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Recent Advances in Passive Cooling Techniques for Indoor Thermal Comfort

Shivendra Singh[1], Amit Vishwakarma[2], N.K. Sagar[3]

[1]*Assistant Professor, Department of Mechanical Engineering, Sagar Institute of Research and Technology, Bhopal*
[2]*Assistant Professor, Department of Mechanical Engineering, Sagar Institute of Research and Technology, Bhopal*
[3]*Head of Department, Department of Mechanical Engineering, Sagar Institute of Research and Technology, Bhopal*

Abstract

Passive cooling techniques are proving to be effective and sustainable approaches to achieve adequate indoor thermal comfort in buildings with less energy consumption. With the rising atmospheric temperature and the rapid growth of the urban population along with the negative environmental effects of air-conditioning systems, energy efficient cooling solutions have become more important than ever. This review paper covers the recent developments of the passive cooling methods to provide comfortable indoor environments by natural cooling process and climate responsive building design. The study emphasizes to the main passive cooling methods: natural ventilation, shading systems, thermal mass, evaporative cooling, windcatchers, green roofs, and innovative building material. New advances in adaptive ventilation, smart shading and sustainable architecture are also mentioned. Also, the review will investigate the contribution of passive cooling to achieve a better indoor environment and to enhance the well-being of the occupants. The results show a significant improvement in thermal comfort and a decrease in cooling loads and environmental impacts when multiple passive cooling strategies are combined. In conclusion, passive cooling technologies are viable and sustainable solutions for future building design with an aim to low energy consumption.

Keywords; Passive Cooling Techniques, Thermal Comfort, Natural Ventilation, Air Quality, Indoor Air Temperature.

INTRODUCTION

In recent years, passive cooling has become a topic of great interest because of the growing demand for sustainable and energy-efficient building solutions. Indoor cooling demand has significantly increased due to rapid urbanization, industrialization and global climate change, leading to increased energy demand and greenhouse gas emissions from traditional air-conditioning systems [1]. In this context, passive cooling has become an alternative option that respects the natural conditions and heat transfer mechanisms to achieve comfortable indoor temperatures with less need for mechanical cooling appliances and systems [2]. The passive cooling strategies aim for minimizing heat gain and improving heat dissipation by architectural planning, building materials, and natural cooling techniques. Some of these methods are shading devices, thermal mass, evaporative cooling, windcatchers, green roofs, courtyards, and optimizing building orientation [3]. Building design can incorporate such strategies to enhance thermal comfort inside the building without using too much energy and operational costs. In educational buildings, residential premises and commercial buildings, passive cooling is a key element in maintaining comfort, productivity and health of the occupants [4]. A number of different factors affect the thermal comfort in an indoor environment, including air temperature, air humidity, air velocity and radiant heat. Thermal conditions can be sub-optimal and cause discomfort, decrease in work performance, fatigue and health problems. Thus, adequate passive cooling strategies are becoming crucial for achieving comfortable indoor climate, especially in hot climate areas [5], [6].

Advances in Natural Ventilation Techniques

One of the most widely used passive cooling techniques to enhance the thermal comfort and air quality in buildings is natural ventilation. The recent developments in the field of natural ventilation have been directed towards more effective distribution of the ventilation flow and towards more efficient heat removal from the buildings [7]. Adopting cutting edge ventilation concepts, including cross ventilation, stack ventilation, hybrid ventilation and wind-driven air flow management, in modern architecture, helps to optimise passive cooling performance [8]. Optimisation of the siting of windows and openings to take advantage of wind direction and prevailing winds have been significantly enhanced throughout cross ventilation. Computer programs are increasingly being used to calculate optimum dimensions and locations of inlet and outlet openings to ensure efficient circulation of airflow [9] . In much the same way, stack ventilation systems have evolved using atriums, solar chimneys and ventilation shafts, which take advantage of thermal buoyancy to increase airflow and move heat inside the building [10].

Another important improvement on the passive ventilation systems is the windcatcher. The traditional windcatchers have been redesigned and optimized by using aerodynamic design and computational optimization methods to increase the efficiency of air capture and the cooling performance [11]. Multi-directional windcatchers and hybrid windcatcher system with evaporative cooling has been proven to provide better ventilation efficiency in hot climatic conditions. Recent studies also focus on adaptive ventilation systems that adjust to variable environmental conditions by opening and closing automatically and controlling the system with smart technology [12]. These systems adjust the air flow rates based on the room temperature and humidity, and the occupancy of the room, which enhances the thermal comfort and reduces energy consumption. Moreover, the incorporation of Computational Fluid Dynamics (CFD) simulations has made a significant progress in understanding airflow patterns and thermal behavior of naturally ventilated spaces [13]. Through CFD, stagnation zones, recirculation regions and temperature distribution in the system are determined, which allows a better design of the ventilation system. Overall, the recent development of natural ventilation has brought gains to the comfort of indoor spaces, the decrease of cooling loads and the development of sustainable building [14].

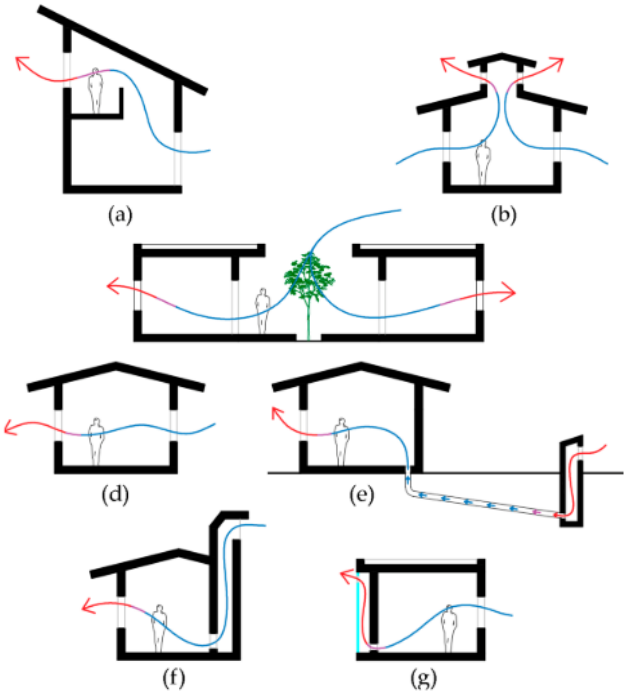

Figure 1: Example of natural ventilation techniques [15]

Innovative Passive Cooling Technologies

In recent years, passive cooling has gained attention, with new technologies emerging that offer innovative solutions to reduce heat gain and enhance thermal comfort in buildings. A significant development is the use of high-performance building materials with better heat insulation and heat storage characteristics [16]. The use of materials with high thermal mass, phase change materials (PCMs) and reflective coatings is growing in use to help manage the indoor thermal environment and reduce cooling requirements. Green roof and Green wall are gaining popularity as passive cooling technologies in cities. Tree layer on building surfaces can decrease solar heat gain, increase the insulation value and help to increase the evaporative cooling effect [15]. These systems also help to alleviate urban heat island effects and enhance environmental sustainability. Likewise, cool roofs with high solar reflectance and thermal emittance can reduce the amount of heat absorbed to keep the indoor temperature down [17]. Mainly in hot and dry climates, the use of evaporative cooling techniques has also made great strides. Indirect evaporative cooling systems and hybrid evaporative cooling systems are available that are efficient for cooling without using too much water. These systems can enhance thermal comfort and also require much less energy than typical air-conditioning systems [18].

Dynamic shading systems like automated louvers, smart blinds, and responsive façade systems are also a new and innovative development. These technologies can control shading based on the intensity of the sun and the environment to minimise heat gain in the building and enhance the comfort of the building occupants [19]. There has been increasing interest in recent years to integrate renewable energy technologies with passive cooling systems. Solar assisted ventilation systems and PV incorporated shade structure improve the energy performance and sustainability of buildings [20]. These technologies are widely used, and advanced computational modeling and building simulation tools are used to optimize and evaluate the effectiveness of these technologies under varying climatic conditions. In conclusion, innovative passive cooling technologies offer sustainable solutions that can help provide thermal comfort in indoor environments, while minimizing energy consumption and environmental impacts [21], [22].

Thermal Comfort Assessment and Indoor Environmental Quality

Thermal comfort assessment is currently an important field of study in building sustainable and energy efficient buildings. The assessment of indoor thermal comfort and indoor environmental quality (IEQ) is closely related to recent developments of passive cooling methods. The thermal comfort is affected by the environmental factors like air temperature, relative humidity, airflow velocity, mean radiant temperature and personal factors like metabolic activity and clothing insulation [23]. International standards are used in thermal comfort assessment like the Predicted Mean Vote (PMV) and the Predicted Percentage of Dissatisfied (PPD) indices are used to assess the comfort level of the occupants. Experiments and numerical simulations are increasingly used together to analyse the thermal conditions in indoor spaces [24]. Indoor environmental quality also refers to the quality of the air inside, lighting and acoustic comfort. Uncomfortable indoor thermal conditions and poor indoor ventilation can cause discomfort, decrease productivity, fatigue and health issues. The passive cooling systems should not only lower the temperature, but also ensure the right air flow and removal of contaminants in the occupied spaces [25].

Occupant-centered evaluation of thermal comfort has been highlighted for recent studies, taking into account the adaptive thermal comfort models and the reactions of the human body to changing environmental conditions. Smart sensors and real-time monitoring systems are becoming more common for collecting data on the indoor environmental conditions and optimizing the passive cooling strategies dynamically [26]. In schools and office spaces, better thermal comfort has been linked to better focus, learning ability, and well-being of the occupants. The application of passive cooling systems along with effective natural ventilation can play a significant role in maintaining a healthy indoor environment with a reduced energy consumption. The overall trend in recent years is that development of passive cooling system design and evaluation for thermal comfort and indoor environmental quality has been enhanced, aiding the development of sustainable and occupant-friendly building [27].

LITERATURE REVIEW

(Bello et al., 2025) [28] examines how passive cooling techniques are used into the architecture of Abubakar Tafawa Balewa University's (ATBU) Faculty of Architecture in Bauchi, Nigeria. The goal of the project is to create an energy-efficient and sustainable educational institution that is adapted to the hot, dry climate of the area. In order to mitigate environmental impacts, enhance indoor thermal comfort, and reduce dependence on mechanical cooling systems, the building design incorporates critical analyses and integrations of vital passive cooling techniques, including solar shading, natural ventilation, thermal mass optimization, and landscape design. These findings highlight the possibility of improved occupant comfort and adherence to Nigeria's building energy efficiency regulations. In order to promote sustainable architectural practices in Nigeria's educational sector, the study ends with design ideas and a discussion of policy implications.

(Kusi et al., 2025) [29] The Classroom ESABSF was selected for the airflow investigation on thermal comfort in a naturally ventilated university classroom. The choice was made in accordance with the observed and simulated indoor thermal ambient conditions. In order to investigate the variation in the room's ventilation properties, a variety of window opening configurations and positions were used throughout the research. The classroom's average air temperature and velocity were recorded and forecasted at a height of 1.1 meters above the ground. According to the study, radiant temperature, relative humidity, and indoor air temperature all decrease when air flow increases. Compared to the empty classroom, the crowded classroom was unpleasant in both the dry and rainy seasons. In order to improve air flow in naturally ventilated classrooms, the research advised architects to make every effort (wall-to-window ratio) during the design phase.

(Alhmoud & Alhmoud, 2024) [30] Analyze and critically assess the thermal comfort and usefulness of historic architectural elements, paying particular attention to the conventional techniques for improving humidity management and thermal regulation in response to dry and hot weather. The research also looked into the spatial changes brought about by new functional and design interventions in old buildings' exteriors and interiors. The architectural, historical, and functional aspects of the structure were thoroughly examined for this paper's findings. This was accomplished by using a two-pronged strategy: a careful visual inspection of the building's physical characteristics and an in-depth review of pertinent textual sources. When combined, these techniques provide a comprehensive knowledge of the building's initial design purpose and how its later modifications improved humidity and thermal management.

(Bema & Ozarisoy, 2024) [31] examines the energy efficiency of cutting-edge passive systems in four different climates—"Canada, India, Abu Dhabi, and the Eastern Mediterranean basin"—in order to provide neutral adaptive thermal comfort for senior citizens. The study's primary goal is to create a useful scientific framework for the ongoing advancement of adaptive thermal comfort theory. The findings demonstrated that the data from the in situ field investigations and "the ASHRAE Global Thermal Comfort Database II" differed. By examining the current approaches used worldwide, the study's conclusions advance the notion of adaptive thermal comfort. Additionally, while determining neutral adaptive thermal comfort, a thorough analysis of the importance of occupant age variations should be carried out.

(Ma et al., 2024) [32] The necessity of building energy conservation has been brought to light by the rising worries about climate change and energy shortages. Renowned for their efficient ventilation qualities, windcatchers have become an essential tool for energy conservation and enhancing indoor thermal comfort. The study concludes that using different wind catchers in hot and dry climates may increase indoor air velocity by approximately 10–50%, reduce building energy consumption by approximately 20–50%, and extend thermal comfort by approximately 25–50% after examining previous research. The essay offers a fresh viewpoint on the research of windcatchers by fusing the viewpoints of several academic fields, including sustainable design, environmental engineering, and architecture. In addition to summarizing the performance and design of current wind catchers, the article offers 13 recommendations for wind capture tower design. Furthermore, it pinpoints areas that require additional investigation, including the integration of wind capture devices with other passive cooling technologies and the evaluation of their efficacy in a variety of urban and climatic environments.

(Oleiwi et al., 2023) [33] Examine and discuss possible passive cooling methods to lower energy use in hot, humid settings. It was discovered that while certain passive cooling techniques are not advised, several studies have emphasized the need of employing a variety of passive cooling techniques to improve thermal comfort within buildings in hot, humid climates. The best passive cooling techniques for hot, humid climates include shielding buildings from direct sunlight and using natural ventilation. In order to identify the best passive cooling techniques for each climate type, the study suggested reviewing the suitability of various passive cooling strategies in various climate types.

(Al-shamkhee et al., 2022) [34] provides a comprehensive literature review and idea summary for passive cooling and ventilation in buildings, as well as an explanation of the fundamental concepts of these approaches. This study also offers a critical summary of current passive cooling technologies and state-of-the-art research. Additionally, buoyancy air-driven ventilation is the article's main topic. In addition to sun control approaches, heat modification and dissipation techniques are explained and categorized. The design concerns of various passive ventilation systems are discussed in this study, along with suggestions for future research aimed at achieving pleasant, affordable living. New systems are also studied and discussed in order to understand the role of "Phase Change Material (PCM)" in passive cooling systems.

(Ahmed et al., 2021) [35] investigated how, in hotter climates, natural ventilation might provide adequate "thermal comfort, heatwave resistance, and high-quality indoor air". When it comes to lowering indoor air temperatures relative to outdoor ones, cross ventilation performs better than single-sided ventilation, which has the lowest capacity to offer thermal comfort. However, by generating comparatively high "ventilation rates, windcatchers and solar chimneys" performed even better. During heat waves and future climate scenarios, natural ventilation through cross-ventilation failed to meet interior thermal comfort standards. Combining water evaporation cooling with solar chimneys or windcatchers might be a low-energy alternative. These systems may provide high ventilation rates and maintain indoor temperatures around 8 °C lower than outside temperatures in warm weather (>35

°C), according to a careful synthesis of the research. Nevertheless, no research comparing these systems to future climatic scenarios was discovered, and more research is advised.

(Rana, 2021) [36] enhance a naturally ventilated home's thermal comfort performance by identifying and assessing the optimal collection of passive design techniques. The case study dwelling was chosen to be a two-story home with a moderate environment in Washington, USA. Following the integration of four critical interventions, three zones—the library, bedroom 1, and bedroom 2—met the target discomfort hours, with reductions in discomfort hours of 53.03%, 60.42%, and 58.94%, respectively. The two remaining zones—living and lounge—also shown a discernible improvement, with decreases of 43.93% and 45.99%, respectively. This study showed that the proper application of passive heating and cooling techniques may greatly enhance occupant thermal comfort all year round, lowering energy use and the environmental effect of buildings.

(Yao et al., 2020) [37] In this project, the interior spaces of courtyard buildings in southern Shaanxi were completely passively cooled throughout the summer using a method that utilizes the common cold tunnels found in the exterior walls of historic cities and buildings. While the building is ventilated and cooled, the system's air wall may successfully prevent direct contact between the interior and outside temperatures and reduce the impact of thermal wall radiation on the interior. Previous studies on the passive design of courtyard dwellings used simulations that must be considered the effect of thermal wall radiation on internal temperature. Therefore, when estimating thermal conversion in this study, we also independently determined whether to take into account the difference between the scenario with and without wall heat radiation (WHR). According to the final figures, the building's yearly cooling demand without WHR was 4786.494 kW·h when the cooling system was implemented. WHR, on the other hand, reduced the cooling demand by 2989.128 kW·h, a difference of 1797.336 kW·h.

DISCUSSION

In recent years, passive cooling methods have shown great promise in enhancing thermal comfort in buildings without relying on mechanical cooling systems. Natural ventilation is still one of the most effective passive strategies because it can improve the ventilation qualities, decrease the amount of heat buildup inside the room and affect the indoor air quality. The reviewed studies show that building orientation, window placement and advanced ventilation systems like windcatchers, solar chimneys, and the hybrid solutions are crucial in ensuring efficient airflow distribution. The additional passive cooling contribution from innovative technologies, such as green roofs, cool roofs, PCM and adaptive shading, has further enhanced passive cooling performance by minimizing solar heat gains and stabilizing indoor conditions. Not only do these technologies increase energy efficiency, but they also have the potential of decreasing greenhouse gas emissions and operating costs, which promotes environmental sustainability. Some of the studies also highlighted the need for the integration of several passive cooling methods for improved climatic performance performance under different climatic conditions. There are references in the literature that relate high level of comfort of the occupants and high quality of indoor environment to the flow of airflow and temperature distribution and to humidity control. Better thermal conditions in educational and residential facilities leads to better well-being, productivity and health for users. Furthermore, adaptive and climate-responsive design strategies are becoming increasingly important in modern sustainable architecture. In conclusion, passive cooling technologies have seen significant progress in recent years, offering practical and environmentally friendly solutions for achieving energy-efficient and comfortable indoor environments.

CONCLUSION

Passive cooling systems have a significant contribution in enhancing thermal comfort and energy efficiency in buildings. The reviewed studies show that natural ventilation, shading systems, windcatchers, thermal mass, evaporative cooling and green building technologies are effective in decreasing the heat gain and improving airflow distribution in the interior. Passive cooling methods have also gained significant benefits from recent developments in adaptive ventilation systems, smart materials, and sustainable building design, enhancing their effectiveness and versatility across various climatic regions. Multiple passive cooling technologies offer improved thermal performance and less air conditioning dependency, which decreases the impacts and operating costs of traditional air-conditioning systems. Passive cooling also helps to provide better indoor environment quality, better occupant comfort and health. The review addresses the increasing significance of the building design and sustainable construction for future energy-efficient buildings in relation to climate. Passive cooling technologies are overall effective and environmentally friendly technologies for achieving comfortable indoor environments in residential, educational, and commercial buildings.

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