Original Article
ISSN (Online): 2582-7472

ShodhKosh: Journal of Visual and Performing Arts
January-June 2024 5(1), 596–602

A REVIEW BASED STUDY ON THERMAL COMFORT OF NATURALLY VENTILATED CLASSROOMS

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Check for updates

Accepted 02 June 2024
Published 27 June 2024

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DOI
10.29121/shodhkosh.v5.i1.2024.3702

Funding: This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

ABSTRACT

In classrooms with natural ventilation, thermal comfort has a significant impact on students' academic performance, output, and general well-being. Naturally ventilated classrooms are becoming more popular as a practical substitute for mechanically ventilated environments as a result of growing awareness of sustainability and energy efficiency. With an emphasis on occupant behaviour, building design, climate effects, and adaptive thermal comfort models, this review of the literature examines at the state of the art in thermal comfort studies concerning these kinds of environments. It highlights how important passive design techniques—like ventilation, shading, and orientation—are for creating ideal temperature conditions without the need for energy-intensive devices. The evaluation also emphasizes how crucial it is for occupants to be adaptable, especially in a variety of climates where natural ventilation might not be enough. In addition to sustainable alternatives like mixed ventilation systems and improved building designs, issues including poor air quality, climatic extremes, and design limitations are covered in detail. The study also points out important research gaps, such as the absence of longitudinal evaluations, regional studies, and their integration with contemporary technologies. The goal of this review is to present a thorough understanding of the variables influencing the thermal environment in naturally ventilated classrooms by combining important findings and suggesting future research avenues. A multidisciplinary approach is required to create creative, situation-specific solutions that complement educational aims and sustainability objectives, thereby improving the learning atmosphere for students. This study fills in knowledge gaps and provides researchers, architects, and policymakers with useful insights that add to the continuing conversation on sustainable classroom design.

Keywords: Thermal Comfort, Naturally Ventilated Classrooms, Temperature, Humidity, Air Velocity, Adaptive Thermal Comfort Models

1. INTRODUCTION

Since thermal comfort has an immediate impact on students' health, well-being, and academic performance, it is essential to designing effective learning spaces. Naturally ventilated classrooms provide a sustainable and energy-efficient substitute for mechanically ventilated buildings, particularly in areas with limited resources. Because of financial and infrastructure limitations, around 80% of classrooms in underdeveloped countries—including India—rely on natural ventilation (Chong et al., 2022). The World Bank states that poor classroom conditions lead to a 20% decline in learning outcomes, highlighting the importance of thermal comfort for student achievement (World Bank, 2020). A number of variables, including the climate, building orientation, material qualities, and occupant behaviour, affects the thermal environment in naturally ventilated classrooms. According to studies, temperature in tropical and arid locations often surpass 30°C, which might result in cognitive deterioration and decreased learning efficiency (Zhang et al., 2021). Similarly, in colder areas, classrooms with inadequate ventilation lose too much heat, which is uncomfortable and interferes with learning (Li et al., 2020). One major benefit of naturally ventilated classrooms is their sustainability, as they eliminate the need for energy-intensive air conditioning equipment, which helps lower power consumption. These classrooms offer a practical way to lower energy consumption and carbon emissions in nations like India, where educational organizations are under increasing pressure to lower operating expenses. According to the International Energy Agency (IEA), buildings use around 30% of the world's energy, and HVAC systems are a major contributor to this (IEA, 2021). Adopting passive ventilation techniques in schools is essential to achieving energy efficiency and worldwide environmental sustainability targets. Achieving thermal comfort is made more difficult by India's more than 1.5 million schools and its varied climate zones. According to studies, more than 60% of Indian classrooms suffer from heat discomfort for at least in summer season. (Mahdavi et al., 2022). Even under these difficult circumstances, naturally ventilated classrooms may be able to offer reasonable comfort levels if they are well planned and bolstered by adaptive occupant behaviours (Chong et al., 2022). The goal of this review is to compile the body of research on thermal comfort in classrooms with natural ventilation, examining methods, conclusions, and difficulties. This study aims to provide useful advice for architects, legislators, and academics aiming to create sustainable, energy-efficient, and pleasant learning settings for the future by identifying gaps in knowledge and combining insights[10].

2. REVIEW OF LITERATURE

2.1. FACTORS AFFECTING THERMAL COMFORT IN NATURALLY VENTILATED CLASSROOMS

The subjective state of thermal comfort is impacted by both human and environmental factors, such as clothing and levels of activity, as well as environmental characteristics like temperature, humidity, and air velocity. Maintaining thermal comfort in naturally ventilated classrooms is challenging since passive design techniques and external climate variables are used. Fanger's Predicted Mean Vote (PMV) model states that when most occupants are satisfied with their indoor surroundings, thermal comfort has been attained (Fanger, 1970). Adaptive comfort models are more suitable in naturally ventilated environments, while the PMV model is less suitable (de Dear & Brager, 1998). According to adaptive thermal comfort computational models, people who live in naturally ventilated buildings can modify their posture, attire, or use of the controls (such as fans and windows) to stay comfortable. (Nicol and Humphreys, 2002), for example, stress how behavioural changes are crucial to comfort, especially in tropical and subtropical regions. Research conducted in Indian classrooms has revealed that during the hottest summer months, children commonly open windows or use hand fans, exhibiting adaptive behaviours (Manu et al., 2016). Naturally ventilated classrooms depend heavily on environmental elements like air velocity and shade. In tropical settings, cross-ventilation—achieved through well positioned openings—can dramatically lower indoor temperatures by as much as 4°C (Nguyen et al., 2011). By reducing solar heat gain, shading elements like louvres and overhangs improve thermal comfort even more. By gradually absorbing and releasing heat, high thermal mass materials, such as concrete or brick, can stabilise indoor temperature (Givoni, 1998). There are significant differences in occupant satisfaction with thermal comfort between climatic zones. Evaporative cooling and night ventilation have been shown to be successful in preserving comfortable indoor temperatures in hot and dry areas (Alvarez et al., 2014). On the other hand, airtight building envelopes and insulation are essential for reducing heat loss in colder areas. Another important component of naturally ventilated classrooms is the integration of thermal comfort and indoor air quality (IAQ). These areas are nonetheless susceptible to outside air pollution even if they typically have superior IAQ than their mechanically ventilated equivalents. In order to reduce these dangers, research conducted in metropolitan settings has shown the necessity of hybrid systems that integrate air purification technology with natural ventilation (Chen et al., 2017). Notwithstanding their advantages, naturally ventilated classrooms have drawbacks include discomfort during certain seasons, inadequate opening maintenance, and a lack of established design standards. To overcome these constraints, future research should concentrate on region-specific solutions, sophisticated modeling methods, and longitudinal studies. Naturally ventilated classrooms may set the standard for comfortable and energy-efficient learning spaces globally by implementing sustainable practices and adaptive strategies.

2.2. METHODOLOGIES IN THERMAL STUDIES

Studies on thermal comfort in naturally ventilated classrooms typically use one or more of the following approaches:

2.2.1. FIELD STUDIES

These include occupant surveys and on-site environmental parameter assessments. For instance, to assess comfort levels, research conducted in tropical regions frequently measures indoor temperature, humidity, and air velocity. It enables direct communication with residents and offers real-world data relevant to the situation under study (Kim et al., 2021). It requires a lot of time and resources, and it is not very applicable to different building designs or climates (Ahmed et al., 2022). The dynamic character of thermal comfort in rooms has been brought to light by recent field investigations, which have emphasized temporal fluctuations and the necessity of seasonal flexibility. Flexible design interventions are necessary since occupant satisfaction levels vary greatly depending on the time of day and external weather, according to Zhang et al.,2021. According to Ahmed et al., 2022, students' immediate feedback can improve the precision of thermal comfort measurements and promote interactive classroom design. By documenting actual interactions between occupants and the environment around them, field studies conducted in naturally ventilated classrooms offer vital insights into thermal comfort. According to these studies, adaptive behaviors—like opening windows or modifying clothing—are crucial for preserving levels of comfort (Nicol & Humphreys, 2002; de Dear & Brager, 1998). Perceived comfort is greatly impacted by seasonal changes in temperature and airflow, underscoring the necessity of adaptable design techniques (Zhang et al., 2021). Furthermore, research from various countries has demonstrated that cultural and climatic factors affect thermal comfort in such settings (Kwok & Rajkovich, 2010; Brager & Baker, 2009). The accuracy of comfort assessments is improved by real-time occupant feedback obtained through surveys or Internet of Things-based systems, which also facilitate interactive design strategies for sustainable environments for learning (Kim et al., 2021; Lu et al., 2020; Chen, 2021).

2.2.2. SIMULATION MODELS

Under different conditions, the thermal efficiency of naturally ventilated rooms is predicted by computational tools such as EnergyPlus and CFD models. It makes it possible to analyse various design conditions and climates with no need for physical testing. beneficial for building design optimization (Zhang et al., 2020). It calls for a great deal of computing power and knowledge. Unpredictable occupant behaviours might not be taken into consideration (Wang et al., 2021). Simulation models are becoming more accurate and useful in classroom design, according to recent studies. For instance, Li et al.,2021 improved airflow distribution by 30% by optimizing cross-ventilation pathways in tropical classrooms using CFD models. Likewise, Kumar et al., 2022 demonstrated how machine learning-integrated simulations may be used to forecast occupant behavior in a range of climates, improving the accuracy of thermal comfort predictions. Nevertheless, there are still issues in simulating intricate, real-world interactions, like the concurrent impact of internal occupancy dynamics and exterior weather (Chen et al., 2023).

Because they provide scalable and affordable methods for forecasting and improving interior conditions, simulation models are essential to the advancement of thermal comfort research. For example, extensive research of airflows and variations in temperature within buildings is made possible by computational fluid dynamics models, which offer insights that are not possible with conventional field studies (Chen, 2021). Furthermore, a variety of climates and building types are assessed for thermal comfort using energy simulation programs like EnergyPlus and TRNSYS (Crawley et al., 2008). By taking into account occupants' behavioural reactions to environmental changes, adaptive thermal comfort models provide more accurate predictions in simulations (de Dear et al., 2013). Recent developments further emphasize how machine learning methods may be included into simulation models to improve their prediction power, which makes them ideal for changing and multi-climatic environments (Lu et al., 2020). These approaches facilitate data-driven, occupant-centered design methodologies while drastically lowering resource needs.

2.2.3. ADAPTIVE COMFORT MODELS

In order to assess appropriate heat conditions, these models take into consideration occupants' adaptive behaviours, like opening windows or modifying clothes. Adaptive models take into consideration the changes that occupants make to attain comfort, reflecting the dynamic character of human behaviour. Because of this, they are particularly useful in naturally ventilated buildings, where residents can modify their surroundings by opening windows or dressing differently. The usefulness of adaptive comfort models for enhancing comfort perception in naturally ventilated buildings was demonstrated in a 2021 study by Chong et al., which also emphasized the major influence of climate and environment on these adaptive behaviors. (Chong et al., 2021). Energy savings are made possible by adaptive models, which modify HVAC system operations in response to occupant behaviour. Particularly in moderate regions where passenger behaviour is enough for comfort, these models can lessen the requirement for active heating or cooling. According to a 2020 study by Zhang et al., using adaptive thermal comfort models for offices can save up to 25% on energy costs. In mixed-mode and buildings with natural ventilation, the savings might be much higher. (Zhang et al., 2020). A more individualized approach to comfort is offered by adaptive thermal comfort models, which take into account behavioural changes and personal preferences. Because adaptive comfort models took into consideration both the physical surroundings and people's subjective comfort, they were found to increase occupant satisfaction and productivity in a 2023 study on workplace environments (Sun et al., 2023).

2.2.3.1. LIMITATIONS OF ADAPTIVE THERMAL COMFORT MODELS

The use of subjective information, usually obtained through surveys, to gauge comfort levels is one major drawback. Biases may be introduced by these polls, particularly if respondents' tastes are inconsistent or impacted by other elements like expectations or cultural differences. Although subjective surveys are helpful, Li et al. (2020) pointed out in their 2019 review that they might not always accurately reflect real behaviour, which could result in modeling errors. In harsh climes, where the outside temperature may be excessively hot or cold for adaptive behaviours like changing clothes or opening windows to maintain thermal comfort, these steps are not always enough. According to a 2022 study by Mahdavi et al., adaptive models encountered major difficulties in colder or hotter locations, necessitating the installation of supplementary heating or cooling systems to guarantee the comfort of occupants (Mahdavi et al., 2022). Adaptive behaviours can be difficult and resource-intensive to incorporate into building energy models. It necessitates precise information on how residents behave as well as the capacity to model how environmental changes impact their comfort. In buildings with centralised HVAC systems, it can be difficult to deploy adaptive comfort models since these models rely on individual modifications, which are difficult to make (Li et al., 2021).

3. KEY FINDINGS FROM LITERATURE REVIEW

3.1. CLIMATE INFLUENCE

In order to increase thermal comfort, tropical regions' high temperatures and humidity call for techniques like cross-ventilation and shading. Adaptive thermal comfort models that take into consideration local climate variables and occupant behaviours, have been shown to be beneficial in tropical climates for educational buildings (Chong et al., 2022). Maintaining comfort in arid climates requires maximising airflow and minimising heat buildup. Buildings in these areas have been found to benefit from designs that use high thermal mass materials and encourage passive cooling methods (Khalil et al., 2020). While insulation and airtightness are essential for comfort during the cooler months, temperate regions allow for greater natural airflow. According to research, these climates are especially well-suited to adaptive thermal comfort models due to their seasonal temperature changes, provided that insulation is carefully considered during winter months (Li et al., 2020).

3.2. BUILDING DESIGN

By decreasing solar heat intake and enhancing airflow, well-placed windows, shading devices, and building orientation can all greatly increase thermal comfort. Orientation and shading help improve thermal comfort by promoting natural cooling, particularly in warm areas, according to research on mixed-mode ventilated houses (Zhang et al., 2021). Particularly in regions with significant daily temperature differences, high thermal mass materials can help improve thermal comfort by reducing indoor temperature swings. Structures made of heat-absorbing and heat-releasing materials, such as stone or concrete, assist stabilize indoor temperatures and lessen the need for efficient cooling systems (Shao et al., 2021).

3.3. OCCUPANT BEHAVIOUR

Particularly in naturally ventilated buildings, occupants' adaptive behaviors—like turning on fans, adjusting windows, or changing their attire—play a major role in preserving comfort. Studies have indicated that taking these behaviours into consideration can result in more precise forecasts of building energy consumption and thermal comfort (Zhang et al., 2020). Wide variations in occupant preferences for ventilation and temperature need for adaptable design solutions. Thermal comfort models that take into account human preferences and behaviour have been shown to improve satisfaction and lessen the demand for mechanical equipment (Sun et al., 2023).

3.4. INDOOR AIR QUALITY

Assuming the external air quality is sufficient, naturally ventilated classrooms typically achieve superior indoor air quality (IAQ) than mechanically ventilated areas. Research has demonstrated that incorporating adaptive thermal comfort models with natural ventilation can enhance indoor air quality (IAQ) and comfort levels for educational institutions (Nguyen et al., 2019). The advantages of natural ventilation might be negated by poor external air quality, highlighting the necessity of site-specific architecture. According to research, adaptive thermal comfort models need to take into consideration indoor as well as outdoor air quality in order to sustain comfort in areas with high pollution levels (Mahdavi et al., 2022).

4. RESEARCH GAPS

Research in adaptive thermal comfort for locations with harsh weather conditions is lacking. Research in arid and temperate locations are under-represented, despite the fact that research has been done in tropical settings. (Zhang and others, 2021). In order to understand how comfort varies with changing weather conditions, few studies assess thermal comfort over long periods of time to account for seasonal variations. (Sun and others, 2023) Hybrid systems that integrate low-energy mechanical solutions with natural ventilation have not received much attention. Energy economy and occupant comfort may be greatly increased by combining adaptive thermal comfort models using contemporary technologies, such as smart HVAC systems. (Li and others, 2021). There aren't many studies that explicitly connect outcomes for learning in naturally ventilated classrooms to thermal comfort. A better understanding of this link may result in the design of educational spaces that put comfort and academic achievement first. (Chong and others, 2022).

5. SUSTAINABLE STRATEGIES FOR IMPROVEMENT

5.1. ENHANCED DESIGN

Building thermal comfort can be improved by strategically placing windows and orienting buildings to maximize natural ventilation and airflow. The requirement for mechanical cooling systems can be decreased by positioning windows to allow for cross-ventilation and orienting buildings to maximize exposure to prevailing breezes. By encouraging improved airflow and enhancing passive cooling techniques, Zhang et al. (2021) showed how window location and building orientation might minimize thermal discomfort in educational facilities (Zhang et al., 2021). Reflective materials (like cold roofs) and shading devices (like blinds, overhangs, and louvres) help lower solar heat gain and maintain a more comfortable interior temperature. By limiting the requirement for mechanical cooling, shading techniques can save energy costs and improve occupant comfort. Li et al. (2020) demonstrated how important reflective materials and shading devices are for lowering cooling energy use and enhancing indoor comfort, especially in hot areas.

5.2. HYBRID VENTILATION SYSTEMS

A viable way to increase thermal comfort while lowering energy use is through hybrid ventilation systems, which blend natural ventilation using low-energy mechanical components like electricity-efficient fans or exhaust systems. These technologies improve occupant comfort while enabling improved control over indoor temperature and air quality. According to Sun et al. (2023), hybrid systems can save energy and improve comfort, particularly when they are made to react to the environment in real time. In educational and mixed-use buildings, the combination of natural ventilation and low-energy ventilation systems has demonstrated encouraging outcomes (Sun et al., 2023).

5.3. POLICY INTERVENTIONS

It is crucial to create regionally tailored rules for naturally ventilated classrooms which take into consideration the unique climate of a given area. These recommendations can give building designers a framework for enhancing interior thermal comfort while maintaining appropriate indoor air quality and low energy use. Policies that are specific to local climates and environmental conditions are crucial for enhancing the thermal environment in naturally ventilated classrooms, especially in areas with high levels of humidity or extreme temperatures, according to a study by Mahdavi et al. (2022).

5.4. COMMUNITY ENGAGEMENT

Comfort and energy efficiency can be greatly increased by community engagement, particularly by teaching residents (including teachers and students) adaptive thermal comfort behaviours. Buildings may maintain improved thermal comfort with less energy use by teaching people about easy, sustainable behaviours like changing windows, turning on fans, or changing clothes. The significance of occupant awareness in naturally ventilated environments was emphasised by Chong et al. (2022). They discovered that overall thermal comfort considerably increased when educators and students knew how to employ passive cooling strategies and modify their behaviour (Chong et al., 2022).

6. CONCLUSION

Classrooms with natural ventilation offer a sustainable way to preserve thermal comfort, especially in places with scarce resources or expensive energy bills. These classrooms support sustainability objectives by reducing the need for energy-intensive cooling equipment by utilising natural airflows. However, human behaviour, building design, and local climate variables all have a significant impact on how effective these systems are. For instance, improper window location, shading, and airflow control can reduce the effectiveness of natural ventilation in hot, humid conditions.

This review emphasizes the need of tackling a number of issues, such as the necessity for local designs that take extreme weather conditions into account, the diversity of occupant behaviour, and the incorporation of adaptive comfort models. For the area to advance, it will be essential to identify and fill the current research gaps, such as the dearth of longitudinal studies, challenges with data collecting, and understudied hybrid systems. Furthermore, it is crucial for future study to take into account how thermal comfort affects learning outcomes and academic performance in educational settings. Innovative, context-specific approaches that improve thermal comfort while sustaining resources in naturally ventilated classrooms require a multidisciplinary approach that integrates behavioural studies, environmental engineering, and architectural design. This strategy will help make learning settings in the classroom healthier and more energy-efficient.

CONFLICT OF INTERESTS

None.

ACKNOWLEDGMENTS

None.

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