016). Performance evaluation of long-term thermal comfort indices in building simulation according to ASHRAE Standard 55. *Building and Environment*, Vol. 102, pp. 95–115. DOI: 10.1016/j.buildenv.2016.03.004.
- Simova, I., Angelova, R. A., Markov, D., Velichkova, R., and Stankov, P. (2021). Thermal manikins – general features and applications. In: *2021 6th International Symposium on Environment-Friendly Energies and Applications (EFEA)*, March 24–26, 2021, Sofia, Bulgaria. DOI: 10.1109/EFEA49713.2021.9406231.
- Soflaei, F., Shokouhian, M., Tabadkani, A., Moslehi, H., and Berardi, U. (2020). A simulation-based model for courtyard housing design based on adaptive thermal comfort. *Journal of Building Engineering*, Vol. 31, 101335. DOI: 10.1016/j.jobe.2020.101335.
- Stoops, John L. Indoor Thermal Comfort, an Evolutionary Biology Perspective, article, April 15, 2006; Berkeley, California, University of North Texas Libraries, UNT Digital Library, <https://digital.library.unt.edu>; crediting UNT Libraries Government Documents Department, <https://digital.library.unt.edu/ark:/67531/metadc901474/> [Date accessed 10/06/2026].
- Surendran, V. M., Irulappan, C., Jeyasingh, V., and Ramalingam, V. (2023). Thermal performance assessment of envelope retrofits for existing school buildings in a hot–humid climate: a case study in Chennai, India. *Buildings*, Vol. 13, Issue 4, 1103. DOI: 10.3390/buildings13041103.
- Teitelbaum, E., Miller, C., & Meggers, F. (2023). Highway to the Comfort Zone: History of the Psychrometric Chart. *Buildings*, 13(3). <https://doi.org/10.3390/buildings13030797>.
- Thapa, S., Rijal, H. B., Pasut, W., Singh, R., Indraganti, M., Bansal, A. K., and Panda, G. K. (2023). Simulation of thermal comfort and energy demand in buildings of sub-Himalayan eastern India - impact of climate change at mid (2050) and distant (2080) future. *Journal of Building Engineering*, Vol. 68, 106068. DOI: 10.1016/j.jobe.2023.106068.
- Tomrukcu, G. and Ashrafiyan, T. (2024). Climate-resilient building energy efficiency retrofit: evaluating climate change impacts on residential buildings. *Energy and Buildings*, Vol. 316, 114315. DOI: 10.1016/j.enbuild.2024.114315.
- Tungnung, K., Varma, A., Kodama, Y., Takemasa, K., Pde, G., and Roy, S. (2023). Parametric strategies on passive heating techniques in cold-cloudy climate, Shillong towards net-zero energy. *AIP Conference Proceedings*, Vol. 2760, Issue 1, 020022. DOI: 10.1063/5.0149181.
- Van Hoof, J. (2008). Forty years of Fanger's model of thermal comfort: comfort for all? *Indoor Air*, Vol. 18, Issue 3, pp. 171–258. DOI: 10.1111/j.1600-0668.2007.00516.x.
- Wang, X.-L. (1990). A dynamic model for estimating thermal comfort. In: *Indoor Air Quality And Ventilation In Warm Climates*, April, 24–26, 1990, Lisbon, Portugal.
- Wang, R., Lu, S., and Feng, W. (2020). A three-stage optimization methodology for envelope design of passive house considering energy demand, thermal comfort and cost. *Energy*, Vol. 192, 116723. DOI: 10.1016/j.energy.2019.116723.
- Webb, C. G. (1959). An analysis of some observations of thermal comfort in an equatorial climate. *British Journal of Industrial Medicine*, Vol. 16, Issue 4, pp. 297–310.
- Weng, J., Zhang, Y., Chen, Z., Ying, X., Zhu, W., and Sun, Y. (2023). Field measurements and analysis of indoor environment, occupant satisfaction, and sick building syndrome in university buildings in hot summer and cold winter regions in China. *International Journal of Environmental Research and Public Health*, Vol. 20, Issue 1, 554. DOI: 10.3390/ijerph20010554.
- Xie, X., Liu, Y., and Hou, J. (2014). An analysis on behaviors of real estate developers and government in sustainable building decision making. *Journal of Industrial Engineering and Management*, Vol. 7, Issue 2, pp. 491–505. DOI: 10.3926/jiem.1042.
- Xu, Y., Chen, J., Cai, J., Li, S., and He, Q. (2023). Simulation-based trade-off modeling for indoor infection risk of airborne diseases, energy consumption, and thermal comfort. *Journal of Building Engineering*, Vol. 76, 107137. DOI: 10.1016/j.jobe.2023.107137.

- Yaglou, C. P. and Minard, D. (1957). Control of heat casualties at military training centers. *A.M.A. Archives of Industrial Health*, Vol. 16, No. 4, pp. 302–316.
- Yamamoto, T. (2023). Evaluation of thermal comfort with and without fill using a thermal environment analysis method for building envelopes with thermally complex geometry: a case study in Hokkaido, Japan. *Buildings*, Vol. 13, Issue 7, 1646. DOI: 10.3390/buildings13071646.
- Zasimova, M. A., Podmarkova, A. D., Ivanov, N. G., and Marinova, A. A. (2023). Evaluation of CFD-predicted thermal comfort uncertainties based on a seated thermal manikin test case. *IOP Conference Series: Earth and Environmental Science*, Vol. 1185, 012041. DOI: 10.1088/1755-1315/1185/1/012041.
- Zuo, C., Luo, L., and Liu, W. (2021). Effects of increased humidity on physiological responses, thermal comfort, perceived air quality, and sick building syndrome symptoms at elevated indoor temperatures for subjects in a hot-humid climate. *Indoor Air*, Vol. 31, Issue 2, pp. 524–540. DOI: 10.1111/ina.12739.

ЭВОЛЮЦИЯ И ДОСТИЖЕНИЯ В ИССЛЕДОВАНИЯХ ТЕПЛОвого КОМФОРТА: НАРРАТИВНЫЙ ОБЗОР ЛИТЕРАТУРЫ

Шивани Сентилкумар^{1*}, Пуломи Гош²

¹Научный сотрудник, Университет NICMAR (Национальный институт управления и исследований в строительстве), Пуна, Индия – 411045

²Факультет недвижимости и управления объектами, Университет NICMAR (Национальный институт управления и исследований в строительстве), Пуна, Индия – 411045

*E-mail: shivani.phd2@pune.nicmar.ac.in

Аннотация

Введение. Изменение климата, аномальная жара, выбросы парниковых газов и глобальное потепление образуют бесконечный цикл, разрушающий окружающую среду и приводящий к дискомфорту человека и других живых существ. С 1946 года проводятся исследования в области теплового комфорта в зданиях, охватывающие как пассивные, так и активные стратегии. Настоящая статья направлена на изучение эволюции исследований в области теплового комфорта и принципов, на которых они основаны. **Методы.** Для анализа прогресса в области теплового комфорта использовался метод нарративного обзора литературы. В исследование были включены 122 статьи, рассматривающие концепции, модели, архитектурные подходы, стандарты и нормативные документы, связанные с тепловым комфортом. **Результаты и обсуждение.** Исследования в области теплового комфорта прошли путь от изобретения кондиционирования воздуха до внедрения пассивных стратегий в строительстве. В ходе этих исследований были выделены шесть ключевых параметров, способствующих более глубокому пониманию теплового комфорта в помещениях. Кроме того, использование инновационных технологий в исследованиях теплового комфорта позволяет улучшать самочувствие пользователей зданий. В связи с этим представляется необходимым междисциплинарный подход к изучению теплового комфорта. **Рекомендации.** В статье систематизируются основные этапы развития исследований в области теплового комфорта, включая инновации в моделировании и прогнозировании, а также сопутствующие проблемы. Данная работа может помочь будущим исследователям, разработчикам и другим специалистам строительной отрасли выявить имеющиеся пробелы и связать достижения прошлого с перспективными направлениями.

Ключевые слова: тепловой комфорт, хронология исследований в области теплового комфорта, модели теплового комфорта, адаптивная модель теплового комфорта.