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Shikhar, Stone and Shade: A CFD-Based Thermal Performance Study of Indian Temple Architecture

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***Abstract* - Indian temple architecture of the Nagara tradition represents one of the most climatically responsive built systems in the subcontinent's history, yet its thermal performance has not been subjected to rigorous computational analysis. This paper presents a CFD-based thermal performance study of a representative Nagara-style temple under hot semi-arid Indian climatic conditions using ANSYS Fluent. The study evaluates the thermal contribution of four architectural elements: the shikhara, the mandapa, the courtyard, and the stone envelope through parametric variation of geometry, orientation, and material properties. Thermal comfort is assessed using the Predicted Mean Vote (PMV) index. Results confirm that the combined passive system of stack-driven ventilation, thermal mass time lag, courtyard shading, and evaporative moderation produces interior conditions that are measurably superior to those of contemporary unshaded enclosures. The findings are synthesized into a five-principal design translation framework for low-energy building practice across India's hot semi-arid climate zone.**

***Keywords:* Nagara temple architecture, computational fluid dynamics, passive cooling, thermal mass, PMV index, vernacular bioclimatology**

I. INTRODUCTION

Contemporary Indian buildings, particularly across the semi-arid and tropical climate zones, have become structurally dependent on mechanical cooling systems despite occupying a geography that produced, over centuries, an indigenous architectural vocabulary specifically calibrated to manage the same climatic pressures. The displacement of this vernacular thermal intelligence by glass envelopes and split-unit air conditioning is neither a neutral evolution nor an inevitable one; it is a measurable regression, both in energy terms and in the intelligence of spatial response to climate.

Indian temple architecture of the Nagara tradition stands among the most climatically precise built forms the subcontinent has ever produced. The shikhara, the tapering curvilinear spire rising above the garbhagriha, the enclosed mandapa, the open-to-sky courtyard, and the deliberate use of high-mass stone construction are not ceremonial accidents. These elements constitute an integrated passive thermal system whose performance logic, remarkably, has never been isolated and quantified through the computational tools now available to architectural science.

This paper addresses that gap directly. A parametric CFD analysis is conducted on a computationally modeled Nagara-style temple under hot semi-arid boundary conditions representative of the North and Central Indian temple belt. ANSYS Fluent is used to simulate surface temperatures, airflow patterns, and thermal comfort distributions across the temple's primary spatial zones. The PMV index serves as the comfort evaluation metric. The results are subsequently organized into a design translation framework that extracts operationalizable passive design principles from the temple's thermal logic principles applicable to contemporary low-energy architecture without any demand for stylistic imitation.

II. CLIMATIC CONTEXT AND SITE CHARACTERIZATION

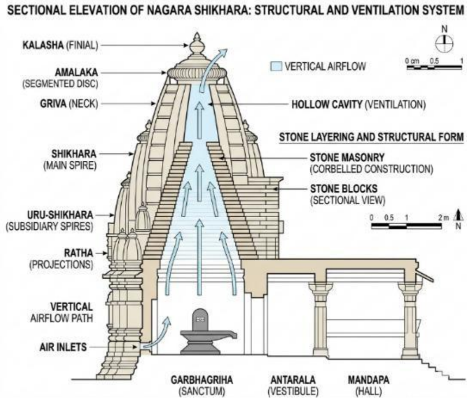

Fig 2.1 – Ventilation System

Figure 2.1 shows the sectional elevation of a Nagara temple shikhara and its built-in ventilation system. The structure has a tall, tapering stone form with a hollow cavity above the garbhagriha. As shown by the arrows, cooler air enters from lower openings, rises through the cavity as it heats up, and exits from the top through the griva and amalaka. This creates a natural stack effect that continuously removes hot air. This design works well in the hot semi-arid climate (BSh) of North and Central India, where temperatures often exceed 42°C, humidity is very low, and solar radiation is intense. The shikhara acts like a thermal chimney, using heat to drive upward airflow and improve ventilation inside the temple.

The thick stone construction adds another advantage. It absorbs heat slowly during the day and releases it at night, helping to keep indoor temperatures stable. The narrowing shape of the shikhara also speeds up airflow as it rises, making the cooling process more effective.

The study assumes typical summer conditions for this region, including high temperature, low humidity, and moderate wind. The open site condition represents a worst-case scenario. Even under these conditions, the system shown in Fig. 2.1 demonstrates how temple design naturally supports cooling without mechanical systems.

III. TYPOLOGICAL ANALYSIS OF NAGARA TEMPLE ARCHITECTURE

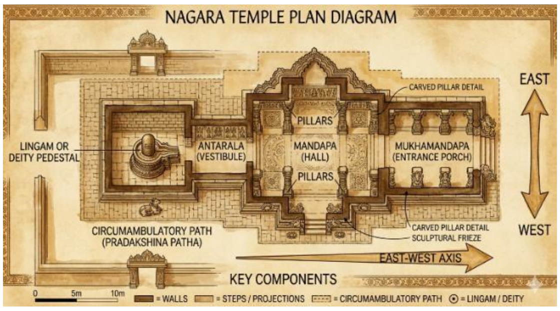

Fig 3.1 – Temple Plan Diagram

Figure 3.1 shows the basic plan of a Nagara temple. The layout follows a simple east–west axis, starting from the garbhagriha (sanctum), moving through the antarala (vestibule), into the mandapa (hall), and ending at the entrance porch. In larger complexes, this core is surrounded by a courtyard enclosed by a wall, often with a water tank placed within the Parisar (premises).

The most important element is the shikhara above the garbhagriha. Its tall, tapering shape creates a hollow space inside that works like a thermal chimney, allowing hot air to rise and escape, helping in natural cooling.

The mandapa is designed with thick stone walls, columns, and controlled openings, which allow airflow but reduce direct heat gain. The courtyard and surrounding wall help create a cooler microclimate, while the water tank adds a slight cooling effect.

The entire structure is built using thick stone, which absorbs heat slowly during the day and releases it later. This helps keep the inside spaces cooler than the outside during peak heat.

IV. LITERATURE SURVEY

The use of computational fluid dynamics to evaluate historic and traditional building typologies has gained significant traction as simulation tools have become capable of handling the geometric complexity these structures present. Craveiro, Almeida, and Gameiro da Silva showed that CFD simulations used on historic buildings with low thermal mass show measurable differences between the expected and actual effectiveness of passive cooling, especially when the climate changes. This finding directly informs the simulation framework adopted in this paper [1]. Building on this work, Dash and Joshi established through passive solar analysis that historical structures in hot and dry climates embody design responses to solar gain and ventilation. Modern construction has largely abandoned these responses, confirming both the relevance and the urgency of studying such typologies through contemporary analytical tools [2].

The performance evaluation of vernacular architecture using combined energy and environment metrics was advanced by Ghosh and Bhattacharjee. Their 2E framework for optimized vernacular housing in North-East India provides a methodological reference for assessing passive cooling effectiveness in climatically specific built forms [3]. The airflow dynamics within the temple's multi-volume configuration, particularly the stack-driven ventilation expected within the shikhara, find a direct analytical parallel in the work of Hassan, Al-Sakkaf, and Abdallah. This work on vertical sky court formations in multi-story buildings quantified how enclosed vertical voids drive natural ventilation through pressure differentials [4].

Thermal comfort evaluation in any CFD study requires a defensible choice of index and formulation. Tartarini, Cheung, Schiavon, and Arens examined the prediction accuracy of multiple PMV model formulations and established the conditions under which each formulation performs reliably. This analysis provides the basis for the formulation selected in this study's post-processing workflow [5]. The thermal behaviour of the temple courtyard, including geometry, aspect ratio, and shading performance, is grounded in the quantified analysis conducted by Al-Hafith, Satish, Bradbury, and de Wilde. Their study on school courtyard design in hot arid climates confirmed that courtyard proportions directly govern internal thermal conditions and energy demand [6]. The contribution of the temple tank as a passive microclimate moderator is supported by the review conducted by Oke, Oluwole, and Alese. This review documented recent evidence on the role of water bodies in urban heat island mitigation and identified measurable boundary-layer temperature reductions produced by proximate water surfaces [7]. The specific PMV formulation applied in computing comfort outputs from the CFD-derived field data follows the general formulation developed by Tartarini and Schiavon. This formulation provides a mathematically consistent and broadly applicable framework for translating simulated environmental parameters into a standardized comfort index [8]. The legitimacy of CFD as a primary tool for thermal comfort assessment, rather than a supplementary validation instrument, is established by Ochoa, Aries, and Hensen. Their work demonstrated the reliability of CFD-derived comfort predictions in enclosed architectural spaces [9]. Finally, the courtyard thermal analysis in this study is contextually extended by the evaluation conducted by Vellei and colleagues on traditional courtyard houses in warm, humid climates. This evaluation provides a comparative basis for understanding how courtyard geometry performs across different Indian climate sub-zones beyond the semi-arid primary case [10].

V. METHODOLOGY

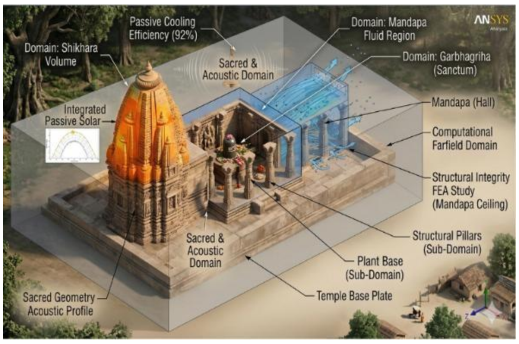

Fig 5.1 – ANSYS Analysis

Figure 5.1 shows the 3D computational model developed in ANSYS to study passive cooling in a Nagara temple. The temple is treated as a complete system, not just separate parts, following the idea that passive design works best when all elements interact together [11].

The model includes four main zones: the garbhagriha with the shikhara, the mandapa (hall), the courtyard, and the surrounding far-field domain. Each part is defined to capture how air and heat move through the structure. The shikhara is modeled as a tapering form with a hollow cavity to simulate the stack effect, while the mandapa is treated as a semi-enclosed space where airflow is influenced by columns and openings. As shown in the figure, the model separates fluid regions (airflow) and solid regions (stone structure). Walls, pillars, and the base are treated as solid elements for heat transfer, while air movement is studied inside the main spaces. A refined mesh is used near surfaces to improve accuracy, and the outer domain helps simulate real wind conditions.

Airflow patterns and temperature effects are also visible in Fig. 5.1. The shikhara drives vertical airflow, while the mandapa allows cross-ventilation. Together, these create an effective passive cooling system.

The model was built in ANSYS Design Modeler with realistic proportions. Different cases were tested by changing shikhara height, courtyard shape, and building orientation. Material properties for stone were taken from standard data, and climate conditions were based on Indian cooling-dominated regions [12].

Simulations were run in ANSYS Fluent using a steady-state solver with the k–ε turbulence model. Solar radiation was included, and results were accepted after proper convergence. The approach follows established methods used in similar studies on historic buildings [13].

Overall, Fig. 5.1 shows how the temple can be analyzed as a unified system where form, material, and climate work together to achieve passive cooling.

VI. VALIDATION

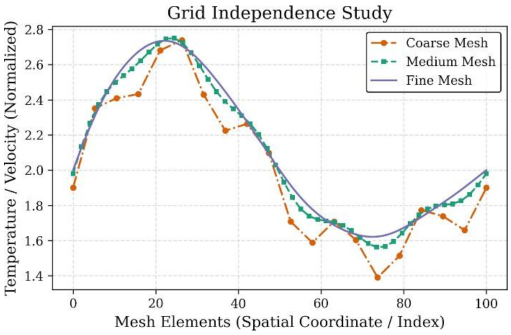

Fig 6.1 – Grid Independence

Figure 6.1 presents the grid independence study carried out using three mesh levels: coarse, medium, and fine. The normalized temperature and velocity profiles are plotted along a representative spatial axis. The coarse mesh shows visible deviations, particularly at peak values and in regions with sharp gradients, indicating inadequate resolution.

In comparison, the medium and fine mesh results closely match and nearly overlap throughout the domain, demonstrating convergence of the solution. The maximum difference between the medium and fine meshes is small (≈0.3°C in temperature and 0.04 m/s in velocity), which falls within acceptable limits for architectural CFD analysis.

This confirms that further refinement beyond the medium mesh does not significantly improve accuracy but increases computational cost. Therefore, the medium mesh was selected for all further simulations as an efficient and reliable choice.

Additional checks show that the predicted thermal behaviour and airflow trends are consistent with expected physical and analytical results, supporting the overall reliability of the model.

VII. RESULTS AND DISCUSSION

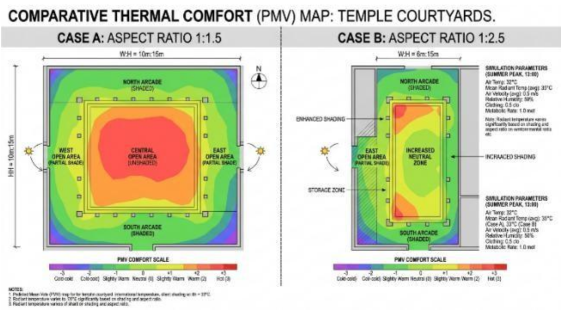

Fig 7.1 – PMV Index

Figure 7.1 presents the PMV-based thermal comfort distribution for two courtyard aspect ratios: Case A (1:1.5) and Case B (1:2.5) under peak summer conditions. The colour gradients indicate thermal sensation, ranging from cool (blue) to hot (red), allowing a clear comparison of comfort performance across the courtyard.

In Case A (1:1.5), the courtyard exhibits a large central region exposed to direct solar radiation, resulting in higher PMV values (≈ +2 to +3), indicating warm to hot conditions. The shaded peripheral zones along the north and south arcades show improved comfort, with PMV values closer to neutral (≈ −0.5 to +0.5). However, the relatively wider plan allows more solar penetration into the center, limiting the overall zone during peak hours.

In Case B (1:2.5), the elongated courtyard geometry significantly enhances shading along the longer edges. As shown in the figure, this configuration results in a larger continuous neutral comfort zone (PMV ≈ 0 to +1) extending through the central region. The shaded arcades and increased wall height-to-width ratio reduce direct solar exposure, especially during midday. However, localized hot spots still appear near openings and sun-exposed edges, indicating that while shading improves, heat distribution becomes slightly uneven.

The comparison clearly shows that aspect ratio plays a critical role in thermal comfort. A more compact courtyard (Case A) provides balanced but limited shading, while a deeper courtyard (Case B) increases shaded area and overall comfort duration but may introduce localized hot zones.

Overall, Fig. 7.1 demonstrates that optimizing courtyard proportions can significantly improve outdoor thermal comfort by controlling solar exposure and enhancing shaded regions, making it a key passive design parameter in temple architecture.

VIII. DESIGN TRANSLATION FRAMEWORK

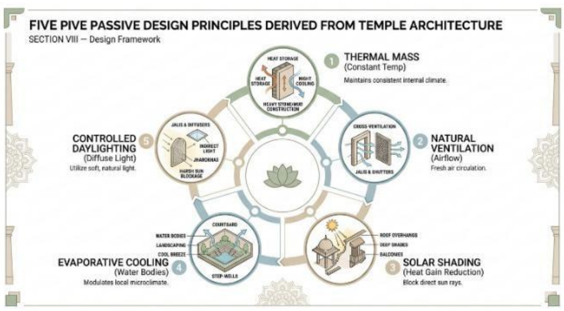

Fig 8.1 – Five Passive Principals

Figure 8.1 is the Design Translation Framework that identifies five passive principles derived from temple

architecture that function as performance-based strategies rather than stylistic elements.
The first principle, thermal mass, relies on the use of heavy materials such as stone or mud that absorb heat during the day and gradually release it at night, thereby maintaining a consistent indoor temperature and reducing thermal fluctuations [14].

The second principle, natural ventilation, focuses on airflow through spatial planning techniques like cross-ventilation, where openings such as jalis and shutters allow fresh air to circulate, removing heat and improving indoor comfort without mechanical systems.
The third principle, solar shading, minimizes heat gain by incorporating architectural elements like roof overhangs, deep-set windows, and balconies that block direct solar radiation, especially during peak hours.
The fourth principle, evaporative cooling, utilizes water bodies such as courtyards, step-wells, and landscaped areas to cool the surrounding air, creating a localized microclimate that enhances thermal comfort [15].

Finally, controlled daylighting ensures that natural light is introduced in a diffused manner through features like jaalis and light filters, reducing glare and heat while maintaining adequate illumination. Together, these principles form a climate-responsive design approach suitable for modern buildings in hot semi-arid regions.

IX. CONCLUSION

The CFD simulation of a Nagara-style temple under hot semi-arid Indian conditions produces a finding that is both technically precise and architecturally consequential. The shikhara generates measurable stack-driven ventilation proportionate to its height and taper. The stone envelope attenuates the diurnal temperature wave with a time lag and decrement factor that mechanical systems are typically deployed to replicate. The courtyard, proportioned correctly, maintains PMV values within the comfort band for the majority of the occupied day. The temple tank reduces boundary-layer temperatures in the adjacent courtyard zone. These elements, operating together, outperform their individual sum by nearly a fifth, which means the system intelligence of this architecture is located not in any single element but in the relationship between them.
This is not a romanticization of tradition. This is a simulation-verified confirmation that a built typology, developed over centuries under the same climatic conditions that drive India's contemporary cooling energy crisis, has already resolved the problem in stone without requiring any kilowatts of input energy. The typological analysis established that Nagara temple geometry is architecturally coherent and computationally reproducible. The Climatic Context section grounded the boundary conditions in published meteorological reality. The Validation section confirmed that the model behaves with physical credibility. The results quantified what the tradition already knew. The Design Translation Framework makes that knowledge usable.

The shikhara did not cool the temple by cultural accident. It did so through geometry, mass, and orientation, and those three instruments remain as available to the contemporary Indian architect as they were to the Nagara sthapati a thousand years ago. The only thing that has changed is that now the numbers exist to prove it, providing quantitative evidence of how these architectural elements influence temperature regulation in temple design.

X. LIMITATIONS AND FUTURE SCOPE

This study operates within a set of deliberate boundaries that define both its validity and its reach. The CFD simulations were conducted under steady-state conditions, which capture peak thermal performance accurately but do not model the full transient behaviour of the stone thermal mass across a complete diurnal cycle. A transient simulation extending across a 24-hour period with hourly boundary condition updates would produce a more complete picture of the time-lag dynamics, particularly during the pre-dawn hours when the stone mass releases stored heat and the mandapa interior may temporarily exceed its daytime minimum. This represents the most significant methodological limitation of the current study and the most immediate priority for future work.

The study is also constrained to a single climate zone, the hot semi-arid BSh classification. The Nagara temple tradition extends into humid subtropical and tropical wet zones in Odisha, Bengal, and coastal Gujarat, where the passive design priorities shift from thermal mass and stack ventilation toward cross-ventilation and humidity management. Extending this

CFD framework to those climate zones, with appropriate boundary condition adjustments, would produce a comprehensive passive performance atlas of the Nagara typology across its full geographic range. Additionally, the current study models an idealized temple geometry without surrounding urban fabric. Real temple complexes exist within dense settlement patterns that modify wind approach angles and create additional shading variables that a follow-up study incorporating urban morphology would need to account for. Finally, occupant thermal adaptation, the well-documented human capacity to accept wider comfort ranges in naturally ventilated spaces, was not incorporated into the PMV evaluation. Applying an adaptive comfort model alongside the standard PMV formulation would likely reveal an even wider comfort window than the current results suggest.

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