HEAT TRANSFER AS A DETERMINING FACTOR IN THE THERMAL PERFORMANCE OF SEMARANG CATHEDRAL

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Abstract: Semarang Cathedral is a historic building that increasingly faces challenges in maintaining thermal efficiency amid climate change and rapid urbanization. This study aims to examine the role of heat transfer as a key factor in shaping the thermal performance of buildings using a quantitative approach. Both experimental and numerical methods were employed, involving direct measurements of the surface temperature, relative humidity, and solar radiation intensity across three primary spatial zones: the nave, transept, and altar. Field data were recorded over a 30-day monitoring period using a MAX6675 K-type thermocouple temperature sensor and an LR8432 heat flow logger, with measurements taken at 10-minute intervals. The heat transfer mechanisms, namely conduction, convection, and radiation, were evaluated using Fourier's law and Nusselt number correlations to estimate the overall heat transfer coefficient. The analysis shows that the plastered brick walls exhibit an average thermal conductivity of 0.65 W/m·K and contribute to a reduction in indoor air temperature of approximately 18.3% relative to outdoor conditions. These results indicate that wall material characteristics and thickness play a decisive role in maintaining the thermal stability within a building. The findings of this study provide a quantitative basis for formulating energy conservation strategies for historic buildings in tropical climates.

Keywords: Heat transfer; thermal performance; historic buildings; Semarang Cathedral; energy efficiency

1. Introduction

Historic buildings play a crucial role in preserving cultural identity and architectural continuity, while often remaining in active use as functional spaces. Beyond their historical and symbolic value, such buildings must respond to contemporary environmental demands, particularly in terms of indoor thermal comfort and energy performance. In recent years, growing attention has been directed toward understanding how historic structures behave thermally, especially given their distinctive material properties and construction techniques, which differ significantly from those of modern buildings [6], [7].

One of the defining characteristics of historic buildings is their high thermal inertia, typically resulting from thick masonry walls and massive construction systems. Previous research has shown that thermal inertia plays a critical role in stabilizing indoor temperatures and moderating heat fluctuations, particularly when combined with passive design strategies [1]. Dynamic analyses of historic and monumental buildings further indicate that thermal mass can significantly influence heat storage and delayed heat release, affecting both thermal comfort and energy performance [3].

Thermal performance assessment becomes even more complex in hot and humid climates, where buildings are exposed to high solar radiation, elevated ambient temperatures, and continuous cooling demands. Studies conducted on historic buildings in Mexico demonstrate that traditional passive systems can still perform effectively under future climate change scenarios, reducing heat gains and supporting indoor thermal comfort without mechanical intervention [2]. These findings highlight the importance of climate-responsive analysis when evaluating historic architecture in non-temperate regions.

At the building-envelope scale, several studies emphasize the importance of understanding heat transfer processes occurring at walls, roofs, and especially window–wall interfaces. Recent investigations show that heat exchange at these interfaces can significantly affect overall thermal behavior and must be carefully addressed in renovation and conservation efforts [4]. Similarly, computational fluid dynamics (CFD) studies reveal that airflow patterns, convective heat transfer, and air infiltration contribute to spatial temperature variations within historic interiors, underscoring the complex interaction between envelope performance and indoor thermal conditions [5].

Despite increasing international research on thermal comfort and energy efficiency in historic buildings, much of the existing literature focuses on temperate or cold climates and retrofit-oriented strategies [6]. Tropical historic buildings remain underrepresented, even though they face distinct challenges related to intense solar exposure and rapid heat transfer. Innovative conservation approaches increasingly stress the need for quantitative, non-invasive methods that enhance thermal comfort while preserving architectural authenticity [7], [8].

In response to this research gap, the present study focuses on a quantitative analysis of heat transfer as a determinant of thermal performance in a tropical historic building. By examining conduction, convection, and radiation processes within the building envelope, this research seeks to clarify how traditional materials and architectural configurations influence indoor thermal conditions. The study aims to contribute empirical evidence and analytical insight that support sustainable conservation strategies and reinforce the relevance of passive thermal principles in the long-term use of historic buildings in hot and humid climates.

2. Research Methods

This study adopted a quantitative approach that combined on-site measurements with numerical analysis to examine heat transfer behavior in the Semarang Cathedral under real climatic conditions. The research began with a field survey to document the building's architectural configuration and material characteristics, including wall thickness, construction materials, and façade orientation, as these factors directly influence solar exposure and thermal response.

Field measurements were carried out continuously for thirty days during the dry season to minimize the effects of short-term weather variations. The monitoring period focused on relatively stable climatic conditions, allowing the dominant heat transfer processes within the building envelope to be observed more clearly. Temperature data were collected using MAX6675 K-type thermocouple sensors installed on interior and exterior wall surfaces, roof elements, and in key interior spaces such as the nave and altar. To capture temporal variations, indoor temperature and relative humidity were recorded at ten-minute intervals using an LR8432 heat flow logger. (see figure 1)

Figure 1. MAX6675 K-type thermocouple sensors and LR8432 heat flow logger

Solar radiation intensity was measured with a portable pyranometer placed in the front courtyard, where exposure to sunlight was unobstructed. This data was used to relate daily solar radiation levels to surface temperature changes on the building envelope. All measurement data were processed statistically and integrated into a numerical model based on Fourier's heat conduction equation to calculate heat transfer through building components. Convective and radiative heat transfer were evaluated using established theoretical correlations, adjusted to reflect natural airflow conditions and material emissivity values specific to the cathedral. Model accuracy was verified by comparing simulated results with measured data, with iterative adjustments applied until the relative error was below five percent. The validated model was then used to assess the contribution of conduction, convection, and radiation to indoor thermal stability, providing a clear basis for evaluating the building's passive thermal performance.

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3. Discussion

The thermal performance of Semarang Cathedral reflects a complex interaction between heat conduction, convection, and radiation, which collectively shape the indoor thermal environment of this historic building. As a structure characterized by thick plastered brick walls and high thermal mass, the cathedral represents a typical example of tropical historic architecture where passive thermal behavior dominates indoor conditions. This discussion focuses on the distribution of heat transfer across building elements, the influence of tropical climatic conditions, and the dominant parameters governing thermal performance.

Field measurements collected over a 30-day monitoring period reveal a pronounced difference between exterior and interior wall surface temperatures (Figure 2). Exterior wall surfaces reached daytime peak temperatures of approximately 42–45 °C, while interior surfaces remained significantly lower, ranging between 30 and 33 °C. This thermal gradient highlights the role of thermal inertia in delaying heat transmission through thick masonry walls, a phenomenon consistently reported in studies of historic buildings with massive envelopes [9], [10], [11]. The walls function as thermal buffers, absorbing heat during peak solar radiation and releasing it gradually during the late afternoon and evening.

The asymmetric temperature distribution indicates that heat conduction through the wall fabric is the dominant heat transfer mechanism. According to Fourier's law, the moderate thermal conductivity of plastered brick walls limits the rate of heat flow toward the interior, resulting in damped indoor temperature fluctuations. This behavior aligns with previous findings on traditional construction materials in historic buildings, which demonstrate stable but effective thermal resistance under hot climatic conditions [17], [18]. Similar results have been reported in measurement-based and simulation studies emphasizing the importance of thermal mass in tropical historic buildings [10], [16].

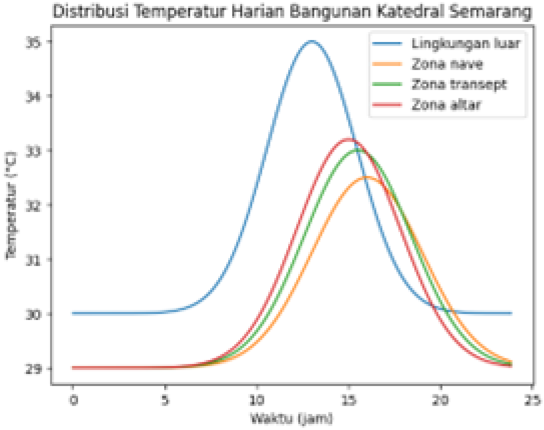

Figure 2. Comparison of exterior and interior wall surface temperature distributions across the nave, transept, and altar (figure space reserved).

The daily temperature profiles further confirm the buffering effect of thermal mass. Outdoor air temperatures reached their maximum values around midday, coinciding with peak solar radiation, whereas indoor temperatures showed a time lag of approximately 2–3 hours before reaching their peak. This delayed response demonstrates the capacity of massive walls to slow heat penetration, a characteristic widely observed in historic buildings located in warm climates [20], [21].

Spatial analysis shows that the altar zone experienced the highest peak temperatures, indicating a stronger influence of façade orientation and direct solar exposure. In contrast, the nave exhibited the most stable thermal profile, likely due to its larger volume, more uniform mass distribution, and fewer direct openings. These findings are consistent with CFD-based and hygrothermal studies of historic religious buildings, which emphasize the role of orientation, geometry, and envelope thickness in achieving indoor thermal stability [12], [13].

Table 1. Average, Maximum, and Minimum Temperature Distribution

Zone	**Average Temperature (°C)**	**Maximum Temperature (°C)**	**Minimum Temperature (°C)**
Outdoor environment	32.80	42.0	30.0
Nave	29.56	33.0	28.0
Transept	29.77	34.0	28.0
Altar	29.86	34.5	28.0

As shown in Table 1, average indoor temperatures across all interior zones ranged between 29.5 and 29.9 °C, remaining noticeably lower and more stable than the outdoor average temperature. This temperature reduction of approximately 3 °C confirms the effectiveness of the plastered brick walls as passive thermal filters, operating without mechanical cooling. The relatively uniform minimum temperatures across zones indicate gradual nocturnal heat release from the building mass, contributing to nighttime thermal stability, as reported in similar studies on historic buildings with high thermal inertia [11], [19].

To further illustrate the heat transfer mechanisms within the interior space, a schematic representation is presented in Figure 3.

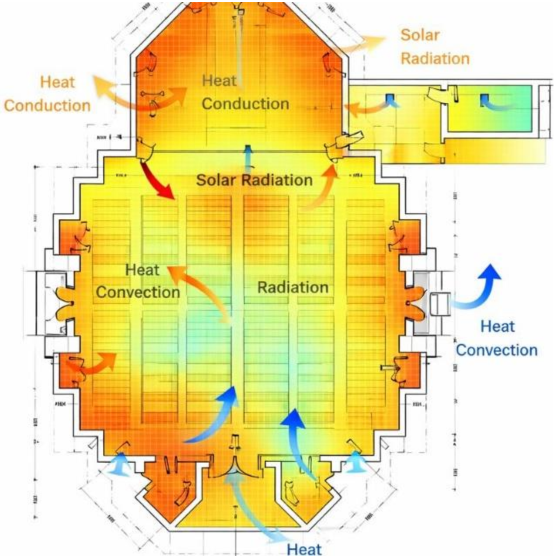

Figure 3. Schematic representation of heat transfer mechanisms and indoor air temperature distribution (figure space reserved).

Figure 3 conceptually illustrates how heat enters the building primarily through solar radiation and conduction across the envelope, then redistributes through buoyancy-driven natural convection. Heat accumulation tends to occur in upper zones due to the large internal volume and high ceiling geometry, a behavior commonly observed in historic church buildings [12], [23].

A comparison between outdoor and indoor air temperatures is presented in Figure 4.

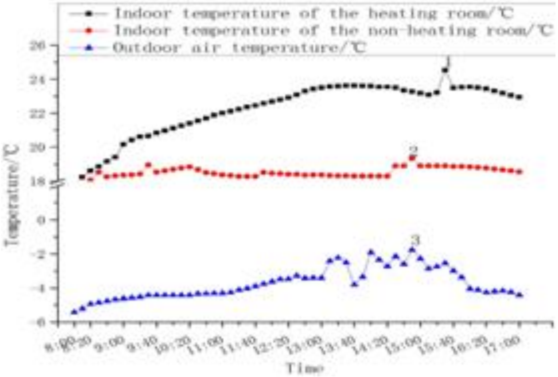

Figure 4. Comparison between outdoor and indoor air temperatures over time (figure space reserved).

Figure 4 shows that indoor temperature fluctuations are significantly damped compared to outdoor conditions, indicating a strong thermal buffering effect of the building envelope. However, sustained solar radiation and high ambient temperatures prevent indoor temperatures from reaching lower comfort thresholds, a challenge frequently reported in tropical historic buildings [20], [21].

In addition to conduction, convection plays a significant role in heat transfer, particularly at exterior surfaces exposed to ambient airflow. Estimated convective heat transfer coefficients derived from Nusselt and Reynolds number analysis are consistent with values reported in CFD-based investigations, confirming the influence of natural convection on surface heat exchange [9], [12]. Solar radiation effects were especially pronounced on façades with direct exposure, reinforcing previous findings that façade orientation strongly affects thermal performance in historic buildings [20].

The validated numerical model, integrating sensor-based data with Fourier-based heat transfer equations, showed good agreement with field measurements, with relative errors below ±5%. This confirms the reliability of combining empirical monitoring and numerical modeling, as recommended in recent methodological studies on historic buildings [9], [16], [25]. The results clearly identify conduction through the wall mass as the dominant mechanism, followed by convection and radiation at exterior surfaces.

Overall, the findings indicate that the thermal performance of Semarang Cathedral results from the combined effects of material properties, solar exposure, natural airflow, and spatial configuration, rather than a single isolated factor. This integrated behavior aligns with existing literature emphasizing that tropical historic buildings require quantitative, measurement-based approaches to fully capture their complex thermal dynamics [10], [11], [19]. The results support passive conservation strategies that enhance thermal inertia while respecting architectural heritage, providing a robust foundation for sustainable thermal management in tropical historic buildings.

4. Conclusion

This study demonstrates that the thermal performance of the Semarang Cathedral is strongly shaped by the combined influence of architectural form, material characteristics, and passive ventilation strategies. Based on thirty days of continuous monitoring using the LR8432 Heat Flow Logger, indoor air temperatures were recorded within a relatively stable range of 29.8 °C to 32 °C, with an average of 30.9 °C. These results indicate that the building is capable of moderating outdoor thermal fluctuations, supporting the assumption that well-considered architectural design can sustain indoor comfort without dependence on mechanical cooling.

The analysis further shows that the cathedral's elongated east–west orientation, together with cross-ventilation facilitated by the transept and clerestory openings, plays a significant role in maintaining airflow throughout the interior space. This ventilation pattern helps reduce heat accumulation and supports thermal equilibrium. In addition, the thick solid brick walls function as a thermal buffer, absorbing heat during peak daytime conditions and releasing it gradually in the later hours. This process limits sudden temperature increases and reflects the effectiveness of traditional passive design approaches.

Taken together, the findings suggest that the thermal efficiency of the Semarang Cathedral is not the result of a single design element, but rather an integrated system in which building form, material mass, ventilation, and local microclimate interact harmoniously. The building illustrates how passive architectural principles, developed long before modern energy systems, remain highly relevant in contemporary discussions on sustainability. As such, colonial-era architecture offers important insights for the development of climate-responsive and energy-efficient buildings in hot and humid regions like Indonesia, while also supporting the preservation of historical and cultural value.

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