Passive Thermodynamics In Traditional Indian Residential Architecture

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Abstract

Traditional architects in India created a sophisticated system of passive cooling and heating that was developed empirically over hundreds of years before the discovery of mechanical cooling. Without the use of any energy source, traditional building methods throughout the five climatic regions of India produced indoor air temperatures at least 5 to 18 degrees Celsius cooler than outdoor air temperatures by incorporating the following four thermodynamic processes: (i) thermal mass and time delay from the use of thick earthen and stone masonry walls; (ii) buoyancy-driven (stack effect) ventilation through deep courtyards; (iii) evaporative cooling from water bodies and vetiver screens; and (iv) ideal solar insulation from overhanging chajjas (awnings) and through perforated jaali (lattice) screens. This literature interprets each of these strategies using the First and Second Laws of Thermodynamics and Fourier, Newton and Stefan-Boltzmann heat transfer principles, along with quantitative field data gathered from measurements taken in various locations.

Keywords: Passive cooling, traditional Indian architecture, thermal mass, stack effect ventilation, evaporative cooling, bioclimatic design, heat transfer, solar insulation

I. INTRODUCTION

According to IPCC AR5 estimates, the built environment accounts for approximately 40% of global final energy consumption, which is about 40% of all global energy use, and space cooling in hot-weather regions is among the fastest-growing components. India alone is expected to see an 8–10× increase in demand for energy to cool buildings by 2050 due to urbanization, rising incomes, and increased heat stress. However, for thousands of years before mechanical refrigeration existed, builders in India had been creating thermally comfortable interiors with no energy input (i.e. passive cooling), using only the science of material properties and geometry, as well as building forms that respond to the climate.

To understand how traditional Indian buildings provided passive cooling, thermodynamic principles must first be applied. The First Law of Thermodynamics states that the rate of heat transferred through a building envelope is equal to the sum of all heat gained and lost by the building. The Second Law of Thermodynamics states that heat will always move from an area of high to low temperature without any assistance, therefore builders in India used various passive venting methods to promote buoyancy, ground cooling, thermal radiation to the sky; in addition to forced (by wind or draft) methods: conduction (based on Fourier's Law), convection (based on Newton's Law of Cooling), and radiation (based on Stefan's Law).

The evaluation analysed houses from five types of residential housing typologies: 1) thick sandstone walls - haveli in Rajasthan; 2) deep-courtyard house - pol house in Ahmedabad; 3) multi-storied house - nalukettu in Kerala; 4) earthen kucchaghari house - Gangetic plain and 5) stone-and-timber house - kath-kuni of the foothills of the Himalayas. Each typology represents a unique engineering solution to the climate in which it was built; however, all typologies can be compared within a common set of thermodynamic terms: heat storage, heat flow, phase change, and radiation transfer.

II. LITERATURE REVIEW

During the energy crisis of the 1970s, systematic studies of the thermal behaviour of traditional Indian buildings became established with a renewed emphasis on passive design principles. Koenigsberger et al. [3] presented the key passive design principles applicable to tropical climates, identifying thermal mass, solar shading, and natural ventilation as the main strategies employed to cool buildings; this set of principles forms the base design of all Indian vernacular construction. Givoni [4] expanded on these principles by developing the Building Bioclimatic Chart to match hot-dry climatic conditions and composite climates to the strategies traditionally used by Rajasthani builders; through this, Givoni showed that evaporative cooling was most beneficial where there was the highest wet-bulb depression.

Rao and Ballard [5] conducted the first field measurements in Ahmedabad by measuring indoor temperatures in pol houses 7–12°C lower than the outside temperature between May and June, attributing indoor cooling to the thermal mass of the buildings, the microclimate created by the shaded courtyards, and the stack effect working together to provide ventilation in the buildings. Jain [6] documented that indoor temperatures in Rajasthani havelis with wall thicknesses of 600–900mm made of sandstone had 10–15°C less temperature than the outside ambient temperature, and there were window-to-wall ratios less than 15%. Kukreja [7] provided an early engineering characterisation of indigenous building materials for the construction of traditional Indian buildings and established thermal conductivity values for rammed earth, burnt brick, lime mortar, and thatch, which are still widely used as standard reference values.

The Bureau of Energy Efficiency tracked thermal performance data for Indian buildings and included Nayak and Prajapati's [8] results, which identified 8–16 hours of time lag for traditional wall assemblies versus 3–5 hours for thin modern RCC assemblies as a result of lower thermal diffusivity of earthen and stone materials. Kumar et al. [9] conducted CFD analysis that demonstrated a reduction in solar heat gain of 55–60% when using jaali screens with a void ratio of 40%. Jain et al. [10] provided measurements from vavs in Gujarat showing air temperature 15-18 °C lower than ambient conditions, which was attributed to thermal coupling to the ground and to evaporation of free water in the well. Mukherjee [11] and Singh and Bhanware [12] produced additional field evidence of the same relationships from eastern and western India, locating 8–14 °C (°F) of cooling due to earthen and rammed earth construction, respectively. Chandel and Aggarwal [13] described the inverse thermodynamic problem of passive solar heating within cold and dry kath-kuni buildings in the Himalayas to round out the dataset of pan-India. In combination, this body of research represents multiple occurrences of consistent empirical data across various climates and structural systems. The accumulation of independent data gathered through multiple field studies conducted throughout Rajasthan, Gujarat, the Gangetic Plain, the coastal region of Bengal, Kerala and the foothills of the Himalayas will provide mutual and compelling verification for the thermodynamic effectiveness of traditional building methods.

III. METHODOLOGY

This paper uses a systematic and qualitative review design that has been applied for assessing the literature regarding thermal performance of buildings. Sources used are from peer-reviewed journals (including Building and Environment, Energy and Buildings, Solar Energy, Architectural Science Review, and Renewable Energy) as well as technical monographs, Bureau of Energy Efficiency (BEE) publications, and the National Building Code of India [14]. All articles were screened for quantitative thermal performance data (measured ΔT, material thermal properties or analytical modelling results based upon field measurements). The analysis was divided into three modes of heat transfer - that being conduction, convection and radiation - and how they are manifested in traditional building elements. The performance measures that were reviewed include thermal conductivity λ (W/m.K), thermal diffusivity α (m²/s), time lag φ (h), decrement factor f (dimensionless), U value (W/m².K), solar heat gain coefficient (SHGC) and measured ΔT (°C).

IV. THERMODYNAMIC MECHANISMS IN TRADITIONAL INDIAN BUILDINGS

A. Thermal Mass and Time Lag

It is possible to characterize thermal mass based on its volumetric heat capacity (ρC_p [J/m³·K]) and also via the thermal diffusivity ($\alpha = \lambda/\rho C_p$). When examining the conduction process through an insulated wall under uniform solar heating (having an angular frequency of $2\pi/86\,400$ (rad/s)) through time, Fourier's conduction equation yields the penetrating thermal wave:

$$\mathbf{T(x,t) = T\_mean + \Delta T \cdot \exp(-x/d) \cdot \cos(\omega t - x/d)} \quad \mathbf{(1)}$$

The thermal penetration depth (m), denoted by " d ", is calculated as $\sqrt{(2\alpha/\omega)}$ where " x " is measured as " d " into the wall. For earthen, ramming compounds (m²/s) = approximately 3.5×10^{-7} , therefore, " d " = approximately 0.17 metres. As such, the surface temperature wave will be attenuated by (exp(-500/170)) = approximately 0.05 within the 500 mm thickness of the wall, which equates to an amount of time lag φ = 8 - 14 hours [8]. Furthermore, according to the principles of the First Law of Thermodynamics, heat that is absorbed and stored during the day can be returned to the environment (through natural ventilation) at night, thus allowing for the indoor environment to remain cool during the daytime. Table 1 presents material thermal data for key traditional wall assemblies versus modern RCC.

Table 1. Thermal properties of traditional Indian wall materials vs. modern RCC.

Material	λ (W/m.K)	ρ (kg/m³)	Cp (J/kg.K)	Time Lag φ (h)	Decrement f
Rammed earth (500 mm)	0.52–0.87	1,600–2,000	840–1,000	8–14	0.05–0.15
Jodhpur sandstone (600 mm)	1.7–2.3	2,200–2,650	900	10–16	0.03–0.10
Burnt brick (350 mm)	0.81	1,920	840	6–9	0.20–0.35
Thatch roof (150 mm)	0.04–0.07	120–150	1,300	—	—
Modern RCC (150 mm)	1.58	2,288	880	3–5	0.50–0.70

Sources: [7, 8, 15, 16].

B. Buoyancy-Driven Ventilation

Buoyancy provides the motive force for natural ventilation through courtyard houses via buoyancy (the "stack effect"). This is a direct manifestation of the Second Law of Thermodynamics that heat naturally flows from warm to cold and warm air rises. The pressure difference, which causes the flow of air between the inlet and outlet openings separated by a height H, is given by:

$$\Delta P = \rho_o \cdot g \cdot H \cdot (T_i - T_o) / T_i \quad \text{(Pa)} \qquad (2)$$

where $\rho_o \approx 1.15$ kg/m³, $g = 9.81$ m/s², and T_i, T_o are absolute indoor and outdoor temperatures (K). For a two-storey haveli with $H = 7$ m, $T_i = 306$ K and $T_o = 318$ K, equation (2) gives $\Delta P \approx 3.0$ Pa — sufficient to sustain interior air velocities of 0.8–1.2 m/s [5]. The resulting convective heat removal rate is:

$$Q_{conv} = \dot{m} \cdot Cp_{air} \cdot \Delta T \quad (\text{where } \dot{m} = \rho \cdot A \cdot v) \qquad (3)$$

The shaded interior courtyard (aangan) further enhances this effect; the floor and walls of this courtyard are protected from direct solar radiation for a significant part of the day, thus maintaining the courtyard's air 3-5 degrees Celsius cooler than the surrounding air, thus creating a cold air pool to supply cold air to those rooms on the ground level. In May and June, Rajasekar and Ramachandraiah [17] measured operative temperatures of 8-12 degrees Celsius lower than the ambient air temperature in Hyderabad, which goes along with the application of Equations (2) – (3).

C. Evaporative Cooling

The latent heat of vaporization of water (Lv) at 30°C (2430 kJ. / kg) is the basis of evaporative cooling. As a result, evaporating a mass of water (m) from the air removes sensible heat (Q, or m · Lv) from the air, which cools the air temperature to the wet-bulb temperature. The maximum achievable cooling is:

$$\Delta T_{evap} = T_{db} - T_{wb} \approx (T_{db} - T_{dp})(1 - RH) \qquad (4)$$

Utilizing the determination that $\Delta T_{\text{evaporated}}$ water (equation (4)), $\Delta T_{\text{evaporated}}$ water, derived from water evaporation at $T_{db} = 44$°C and RH ≈ 15%, yields $\Delta T_{\text{evaporated}}$ water (theoretical) ≈ 13ºC − 16ºC = thermodynamically effective in hot/dry conditions. Traditional (historic) components of building design that utilize the thermodynamic principle of evaporative cooling are: 1) the central courtyard (bathing area) water pool (hauz); 2) unglazed terracotta matka clay pot containers holding drinking water, that, through constant transpiration, maintain a temperature of 8ºC − 12ºC lower than the ambient air surrounding them [4]; 3) tatty (woven vetiver plant fibre screens) create evaporatively cooled and humidified incoming air, analogous to current evaporative coolers. Jain et al. [10] measured the evaporatively cooled spaces in step-well VAV galleries in Gujarat; that is, the evaporatively cooled open water surface due to evaporation and thermal coupling into the earth (ground thermal transfer) at depths where the soil remains at the annual average temperature of approximately 24ºC − 28ºC.

D. Solar Radiation Control

Solar heat gain through walls and apertures is expressed as:

$$Q_{solar} = \alpha \cdot I_s \cdot A_{wall} + SHGC \cdot I_s \cdot A_{glazing} \qquad (5)$$

The traditional buildings of India have been designed in order to minimise solar heat gain and to keep the surface temperatures of walls as low as possible for human occupancy. The exterior walls of many of these buildings are lime-washed with white paint, which can reduce solar wall absorptance from low .65 to .70 for bare masonry walls down to approximately .20 to .25, reflecting 75 to 80 per cent of incident radiation. The introduction of an overhanging chajja eave with a depth-to-height ratio

(D/H) of .50 will prevent direct solar gain to the facade for solar altitude angles greater than 45 degrees, covering the whole of the May to August period at a latitude of 26 degrees north [7].

The use of a jaali (perforated screen) can provide both diffuse ventilation and control of solar gain. Traditional sandstone jaalis have void ratios ranging from 30 to 50 per cent, and can transmit only 30 to 45 per cent of incident solar radiation into the interior, providing a significant reduction in solar heat gain when compared to an open window [7]. The field measurements by Rajasekar and Ramachandraiah [17], taken in jaali-screened spaces in Hyderabad, showed that the velocity of air movement at the hindrances caused by jaalis was measured at between .5 and 1.0 m/s in natural wind conditions, well within the range of adaptive comfort established by Krishan et al. [18]. Long-wave radiative exchange between the occupants and the building is governed by the Stefan-Boltzmann equation: $q_{rad} = \varepsilon \cdot \sigma \cdot T^4$. High-mass walls, or those that are cooled by time lag, have lower surface temperatures than their interiors, providing a lower mean radiant temperature (MRT), and thus an operative temperature that is cooler than the simple reduction of air temperatures would provide alone.

Table 2. Thermodynamic mechanisms — governing equations and field-measured performance.

Element	Mechanism	Governing Relation	Measured ΔT
Thick earthen / stone wall	Thermal mass, time lag	Eq. (1): $T(x,t) = T_{mean} + \Delta T \cdot \exp(-x/d) \cdot \cos(\omega t - x/d)$	8–15°C [6, 11]
Courtyard (aangan)	Stack-effect ventilation	Eq. (2): $\Delta P = \rho \cdot g \cdot H \cdot (T_i - T_o)/T_i$	6–12°C [5, 17]
Hauz / tatty / step-well	Evaporative cooling	Eq. (4): $\Delta T_{evap} = T_{db} - T_{wb}$	10–18°C [10]
Chajja + lime-washed wall	Solar absorption control	Eq. (5): $Q = \alpha \cdot I_s \cdot A$; α: 0.65 to 0.22	Surface 8–12°C cooler [7]
Jaali screen (30–50% void)	Solar filtering + ventilation	Void ratio 30–50%; transmits 30–45% of solar radiation	Interior $v = 0.5$–1.0 m/s [7, 17]

Sources: As cited; compiled from reviewed literature.

V. CLIMATIC ZONATION OF PASSIVE STRATEGIES

India's National Building Code [14] defines five climatic zones. Each presents a distinct thermodynamic challenge, and traditional builders calibrated the four mechanisms described above accordingly. Table 3 summarises the dominant passive strategy, exemplar building typology, and measured ΔT for each zone.

Table 3. Dominant thermodynamic strategy by Indian climatic zone.

Zone	Region	Dominant Mechanism	Typology	ΔT (°C)
Hot-dry	Rajasthan, Gujarat	Thermal mass + evaporative + stack ventilation	Haveli, sandstone house	10–15
Composite	UP, Delhi, MP	Thermal mass + solar shading + ventilation	Courtyard haveli, tehkhana	7–12
Hot-humid	Kerala, coastal Bengal	Maximise ventilation; minimise roof solar gain	Nalukettu, bamboo house	5–8
Temperate	Maharashtra highlands	Moderate mass + cross-ventilation	Wada, stone house	4–6
Cold	Himachal Pradesh, J&K	Passive solar gain + compact insulated form	Kath-kuni stone-timber	+8–12 (heating)

Sources: [8, 13, 14, 18].

The hot dry zones (Rajasthan & Gujarat) experience the operation of all four mechanisms in a synergistic manner. Thermal mass delays the time it takes for heat to enter the building, while the courtyard uses the stack effect to ventilate naturally by creating a breeze, and water features take advantage of the large wet-bulb depression. Lastly, the use of chajjas eliminates any direct solar gain through the roof. As a result, these four mechanisms create the largest (10-15°C) recorded ΔT values for these climates.

In hot, humid coastal regions, such as Kerala, the small difference in daytime/nighttime temperatures (4-6°), along with high levels of humidity (>80%RH) during the night, prevents the ability of thermal mass to effectively cool an interior through night ventilation purging [8]. Thus, the Nalukettu building typology focuses on achieving cross ventilation, along with controlling solar radiation via the use of steep, wide overhanging pitched roofs made of tile materials. In contrast, Chandel and Aggarwal ([13]) reveal that in cold high-altitude areas, the thermodynamic process is reversed: compact stone and wood construction (kath-kuni) with south-facing windows and minimal infiltration retains passive solar gain (for thermal mass) at a difference of 8-12°C from the exterior ambient temperature.

VI. DISCUSSION AND RESEARCH GAPS

Passive thermal performance was achieved by traditional Indian builders using thermal mass stack-effect ventilation, evaporative cooling and solar radiation control in tandem, producing a ΔT value of 5–18°C while using no operational energy. Significant gaps exist in research on this subject, including limited field studies to days or weeks rather than full annual cycles, and variability amongst thermal properties (λ = 0.30–1.20 W/m.K.) for earthen construction, resulting in a lack of comparability between studies due to differences in soil types and compaction. Rapid loss of vernacular architecture due to demolition necessitates a priority of documenting any remaining buildings.

Therefore, the research has importance to public policy. As part of India's National Building Code revision, there is now an opportunity to create a code for minimum requirements on thermal mass, design for stack-effect ventilation with required courtyards, and create standards for shading through jaali lighting so that these hundreds of years of empirical knowledge of thermodynamics can be transformed into enforceable design recommendations for low-energy housing today.

VII. CONCLUSION

Numerous studies have been conducted in the fields of thermodynamics and passive cooling systems, with mostly indicating that traditional Indian homes have demonstrated substantial passive thermodynamic efficiencies through thermal mass (φ = 8-16 hrs; f = 0.03-0.35), buoyancy-driven ventilation ($\Delta P \approx$ 2-5 Pa), evaporative cooling (ΔT up to 16 °C in hot/dry conditions) and control of solar radiation (SHGC ≈ 0.40-0.45), resulting in indoor temperatures that are 5-18 °C lower than the surrounding air temperature and achieved without the use of any energy. The impacts of each of these strategies on the thermal performance of a structure can be related to the thermodynamic principles shown in Equations (1) – (5). Given that the demand for cooling in India continues to grow at an unprecedented rate, a consistent and coordinated reintroduction of traditional Indian architectural strategies into current building codes and housing policies can represent an effective and economical means of accomplishing energy-efficient design through the use of passive thermal strategies.

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