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Research Article

Advancements In Thermal Insulation Strategies For Energy-Efficient Building Envelopes: A Comprehensive Literature Review

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ABSTRACT

This literature review delves into contemporary research endeavors aimed at comprehending and refining thermal insulation strategies for building envelopes. The central emphasis is on meeting the growing need for energy efficiency, mitigating heat gain or loss, and aligning with legislative regulations governing the construction sector. A spectrum of studies by various researchers is surveyed, exploring diverse facets such as cavity wall insulation, the utilization of waste materials, and the consequential impact of insulation on energy conservation. The research landscape encompasses experimental investigations, simulation studies, and real-world applications, offering a comprehensive panorama of the current state of developments in the field. This synthesis contributes to the collective understanding of sustainable building practices and informs the ongoing evolution of thermal insulation strategies, vital for addressing the contemporary challenges of energy efficiency and environmental compliance in construction.

Keywords: Thermal insulation, Cavity walls, Energy efficiency, Heat transfer, Building envelopes, Sustainable construction, Material innovation.

Introduction:

In the relentless pursuit of global sustainability, the construction industry stands at the forefront of transformative change. One pivotal arena within this paradigm shift is the advancement of thermal insulation strategies for building envelopes. This comprehensive literature review delves into recent research contributions that aim to understand and enhance thermal insulation, focusing on the imperative for energy-efficient building envelopes.

1. The Energy Efficiency Imperative:

Buildings currently account for a staggering 40% of global energy consumption and contribute nearly one-third of greenhouse gas emissions. This alarming reality necessitates a fundamental re-evaluation of the construction industry's practices, placing energy efficiency at the core of sustainable building design. The building envelope, comprising walls, roofs, windows, and doors, emerges as a key battleground for curbing energy consumption while ensuring occupant well-being.

2. Global Energy Challenges and Building Envelopes:

As urbanization, population growth, and the expansion of the built environment escalate, the demand for energy intensifies. Realistic data underscores the significance of addressing this challenge within the context of building envelopes. Recent studies indicate that a well-insulated building envelope can lead to up to a 50% reduction in heating and cooling energy consumption. Beyond environmental benefits, this reduction offers economic advantages by lowering operational costs associated with traditional HVAC systems.

3. Focus on Cavity Wall Insulation and Material Innovations:

Within the expansive landscape of thermal insulation, a particular emphasis is placed on cavity wall insulation. Research illuminates the potential gains in thermal performance achieved by optimizing the air gap within cavity walls. The quest for materials that balance efficacy and sustainability has led to innovations such as aerogel-based wallpapers. These materials not only exhibit impressive thermal properties but also offer ease of installation and adaptability, particularly in retrofitting existing structures.

4. The Transformative Potential:

Recent experiments underscore the transformative potential of well-insulated building envelopes. From mitigating heat loss during colder seasons to curbing heat gain in warmer climates, the impact of cavity wall insulation is multifaceted. It contributes not only to a more stable indoor environment but also aligns with resource conservation and environmental stewardship.

5. The Road Ahead:

This literature review unfolds as a journey through recent research, each study contributing a unique perspective to the larger narrative of thermal insulation in building design. From the exploration of unconventional materials to advancements in reflective insulation technologies and nuanced discussions on cavity design, our aim is to provide a holistic understanding of the current state of affairs. This knowledge is intended to empower researchers and practitioners, fostering collaborative efforts toward shaping the future of sustainable construction practices.

Literature Review:

Firake and Kol (2022) conducted research to determine the importance of insulation in achieving energy efficiency, reducing heat gain or loss, and decreasing the demand for heating and cooling systems. The study highlighted the increasing demand for adequate thermal insulation due to legislative regulations and growing public awareness of combating excessive energy consumption. Specifically focusing on cavity wall insulation, the research demonstrated its benefits in terms of thermal reduction, fire resistance, and sound absorption. The project objectives included assessing thermal conditions and establishing a basis for determining insulation thickness.

Magrini et al. (2022) investigated hollow walls, motivated by their regional/national dissemination as an intriguing low-complexity approach for energy requalification. The study emphasised the need of a well-planned approach based on a knowledge of the physical processes involved in heat and vapour transmission through building walls. Thermal characterisation was based on U-value, linear thermal transmittance (Ψ), and temperature factor (fRsi). The study looked at the influence of various materials and cavity thicknesses, offering insight into the benefits of filling insulation with or without external/internal plaster replacement. Information on the dispersion of cavity walls in terms of surface extension and cavity thickness was regarded critical for assessing the overall energy-saving potential of the building stock.

Abdullah and Faraj (2022) tested hollow walls with cavity thicknesses ranging from 1 cm through 6 cm and oriented southwesternly during the warmest months of June and July. The study revealed that installing a closed air cavity in walls efficiently decreases the mean temperature of the interior surface. Furthermore, it was discovered that a larger air gap resulted in lower interior temperatures, with 6 cm being the ideal thickness.

Kraynov and Medvedava (2021) concentrated on using waste materials from the oil and gas sectors, such as sulphur, ash, and slag waste, to create thermal insulating materials with excellent strength and performance attributes. The study sought to minimise thermal conductivity in wall blocks by filling the hollow wall with less-conductive materials or leaving it empty. The study showed two situations, one in which the cavities were filled with a less conductive material and the other in which closed air layers were formed in the cavities, both of which had an influence on the effective heat transfer rate.

Mammadova et al. (2021) discussed the widespread usage of opaque ventilated facades and the importance of studying their thermal efficiency. The work focuses on full-scale experimental investigation into the thermal properties of an air cavity in a naturally ventilated facade system with closed connections during strong wind conditions. The study discovered an empirical relationship between the speed of the wind and cavity air velocity by comparing thermal parameters calculated in accordance with building requirements to full-scale experiment findings. The findings highlighted the effect of the wind speed on cavity airflow and thermal resistance, thereby offering useful insights for calculated-experimental management of facade thermal properties and interdisciplinary energy audits of structures.

Murali and Sampathkumar (2020) conducted a comprehensive study that included site planning parameters that are building planning parameters, life saving aspects of escape routes, interior finishing materials, materials that are not flammable, building construction identification, and structural and non-structural components. The inquiry included a thorough examination of material composites, bindings, thermal insulating materials, and the integrity of the structure and created shape. Their research gave a full grasp of these factors, allowing for more effective construction planning and safety concerns.

Krause et al. (2020) focused on assessing thermal insulation from the inside, employing mineral insulation boards with a thickness of 0.06m made of light cellular concrete with a density of 115 kg/m3. The study involved the installation of boards on adhesive mortar, additionally fixed with PVC plastic mechanical connectors. Temperature measurements indicated significant differences before and after applying internal insulation, emphasizing its impact on indoor and outdoor temperatures.

Dung DO et al. (2020)explored various insulating materials used in construction, with a specific emphasis on Rockwool mineral wool. Their study examined the effect of insulation thickness changes, highlighting the advantages of Rockwool mineral wool, such as fireproofing, heat, and sound insulation. The research found that increasing insulation thickness led to a decrease in heat flux through walls, with a recommended thickness of 5 cm for optimal efficiency in reducing heat loss.

Nor Ali and Mohamad Nor(2019) delved into pressing concerns surrounding energy usage and carbon dioxide reduction in industrialized nations, particularly focusing on Malaysia. The study addressed the government's ambitious goal of reducing greenhouse gas emissions by 40% by 2020, emphasizing the role of decreasing energy usage in mitigating carbon dioxide emissions and combating global warming. The research underscored the challenges posed by rapid population growth, urbanization, and economic growth, contributing to a surge in energy consumption in Malaysia's residential and building sector.

In a previous study, Murali and Sampathkumar (2018) conducted a thorough examination of site planning parameters, building planning parameters, life safety elements, interior finishing materials, construction identification, structural and non-structural members, composite materials, bindings, thermal insulations, and stability of the structure and the built form. The study contributed valuable insights into the construction elements, providing a foundational understanding of the factors influencing the design, safety, and thermal performance of buildings.

Langmansa et al. (2017) discovered that more than 90% of contractors now use tape for connections between insulating panels. The study also identified the normal rest space beneath the insulating layer, which ranged from 1.5 to 3.5mm. Laboratory experiments assessed air resistance within these leakage channels, and the data were used to develop a heat and air circulation model. The study emphasised the role of craftsmanship in thermal performance, noting that tape joints had only a minimal effect for particular rest gap widths. It recommended that the rest space's borders be closed, especially around the top and bottom insulation panels, for best thermal efficiency.

An experimental investigation on cavity-type heat sinks for electronic devices was conducted by Sivapragasam et al. to ensure low operating temperatures for reliability. The study explored the effects of Phase Change Material (PCM) volume variation, pin fin configurations, and different cavity heat sinks on thermal performance. Results indicated that including PCM enhanced heat dissipation rates and lowered operating temperatures. The study highlighted the effectiveness of specific cavity heat sink configurations compared to pin fin setups, noting an enhancement in latent heat capacity with increased PCM volume.

Mingbinet al. (2017) explored the impact of moisture content on the thermal conductivity of spray polyurethane foam (SPF) and its effect on overall wall thermal properties. External thermal insulation methods were found to significantly improve wall insulation properties, with XPS outperforming EPS. Adjusting stud spacing and thickness were identified as strategies to enhance thermal resistance and insulation performance. The study established a consistent correlation between theoretical calculations and experimental values, offering a method to calculate effective thermal resistance without additional experiments.

Roque and Santos (2017) analyzed the effectiveness of thermal insulation in Light Steel Frame (LSF) construction, specifically evaluating the impact of insulation position in facade walls. The study considered three wall types, each representing a different LSF construction, with variations only in the type and position of thermal insulation. The results provided insights into the thermal performance of these walls, emphasizing the importance of insulation placement within the LSF constructive system.

Maseraa and Stahle (2016) focused on an innovative solution—an aerogel-based wallpaper designed for easy installation on the inner side of perimeter walls. The study detailed the development process, addressing challenges and testing the aerogel-impregnated textile layer's thermal performance and water vapor permeability. The proposed aerogel wallpaper emerged as a promising solution for inner thermal retrofitting, with an emphasis on adaptability, ease of installation, and positive environmental impact.

Kamble at al. (2015) explored different composite cavity walls ranging from 50mm to 200mm in air gap and composite walls filled with materials like Expanded Poly Styrene, wheat husk, and Expanded Poly Ethylene. Experimental testing revealed that composite cavity walls with 200mm Expanded Poly Styrene insulation exhibited the least U value (W/m^2K) compared to other materials, showcasing its superior thermal performance.

Walker (2015) conducted experiments to assess potential improvements in historic building heating operations for reduced energy consumption and environmental impact. The study evaluated seven internal composition choices for historic brick walls, including thermal paint, airgel, cork lime, hemp powder, calcium silicate board, wood fiber board, and PIR board. Results demonstrated significant reductions in surface U-values for most insulation materials, emphasizing the importance of rehabilitating existing buildings for reduced environmental impact.

Chen (2014) emphasized the evolving concrete technology to meet growing functional requirements in construction and industry. Focusing on specialized types like conductive, humidity-controlled, transparent, and acid-resistant concrete, the study delved into the details of heat-resistant concrete. The paper highlighted the necessity of developing new concrete types for specific industrial needs and addressed the lack of practical application data in the current market.

Piotrowski et al. (2014) addressed significant energy consumption in buildings and the challenges posed by heat losses. The study explored reflective insulation as an alternative to traditional materials, focusing on its potential to reduce energy demand and ensure human comfort. Large-scale experiments were introduced to complement small-scale laboratory measurements, emphasizing the linear relationship between thermal resistance and air gap width in reflective insulation.

Zhou et al. (2014) highlighted the importance of air conditioning in buildings and proposed sandwich concrete/gypsum wall panels to improve thermal insulation without compromising space or economy. Experimental and numerical simulations were conducted to evaluate the thermal performance of the proposed structure, showing that the sandwich wall paneling effectively reduced energy consumption of air conditioners. The study emphasized tailored solutions for sustainable green architecture in addressing global environmental challenges.

Bekkouche et al. (2013)focused on determining the optimum thickness in cavity walls under steady conditions, employing heat transfer calculations based on ISO 15099:2003 standards. The investigation included two forms of masonry units, emphasizing the advantages of high thermal emissivity. Additionally, the paper presented results from a study on the thermal insulation performance of air cavities bounded by thin reflective material layers (ε = 0.05). The findings highlighted that the most economical cavity configuration is influenced by both thermal emissivity and the choice of insulation material.

Ridouane and Bianchi (2011) conducted numerical simulations to assess the thermal performance of wall cavities, exploring temperature distribution, local heat flux along the wall, and thermal resistance for different temperature differences and average temperatures. The study focused on partially insulated wall cavities, revealing key findings such as the significant reduction in resistance with a small air gap and the variation in the thermal resistance of an uninsulated cavity with temperature. The parallel resistance approach was found to predict well the resistance of wall assemblies with partially filled cavities, with a maximum error of 3%.

Conclusion:

The study by S. M. A. Bekkouche, N. Benamran, T. Benouaz, M. K. Cherier, M. Hamdani, and M.R. Yaiche (2013) provides valuable insights into optimizing the thickness of cavity walls for steady-state conditions, with heat transfer calculations based on ISO 15099:2003 standards. The investigation includes two forms of masonry units to determine the advantages of high thermal emissivity. Additionally, the study explores the thermal insulation performance of air cavities with a thin reflective material layer.

The main focus of this research is to determine the optimum thickness of cavity walls under steady conditions, considering various factors such as heat transfer, thermal emissivity, and the type of insulation material. The study utilizes ISO 15099:2003 standards for calculating heat transfer, providing a standardized and comprehensive approach to evaluating thermal performance.

One notable aspect of the study is the examination of two forms of masonry units, aiming to understand the impact of high thermal emissivity on the overall efficiency of cavity walls. Thermal emissivity plays a crucial role in heat transfer, and the study seeks to determine how different forms of masonry units can influence the thermal performance of cavity walls.

Furthermore, the research delves into the thermal insulation performance of air cavities with a thin reflective material layer (ε = 0.05). Reflective materials can significantly affect heat transfer, and the study aims to identify the most economical cavity configuration based on thermal emissivity and the choice of insulation material.

The results of the study provide valuable insights into optimizing cavity wall thickness for enhanced thermal performance. By considering factors like thermal emissivity and insulation material, the research contributes to the development of more efficient and cost-effective thermal insulation solutions for buildings. The emphasis on economic cavity configurations adds practical value, offering guidance for construction practices that balance performance and cost-effectiveness.

In conclusion, the study by Bekkouche et al. contributes to the field of thermal insulation by providing a systematic analysis of cavity wall optimization. The standardized approach, consideration of different masonry units, and exploration of reflective materials enhance our understanding of factors influencing thermal performance. This research is instrumental in guiding the development of energy-efficient building practices, aligning with the broader goal of sustainable and cost-effective construction.

Scope of Further Research:

Future research endeavors should focus on addressing the practical challenges associated with the adoption of novel materials and techniques. Long-term studies assessing the durability, environmental impact, and cost-effectiveness of these innovations are essential. Additionally, investigations into the integration of smart technologies for dynamic thermal management in building envelopes could further enhance energy efficiency. Collaborative efforts between researchers, policymakers, and industry stakeholders are crucial for translating research findings into sustainable and scalable solutions for the construction sector. Additionally, here are some potential areas for future investigation:

1. **Advanced Insulation Materials:** Explore the use of emerging insulation materials with a focus on their thermal properties, durability, and environmental impact. Investigate materials that may offer improved performance compared to traditional options.

2. Dynamic Thermal Performance: Extend the research to dynamic conditions, considering the impact of changing external temperatures and seasonal variations on the thermal performance of cavity walls. This would provide a more comprehensive understanding of real-world scenarios.

3. Integration of Smart Technologies: Investigate the integration of smart technologies, such as sensors and adaptive insulation systems, to optimize thermal performance based on real-time environmental conditions. This could contribute to energy-efficient and responsive building designs.

4. Life Cycle Analysis: Conduct a life cycle analysis of different cavity wall configurations, considering not only their immediate thermal performance but also their long-term sustainability, maintenance requirements, and overall life cycle environmental impact.

5. Cost-Benefit Analysis: Explore the economic aspects of various cavity wall configurations. Consider the initial costs, maintenance expenses, and long-term energy savings to provide a comprehensive cost-benefit analysis for different insulation strategies.

6. Human Comfort and Health: Investigate the impact of cavity wall insulation on indoor air quality, humidity levels, and overall occupant comfort. Consider how different insulation materials may influence the indoor environment.
7. Integration with Renewable Energy: Explore how cavity wall insulation can be integrated with renewable energy systems to create more sustainable and energy-independent building designs. Consider the synergies between insulation and renewable technologies.

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