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Building Thermal Comforts with Various HVAC Systems and Optimum Conditions

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ABSTRACT: This study evaluates and compares two prevalent methods for assessing thermal comfort in commercial buildings: Fanger's method and the Adaptive method. Through a detailed analysis of indoor temperature distributions and occupant comfort levels, the study aims to determine the effectiveness and practical applicability of these methods. Fanger's method, based on the Predicted Percentage of Dissatisfaction (PPD), categorizes comfort using specific dissatisfaction thresholds, while the Adaptive method defines comfort zones based on occupant acceptability levels, reflecting the ability to adapt to varying thermal conditions. Results from the analysis indicate that both methods predict similar outcomes, with over 70% of occupants likely to be comfortable for more than 90% of the time. This convergence suggests that both approaches are effective tools for evaluating thermal comfort. The study also explores the potential for integrating these methods into a hybrid model to leverage their respective strengths, aiming to enhance HVAC system performance and energy efficiency. Additionally, the research highlights opportunities for future advancements, including the incorporation of real-time data from wireless sensor networks and other smart technologies to further refine comfort assessments.

KEYWORDS: Thermal comfort, HVAC systems, Fanger's method, Energy efficiency, Wireless sensor networks (WSNs), Building design, Adaptive method, Indoor climate.

I. INTRODUCTION

Thermal comfort in buildings is a critical aspect of human well-being, productivity, and overall satisfaction with indoor environments. The concept of thermal comfort is inherently subjective, as it involves the perception of an individual's thermal state, which is influenced by a myriad of factors including air temperature, humidity, airflow, clothing insulation, and metabolic rate.

The American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) has developed standards that define indoor comfort conditions deemed thermally acceptable by at least 80% of a building's occupants [1]. These comfort conditions, often referred to as the "comfort zone," typically range from 20 to 24°C during the winter and from 23 to 26°C during the summer. As people spend an increasing amount of time indoors, whether in homes, offices, or commercial spaces, ensuring optimal thermal conditions becomes paramount [2-4]. This importance has driven the evolution of Heating, Ventilation, and Air Conditioning (HVAC) systems, which are the backbone of maintaining indoor thermal environments across diverse building types and climates.

HVAC systems are engineered to manage and control the indoor environment by providing heating, cooling, ventilation, and humidity regulation. Their role in ensuring thermal comfort cannot be overstated, as they allow for precise control over the various factors that contribute to an individual's perception of comfort. Traditional HVAC systems, such as those based on air-conditioning and heating units, have been widely implemented in buildings for decades. In recent years, the topic of climate control in buildings has garnered significant attention in both academic and industrial circles. HVAC systems are particularly critical in this context, as they account for 40 to 60% of energy consumption in European buildings and over 50% in the United States [5-7]. Consequently, many research groups are focused on developing cost-effective solutions that can reduce the external energy required by HVAC systems while still maintaining comfortable indoor conditions. Achieving such energy savings has become a key goal in efforts to enhance the sustainability of building operations. However, the growing concerns over energy consumption, environmental impact, and the need for sustainability have spurred the development of more advanced, energy-efficient

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HVAC systems. These modern systems often incorporate smart technologies, renewable energy sources, and innovative design approaches to enhance performance while minimizing ecological footprints.

It requires a comprehensive analysis of how different HVAC systems can be optimized to create environments that are both energy-efficient and comfortable. Energy consumption for climate control is projected to rise significantly over the next 30 years [8]. This trend is evident in the rapid growth of the global market for air-conditioning and heat pumps, particularly in developing countries. The surge in demand can be attributed to shifting public perceptions of climate and comfort, where space cooling, once considered a luxury, is now increasingly seen as a necessity, driving a booming market. While energy use for space heating hasn't experienced as dramatic a rise recently, it remains the most energy-intensive function in European buildings, according to the Buildings Performance Institute Europe [8-9]. Achieving thermal comfort is not merely a matter of maintaining a set temperature but involves a delicate balance of multiple factors, such as humidity levels, air distribution, and even the adaptability of the building occupants to the indoor climate [10].

The concept of thermal comfort is also closely linked with energy efficiency, as buildings are responsible for a significant portion of global energy consumption, largely driven by HVAC systems. Thus, optimizing HVAC systems is crucial not only for enhancing occupant comfort but also for reducing energy usage and mitigating environmental impacts. This is especially pertinent in the context of climate change and the push for greener building practices, which demand a reevaluation of how thermal comfort is achieved in buildings.

As the understanding of thermal comfort deepens, there is a growing recognition that a one-size-fits-all approach to HVAC design and operation is inadequate. Different buildings, climates, and occupancy patterns require tailored solutions that account for specific needs and conditions. This has led to the exploration of various HVAC strategies, including the use of advanced technologies such as variable refrigerant flow (VRF) systems, geothermal heat pumps, and integrated building management systems that can dynamically adjust to changing conditions [11]. These innovations offer the potential to optimize thermal comfort while simultaneously addressing the pressing issues of energy efficiency and sustainability.

In developed countries, individuals spend the majority of their time indoors, leading to an increased focus on ensuring thermal comfort in both commercial and residential spaces. This focus significantly influences energy demand, as buildings account for approximately 35% of global energy consumption and over 38% of CO_2 emissions. A substantial portion of this energy is dedicated to meeting the thermal comfort needs of occupants [12]. In recent years, the impact of maintaining thermal comfort on HVAC energy consumption has grown, which contrasts with efforts to reduce energy usage in both individual buildings and building clusters. This growing concern underscores the necessity of improving existing thermal comfort models to develop more accurate and reliable approaches.

Current building design standards predominantly rely on fixed temperature setpoints, with comfort zones typically defined by specific air temperature limits. For instance, the Chartered Institution of Building Services Engineers (CIBSE) recommends a range of 21-23°C for office buildings, while the Occupational Safety and Health Administration (OSHA) suggests 20-24.2°C, and ASHRAE Standard 55 specifies 21.5-24°C. The European standard EN ISO 7730 sets broader temperature guidelines, ranging from 20-26°C. However, as energy-efficient technologies and advanced HVAC systems continue to evolve, there is an increasing demand for more sophisticated thermal comfort models [13]. This need is reflected in the growing attention the scientific community has paid to this issue over the past decade.

Predicting thermal comfort in indoor environments is a complex challenge, and numerous models have been developed to address this task, though only a few are widely adopted in international standards. Among these, Fanger's model, which underpins the ASHRAE-55 and ISO 7730 standards, is the most commonly used adaptive thermal comfort model. This model calculates optimal thermal comfort based on factors like metabolic rate and clothing insulation, using the operative temperature to derive two key comfort indices: the Predicted Mean Vote (PMV) and the Predicted Percentage of Dissatisfied (PPD). Despite its widespread use, several studies have highlighted limitations in Fanger's model. For example, it treats occupants as passive recipients of thermal conditions and overlooks their ability to adapt, which is influenced by physiological and cultural factors

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Fanger's model does not account for variables such as dynamic human activities, age, ethnicity, thermal memory, and climate, all of which play a role in shaping thermal comfort. Additionally, non-measurable socio-psychological and physiological factors are often excluded from this model, despite their importance in accurately assessing indoor thermal sensations [14]. Recognizing these shortcomings, many other models and surveys have been developed to examine the behaviors and actions that occupants take when faced with uncomfortable thermal conditions. Ultimately, because thermal sensation is influenced by a complex interplay of variables, a multi-domain approach to understanding human perception in indoor environments is recommended.

The pursuit of building thermal comfort through various HVAC systems represents a complex challenge that intersects with multiple disciplines, including engineering, architecture, environmental science, and human factors [15]. The ongoing advancements in HVAC technology, coupled with a deeper understanding of thermal comfort principles, are paving the way for more sophisticated and sustainable solutions that promise to enhance indoor environments while reducing the environmental burden of buildings.

II. LITERATURE REVIEW

The investigation of thermal comfort in buildings and the role of HVAC systems in achieving this comfort has been a significant area of research, with studies spanning various disciplines such as engineering, architecture, and environmental science. The adaptive comfort model, proposed by Nicol and Humphreys (2002) [16], has been instrumental in shifting the understanding of thermal comfort from a fixed-temperature approach to one that considers the adaptability of occupants to a wider range of temperatures. Their work highlighted that comfort is not solely dependent on maintaining a constant indoor temperature but is also influenced by factors such as clothing, activity levels, and external weather conditions. This model has been further supported by de Dear and Brager (1998) [17], who demonstrated that allowing occupants some degree of control over their environment, such as through operable windows or personal HVAC controls, can enhance comfort and broaden the acceptable range of indoor temperatures, leading to potential energy savings.

Traditional HVAC systems, designed to maintain a constant indoor temperature, have been critiqued for their high energy consumption and limited responsiveness to varying conditions. Kamel and Memari (2019) [18] explored the potential of Variable Refrigerant Flow (VRF) systems, which offer the flexibility of individual zone control and can adjust cooling and heating outputs based on real-time demand. Their research showed that VRF systems could significantly lower energy consumption while maintaining or even improving thermal comfort, due to their ability to precisely control the indoor climate.

The integration of renewable energy sources into HVAC systems has been another critical focus of research. With the global push towards sustainability, systems such as geothermal heat pumps, solar-assisted HVAC systems, and hybrid configurations have been explored for their ability to reduce dependency on fossil fuels. Xu and Wang (2017) [19] investigated the effectiveness of solar-assisted HVAC systems, particularly in regions with high solar radiation, and found that these systems could substantially decrease energy consumption. Similarly, Omer (2008) [20] examined geothermal heat pumps and demonstrated their potential to provide efficient heating and cooling while significantly reducing the environmental footprint of buildings.

Indoor air quality (IAQ) is another important aspect considered in the design and operation of HVAC systems. Poor IAQ, often stemming from inadequate ventilation or the recirculation of air without proper filtration, can lead to health issues such as sick building syndrome. Fisk et al. (2009) [21] emphasized the need for HVAC systems to ensure both thermal comfort and healthy indoor air. They advocated for systems incorporating advanced filtration technologies and real-time air quality monitoring, which can adjust ventilation rates based on occupancy and pollutant levels, safeguarding occupant health while maintaining comfort.

The drive towards energy efficiency has spurred significant advancements in smart HVAC systems, which utilize sensors, algorithms, and automation to optimize performance. Katipamula and Brambley (2005) [22] examined the role of smart HVAC systems in reducing energy consumption and found that these systems, when integrated with building management systems (BMS), can dynamically adjust heating, cooling, and ventilation based on factors like occupancy

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patterns and weather forecasts. Their research demonstrated that smart HVAC systems could achieve substantial energy savings while maintaining or enhancing thermal comfort.

The literature also highlights the critical role of occupant behavior and preferences in determining the effectiveness of HVAC systems in providing thermal comfort. Studies by Humphreys and Nicol (2002) [23] showed that thermal comfort is not only influenced by physical environmental conditions but also by psychological and contextual factors, such as perceived control, expectations, and cultural differences. This suggests that HVAC systems should be designed considering how occupants interact with their environment, emphasizing the importance of user-centric design approaches.

G. Barone (2023) Indoor thermal comfort is a critical consideration in building design, yet traditional standards often overlook the human body's thermal adaptability. HVAC systems typically operate under a steady-state assumption, which can lead to inaccurate estimations of occupants' thermal needs. This, in turn, results in misleading calculations of energy consumption and improper system sizing. To address these challenges, a physiological thermal comfort model has been developed within the MatLab environment to evaluate the dynamic changes in physiological parameters and accurately characterize occupants' thermal sensations [24].

The model is integrated into a building energy simulation tool known as DETECt 2.4, which is used to test three dynamic control strategies for managing the thermo-hygrometric parameters of a building, as well as the associated heating and cooling demands. These strategies involve hourly adjustments to relative humidity and air temperature, utilizing a two-step optimization process aimed at maximizing occupant comfort while minimizing energy usage. To demonstrate the model's effectiveness, a case study was conducted in an office space, where the heating and cooling demands generated by the new model were compared to those based on traditional fixed set-point values (20°C and 45% relative humidity for heating, and 26°C and 50% relative humidity for cooling). The comparison revealed that the proposed comfort strategies, which account for the dynamic thermal evolution of occupants, generally led to higher energy consumption—ranging from 2% to 16% more than the standard approach. This increase in energy use represents the trade-off required to maximize occupant comfort and eliminate the 3650 hours of discomfort observed in the reference scenario.

Wenqi Guo (2009) This paper examines control strategies for thermal comfort in modern commercial buildings equipped with heating, ventilating, and air-conditioning (HVAC) systems. To enhance the energy efficiency of these systems, there is a growing need for improved system operations and advanced control algorithms. Recent research, primarily from the past decade, indicates that HVAC systems in commercial buildings play a crucial role in affecting the health, satisfaction, and productivity of occupants. Additionally, this paper explores the potential of utilizing wireless sensor networks (WSNs) to boost the energy efficiency of HVAC systems while maintaining a comfortable environment that supports occupant productivity [25].

III. METHODOLOGY

This study employs a comprehensive approach to review and analyze thermal comfort-based control strategies for HVAC systems in modern commercial buildings. The methodology consists of several key steps designed to systematically evaluate the effectiveness of existing strategies, explore innovative approaches, and assess the potential impact of emerging technologies like wireless sensor networks (WSNs) on HVAC system performance and occupant comfort.

The first step in this methodology involves an extensive literature review, focusing on studies published predominantly in the last decade. The review targets research articles, technical reports, and case studies that discuss various thermal comfort control strategies, HVAC system operations, and the integration of energy-efficient technologies. By analyzing a wide range of sources, the study aims to identify common themes, challenges, and gaps in the current body of knowledge. Special attention is given to the development of advanced control algorithms that optimize HVAC performance, reduce energy consumption, and maintain or enhance thermal comfort for occupants.

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Following the literature review, the study conducts a critical analysis of the identified control strategies. This analysis is structured around key performance indicators (KPIs) such as energy efficiency, thermal comfort, system responsiveness, and occupant satisfaction. Each control strategy is evaluated based on these KPIs to determine its effectiveness in real-world applications. The analysis also considers factors such as building type, climate zone, occupancy patterns, and the specific HVAC technologies employed, providing a nuanced understanding of how different strategies perform under varying conditions.

In parallel, the study explores the role of wireless sensor networks (WSNs) in enhancing HVAC system efficiency and occupant comfort. This involves a detailed examination of existing WSN technologies, their integration with HVAC systems, and their impact on system performance. The study reviews case studies and experimental data where WSNs have been implemented in commercial buildings, assessing the outcomes in terms of energy savings, improved thermal comfort, and enhanced occupant productivity. Additionally, the study considers the technical challenges and limitations associated with deploying WSNs in commercial settings, such as network reliability, data accuracy, and integration with existing building management systems (BMS).

To further validate the findings, the study incorporates a comparative analysis of traditional and advanced HVAC control strategies. This comparison involves a series of simulations and modelling exercises using industry-standard software tools. The simulations are designed to replicate real-world conditions in commercial buildings, allowing for the evaluation of different control strategies under controlled scenarios. Parameters such as energy consumption, indoor temperature stability, and occupant comfort levels are monitored and analyzed across different control approaches. The results of these simulations provide empirical data that support the theoretical analysis conducted in earlier stages of the study.

The methodology includes a forward-looking projection of the potential future developments in HVAC control strategies and technologies. This projection is informed by the trends observed in the literature review and the outcomes of the simulation studies. The study discusses the likely evolution of HVAC systems, with particular emphasis on the increasing role of automation, artificial intelligence (AI), and machine learning in optimizing system performance. The potential for further integration of WSNs and other smart building technologies is also explored, highlighting opportunities for continued improvement in energy efficiency and occupant comfort.

This methodology offers a rigorous and multi-faceted approach to understanding and advancing thermal comfort-based control strategies for HVAC systems in commercial buildings. By combining literature review, critical analysis, simulation, and forward-looking projections, the study provides a comprehensive framework for evaluating current practices and identifying promising avenues for future research and development.

IV. RESULTS

Figure 1 illustrates the distribution of samples within the comfort zones according to two different thermal comfort assessment methods. Figure 1a represents the Fanger method, which categorizes comfort based on the Predicted Percentage of Dissatisfied (PPD) values. These categories include PPD values below 6%, 10%, and 15%. For example, if the PPD is 15%, this suggests that 85% of the hypothetical occupants would find the indoor temperature satisfactory. Figure 1b shows the results using the Adaptive method, which defines comfort zones based on occupant acceptability levels. The categories are: Category I, where 90% of occupants are expected to be satisfied, and Category II, with 80% acceptability. The percentages of acceptability indicate the proportion of occupants likely to be comfortable with the indoor temperature.

Table 1 summarizes the data from Figure 6, and a detailed analysis of these results shows that despite the different approaches of the two methods, they yield similar outcomes. In both methods, more than 70% of occupants would be comfortable with the thermal conditions for over 90% of the time. This suggests that even though the methods assess thermal comfort differently, they both predict a high level of occupant satisfaction under the given conditions.

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Table 1: Statistical distribution of indoor temperature measurements for both the Fanger and Adaptive methods: results of thermal comfort categories.

(a) Fanger's method categories		(b) Adaptive method categories	
Category A	39.3%	Category I	77.0%
Category B	71.4%	Category II	91.2%
Category C	92.4%	–	–
Outside the categories	7.6%	Outside the categories	8.8%

[a]100% corresponds to 161 280 one-minute samples of the indoor temperature measured.

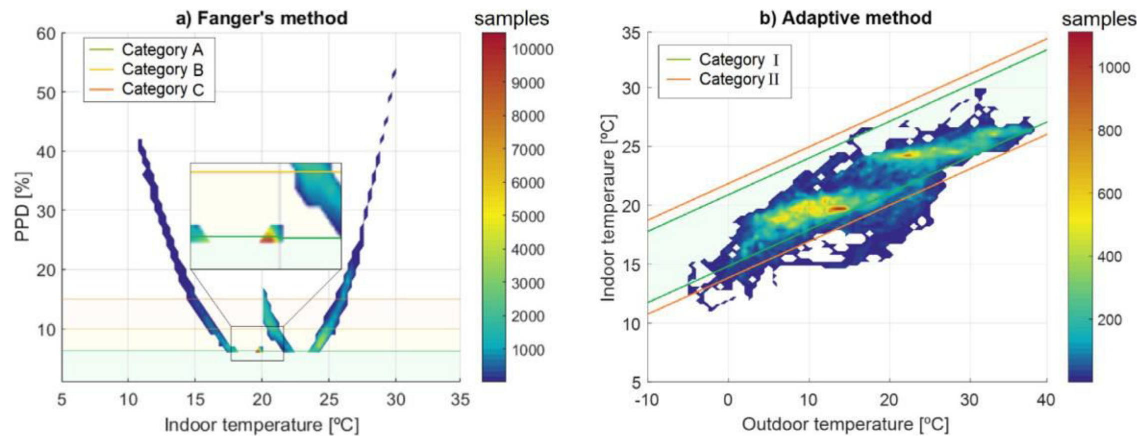

Figure 1: Evaluation of thermal comfort methods: (a) Fanger's Method, and (b) Adaptive model.

V. DISCUSSION

The statistical distribution of indoor temperature measurements for both the Fanger and Adaptive methods provides valuable insights into how these thermal comfort assessment approaches compare and perform in practice. Despite the inherent differences in their theoretical foundations and calculation methodologies, the results indicate a remarkable similarity in the outcomes, particularly in terms of occupant comfort levels.

The Fanger method, which relies on the Predicted Percentage of Dissatisfied (PPD) as a key indicator, classifies comfort based on specific thresholds of dissatisfaction. For instance, a PPD of 15% suggests that 85% of occupants are expected to find the indoor environment thermally comfortable. This method is grounded in the steady-state model, which assumes that occupants are passive recipients of thermal conditions, with comfort being primarily influenced by factors like metabolic rate, clothing insulation, and the operative temperature. While this model has been widely adopted and forms the basis for several international standards, it has been critiqued for its limitations in accounting for dynamic human behavior and adaptation to varying thermal conditions.

The Adaptive method takes into account the occupants' ability to adjust to their thermal environment, whether through behavioral changes, such as adjusting clothing or opening windows, or through psychological adaptation. This method defines comfort zones based on acceptability levels, with Category I representing a 90% acceptability threshold and Category II an 80% threshold. The Adaptive method is particularly relevant in naturally ventilated buildings, where occupants have more control over their thermal environment, and where the indoor climate can fluctuate more than in mechanically conditioned spaces.

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The analysis of the data, as illustrated in Figure 6 and summarized in Table 2, reveals that both methods predict a high level of occupant satisfaction with indoor temperatures. More than 70% of the occupants are expected to be comfortable for over 90% of the time, regardless of the method used. This convergence in results is significant because it suggests that, in practical applications, both the Fanger and Adaptive methods can be reliable tools for assessing thermal comfort, despite their different approaches. This finding also underscores the importance of context when choosing a thermal comfort model. For instance, in a mechanically ventilated building where conditions are tightly controlled, the Fanger method may be more applicable. Conversely, in a naturally ventilated building where occupants have more control, the Adaptive method may offer a more accurate reflection of comfort levels.

Furthermore, the similarity in results between the two methods highlights the potential for integrating these approaches in a hybrid model that leverages the strengths of both. Such a model could provide a more holistic assessment of thermal comfort by combining the steady-state analysis of the Fanger method with the adaptive insights of the Adaptive method. This could lead to more nuanced HVAC control strategies that not only maintain a comfortable indoor environment but also optimize energy consumption by considering the dynamic interactions between occupants and their environment.

The results also raise important questions about the future direction of thermal comfort research. As building technologies continue to advance, particularly with the increasing integration of smart systems and IoT (Internet of Things) devices, there is a growing opportunity to refine these models further. For example, the use of real-time data from wireless sensor networks (WSNs) could enhance the precision of both the Fanger and Adaptive methods, enabling them to adjust to actual occupant behavior and environmental conditions more effectively.

VI. CONCLUSION

This study provides a comparative analysis of two prominent thermal comfort assessment methods—Fanger's method and the Adaptive method—by examining their effectiveness in predicting indoor comfort levels in commercial buildings. The results indicate that despite the different theoretical underpinnings and calculation techniques of the two methods, they yield similar outcomes regarding occupant satisfaction with indoor temperatures. Both methods predict that over 70% of occupants will be comfortable for more than 90% of the time, highlighting their reliability in assessing thermal comfort.

Fanger's method, based on the Predicted Percentage of Dissatisfied (PPD), remains widely adopted and provides a structured approach to comfort assessment through steady-state conditions. However, its limitations in addressing dynamic human behavior and adaptability are noted. In contrast, the Adaptive method, which accounts for occupants' ability to adjust to their environment, offers a more flexible and context-sensitive approach, particularly relevant in naturally ventilated buildings where occupants have greater control over their thermal environment. The convergence of results between the two methods underscores their practical applicability and suggests that both can serve as effective tools for evaluating thermal comfort. This finding opens the door to integrating the strengths of both methods into a hybrid model, which could provide a more comprehensive assessment of occupant comfort and inform more nuanced HVAC control strategies.

As building technologies and smart systems continue to advance, there is significant potential to enhance these models further. Future research could explore the integration of real-time data from wireless sensor networks and other emerging technologies to refine the accuracy and responsiveness of thermal comfort assessments. Such advancements could lead to more energy-efficient and occupant-centered building designs, aligning with the evolving demands for both comfort and sustainability.

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