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Original Research Article

Utilization of Solar Chimney and Thatch Roof to Enhance the Efficiency of Natural Ventilation

(A Case Study: Residential Building in Babol City)*

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Abstract

Problem statement: Despite technological advancements, the utilization of renewable energy strategies in building design, particularly within temperate and humid climates, remains underutilized. Wind energy offers the potential for reducing reliance on mechanical systems and fossil fuels through optimized energy consumption, humidity mitigation, and enhanced thermal comfort. Architectural strategies such as solar chimneys and thatched roofs can further promote natural ventilation and improve building energy efficiency.

Research objective: This research aims to evaluate the impact of integrating a solar chimney, as a contemporary approach, and a thatched roof, as a vernacular building practice, on achieving thermal balance by increasing the efficiency of natural ventilation in buildings situated in Babol's temperate and humid climatic zone.

Research method: The research methodology employed documentary-theoretical analysis (literature review), field investigations, and applied computational simulation. The simulation component was used to assess the performance contributions of the solar chimney and thatched roof utilizing DesignBuilder software, employing both building energy simulation and Computational Fluid Dynamics (CFD) analyses.

Conclusion: The concurrent application of solar chimney-driven ventilation (scheduled operation: 8 PM- 8 AM) and a continuously operating thatched roof (24-hour) within the building during the six-month spring and summer period demonstrates a significant positive influence on the building's thermal conditions. In comparison to a baseline building equipped with a tile roof and lacking a solar chimney over the identical period, this combined strategy yields an average reduction of 438.4kWh in total internal heat gain removed via natural ventilation. It elevates the air change rate by 9.9ACH and diminishes heat absorption through the building envelope by 3613 kWh.

Keywords: *Thermal Comfort, Natural Ventilation, Temperate and Humid Climate, Solar Chimney, Thatched Roof.*

Introduction

Renewable energy sources, including solar, wind, and geothermal power, are recognized as viable sustainable alternatives for diminishing dependence on finite, non-renewable resources (Sartori et al., 2012). These sources underpin the design principles of green and sustainable architecture, offering pathways to reduce operational energy costs and environmental pollution (Yeh et al., 2016). Currently, renewable sources satisfy a mere 14% of the total global

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**Corresponding Author: Farshchi46@kashanu.ac.ir, +989131617591 energy demand (Bahadorinejad & Yaghoubi, 2006). Sustainability in architecture involves the design and construction of buildings that fulfill occupants' needs while concurrently minimizing ecological impact and optimizing the utilization of natural resources (Heath & Gidley, 2012). Natural ventilation emerges as a key strategy for curtailing energy consumption and augmenting thermal comfort and indoor air quality, positioning it as an integral component of sustainable architectural practice (Kohler & Lichtensteiger, 2017). Thermal comfort is defined as the subjective condition of satisfaction with the thermal environment (Ashrae, 2017); conventionally, this comfort zone corresponds to conditions where 80% of occupants express satisfaction (Seyyed Sadr, 2009). Individual factors such as metabolic rate, clothing insulation, physiological state, gender, and age can modulate the perception of thermal comfort (Holger, 2006). Elevated humidity levels characteristic of temperate and humid climates frequently compromise thermal comfort and escalate building energy demands for dehumidification and cooling. Harnessing wind energy and implementing natural ventilation strategies within indoor spaces can effectively mitigate humidity, foster thermal comfort, and reduce the necessity for energy-intensive mechanical and electrical systems. Within the portfolio of natural ventilation techniques, solar chimneys demonstrate efficacy in hot-humid and temperate-humid climatic contexts. Nevertheless, within Iran's temperate and humid regions, particularly the Mazandaran province, the application of solar chimneys for ventilation enhancement and energy conservation remains uncommon. Similarly, thatch, a locally sourced, sustainable material indigenous to Mazandaran and historically employed for roofing, has witnessed diminished use owing to the proliferation of modern roofing alternatives like asbestos cement sheets and ceramic tiles. This research endeavors to investigate the collective impact of implementing a solar chimney (a contemporary technological solution) and a thatched roof (a traditional vernacular solution) on improving indoor ventilation effectiveness and thermal regulation within buildings situated in the temperate and humid climate of Babol.

Research Background

Solar chimneys enhance natural ventilation and thermal comfort by capitalizing on the buoyancy effect generated through solar thermal gain. Their application has been investigated in both residential and non-residential contexts, demonstrating a capacity to reduce energy demands for both cooling and heating. Integration into multi-story buildings is also a recognized feasible application (Zhao et al., 2024). Performance generally improves with increased solar collector surface area and incident solar radiation but can be diminished by elevated ambient temperatures and thermal stratification effects within the chimney shaft (Fine et al., 2022). Incorporating absorber plates within the chimney channel can augment heat transfer to the airflow (He & Lv, 2022). Buildings equipped with solar chimneys often incur a higher initial construction cost compared to conventional structures, with the premium varying based on chimney height, cavity dimensions, aperture design, and material selection (Zhang & Shi, 2018). Studies report cost increases ranging from 1.88% for large houses to 3.72% for small houses. However, the system typically yields electricity consumption savings of 10-20%, enabling recoupment of the initial investment over the long term. Designed for durability, solar chimneys can have lifespans of 40-50years with minimal maintenance requirements (Ratanachotinun et al., 2016), primarily involving periodic inspections to ensure material integrity and prevent obstructions (Singh et al., 2023). Economic analyses estimate payback periods between 6 and 13 years, contingent upon building scale (Ratanachotinun et al., 2016). Complementing passive strategies, thatched roofs, particularly when designed with open eaves on pitched structures, facilitate effective ventilation by allowing warm air to exhaust naturally from the building (Mandal et al., 2021). Comparative analyses indicate that houses with thatched roofs generally exhibit superior ventilation performance compared to those with impervious metal roofs, owing to the inherent breathability of the thatch material (Knudsen et al., 2020). Air permeability within the thatch layers promotes moisture wicking and breathability (Simpson, 2022). Thatch materials range from rigid stems (e.g., wheat, reed) to softer foliage (e.g., palm leaves, rice stalks), each possessing distinct durability characteristics. Rigid thatches can last up to 70 years in temperate zones and 30 years in the tropics, whereas softer types may endure less than 10 years, sometimes only 2, although specialized techniques can extend this lifespan to around 12 years (Hall, 1998). In the Mazandaran region, particularly around Babol, vernacular materials like wheat straw, rice straw, and reeds are readily available from local ecosystems. The presence of a skilled local workforce further contributes to reducing construction expenses. Research suggests that the cost of installing a thatched roof using local resources can be 40-60% lower than employing industrial roofing alternatives like metal sheeting (Ejstrup & Beim, 2023). Maintenance costs are generally low, and often limited to periodic replacement of the outer weathering layer. However, regular upkeep is crucial for sustained ventilation performance, with visual indicators like unevenness or moss growth signaling the need for repair (Hunnisett, 2021). The type of plant material significantly influences longevity, with rigid stems offering greater durability. Considering the robustness of the primary structure and the typical re-thatching cycle of 10-15years for the surface layer, the payback period when utilizing local materials and labor is estimated to be between 3 and 5 years. Existing research predominantly advocates for the use of either solar chimneys or thatched roofs to improve natural ventilation in temperate and humid climates. However, investigations into the synergistic effects of combining these two systems are scarce. This study aims to address this gap by examining the performance implications of integrating both a solar chimney and a thatched roof within a single building design.

Theoretical Foundations

Natural ventilation facilitates the exchange of indoor and outdoor air masses without reliance on mechanical power, driven instead by naturally occurring pressure differentials induced by wind forces and air density variations (buoyancy effect) (Kasmai, 2003). This passive process inherently lowers building energy consumption and enhances indoor air quality. In contrast to mechanical ventilation systems, natural ventilation achieves significant reductions in energy use and associated pollution by obviating the need for extensive mechanical plant. While mechanical systems offer high performance and precise control over indoor air quality and temperature parameters, they often carry a larger environmental footprint (Guardigli & Barbolini, 2014). Natural ventilation systems typically afford less precise control, although their performance can be substantially improved through meticulous design incorporating elements like ventilation shafts and appropriately configured facade openings (Coşar et al., 2023). Ventilation effectively contributes to cooling indoor air, the building fabric, and occupants via convective heat transfer and evaporative processes (Kasmai, 2003). Natural ventilation strategies are broadly classified into single-sided ventilation, cross-ventilation, and stack ventilation, each operating based on specific airflow patterns and pressure gradients (Kalyon, 2010). In temperate and humid regions, cross-ventilation (double-sided) is frequently employed (Ghobadian, 2013). Buildings are often oriented along an east-west axis to capitalize on prevailing breezes through strategically placed openings on northern and southern facades (Kasmai, 2003). Historically, to enhance ventilation and manage humidity, vernacular dwellings were constructed upon elevated foundations of stone, timber, or mud-brick (Memarian, 1997). In coastal zones, thatched roofing served as an effective passive natural ventilation system (Ghobadian, 2013). Thatch, essentially a form of vegetative roofing composed of plant materials like rice straw (Koul et al., 2022), acts as a natural insulator due to its inherent porosity and trapped air pockets. This property enables it to shield buildings from excessive heat gain in summer and heat loss in winter (Madhumathi et al., 2014). The moisture content of thatch is dynamic, influenced by precipitation and solar exposure, but typically dries relatively quickly post-rainfall (Simpson, 2022). Buildings incorporating thatched roofs can realize reductions in energy consumption and cooling demand by as much as 10.5% (Pragati et al., 2023). The substantial thickness of thatch generally provides superior thermal insulation compared to many conventional roofing materials, contributing to its resilience against diverse weather conditions (Simpson & Nevell, 2022). The solar chimney represents another pertinent passive ventilation strategy, particularly suitable for humid, wind-prone areas (Shaeri et al., 2022). Structurally, it comprises a solar collector element integrated with a vertical shaft connecting different levels or spaces within a building (Soto et al., 2021). Air movement within the chimney is induced by the buoyancy effect, stemming from air density changes driven by temperature differentials between the indoor environment and the air within the heated chimney cavity (Shi et al., 2018). They have demonstrated potential to reduce indoor temperatures by 3-7°C in hot-humid climates, whereas windcatchers generally exhibit superior performance in hot-dry climates, achieving temperature reductions up to 3°C (Khakzand et al., 2024). Regarding airflow induction, field measurements indicate solar chimneys can generate air velocities ranging from 0.5to 2.5m/s (Huang et al., 2023), while windcatchers typically induce flows between 0.3and 1.8m/s, proving particularly effective in hot-dry conditions (Farouk, 2020).

Research Method

The methodological framework for this research encompasses three primary components: (1) Documentary-Theoretical Study, (2) Field Investigation, and (3) Applied Simulation. The initial phase involved reviewing existing literature on natural ventilation principles, the characteristics of temperate and humid climates, the design and performance of solar chimneys and thatched roofs, and identifying key climatic factors influencing thermal comfort and ventilation. Fig. 1 provides a schematic representation of vernacular architectural principles relevant to the Mazandaran region. The second phase consisted of field studies to gather qualitative data through site observations, analyzing the natural environmental characteristics and climatic conditions pertinent to designing and simulating natural ventilation strategies for the case study building. The third phase focused on computational simulation, specifically modeling the energy performance and natural ventilation behavior of a representative residential building in Babol. This involved employing DesignBuilder software to conduct both whole-building energy simulations and CFD[1] analyses to investigate airflow patterns. The findings presented herein are derived from the analysis of this specific Babol case study, selected for its representativeness of sustainable architectural practices adapted to the local temperate and humid climate, incorporating vernacular design principles. Extrapolation of these findings to a broader building stock necessitates further investigation.

Field Studies

Examination of vernacular buildings in the Babol region allowed for the identification of key climatic factors influencing natural ventilation and thermal comfort strategies. Buildings typically exhibit an east-west orientation to harness prevailing air currents and benefit from passive solar gain during winter months. Elevating the structure through features like crawl spaces[2] and raised platforms[3] provides protection against ground moisture. Site planning often features a scattered layout with low boundary walls, promoting airflow around buildings. Large window openings are characteristic, designed to facilitate cross-ventilation. Pitched roofs ensure efficient shedding of rainwater, while semi-enclosed spaces such as verandas and terraces offer shaded areas conducive to comfortable airflow. Living accommodations are commonly situated on the ground floor. Construction relies heavily on durable, locally sourced natural materials like stone, timber, and ceramic tile. Figs. 2 & 3 provide visual documentation.

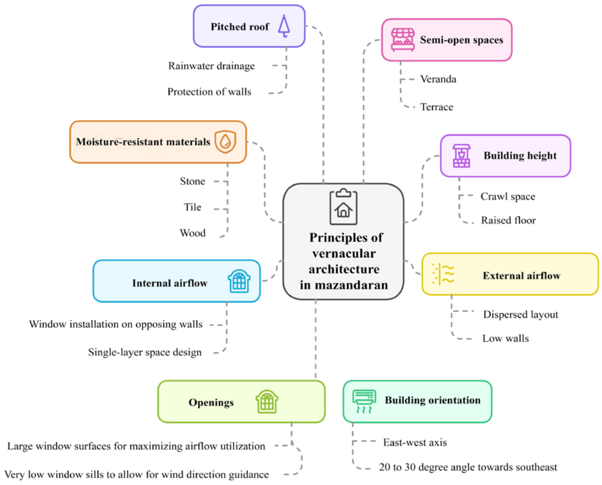


Fig. 1. Diagram illustrating principles of vernacular architecture in mazandaran. Source: Kasmai, 2003.

- **Case study description**

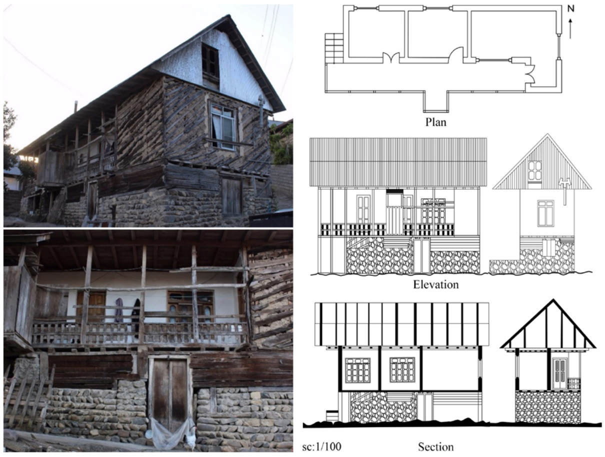
The selected case study building is situated within a 10,000 m^2 residential development site in Babol, representing one of four distinct typologies. The analyzed typology features a 20-degree rotation relative to cardinal directions and maintains a 12-meter separation from adjacent structures. The building is configured as a triplex[4] dwelling. Floor areas are distributed as follows: ground floor (135 m^2), first floor (70m^2), second floor (120 m^2), third floor (85m^2), and an attic space (45m^2). A solar chimney is integrated into the central and southern portions of the building plan to augment natural ventilation performance. The foundation incorporates a ventilated crawl space to assist with subfloor ventilation and moisture control. Fig. 4 presents the architectural documentation for this case study.

Discussion

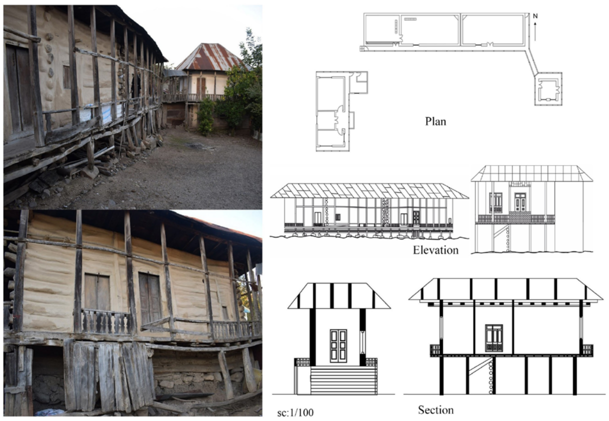
- **Climate consultant software output analysis**

Given the unavailability of a dedicated TMY weather file for Babol city, meteorological data from the nearby Babolsar station, known for its higher data fidelity, was utilized. Fig. 5 displays psychrometric charts and wind rose diagrams corresponding to the three summer months, generated using Climate Consultant software for climatic analysis and subsequent input into the DesignBuilder simulation environment. The psychrometric analysis indicates that during the warmer seasons, achieving the ASHRAE comfort zone necessitates approximately 12.7% reliance on natural ventilation strategies, 17.4% on dehumidification processes, and a 60.5% sensible cooling load. The wind rose reveals that the predominant wind direction is westerly, characterized by speeds exceeding 10 m/s and associated temperatures ranging from 27°C to

Fig. 2. Photographic examples of vernacular buildings in villages near Babol. Source: Authors Archive.



Architectural survey documents of the first case study 1



Architectural survey documents of the first case study 2

Fig. 3. Sample field survey drawings documenting vernacular architecture in Babol. Source: Authors Archive.

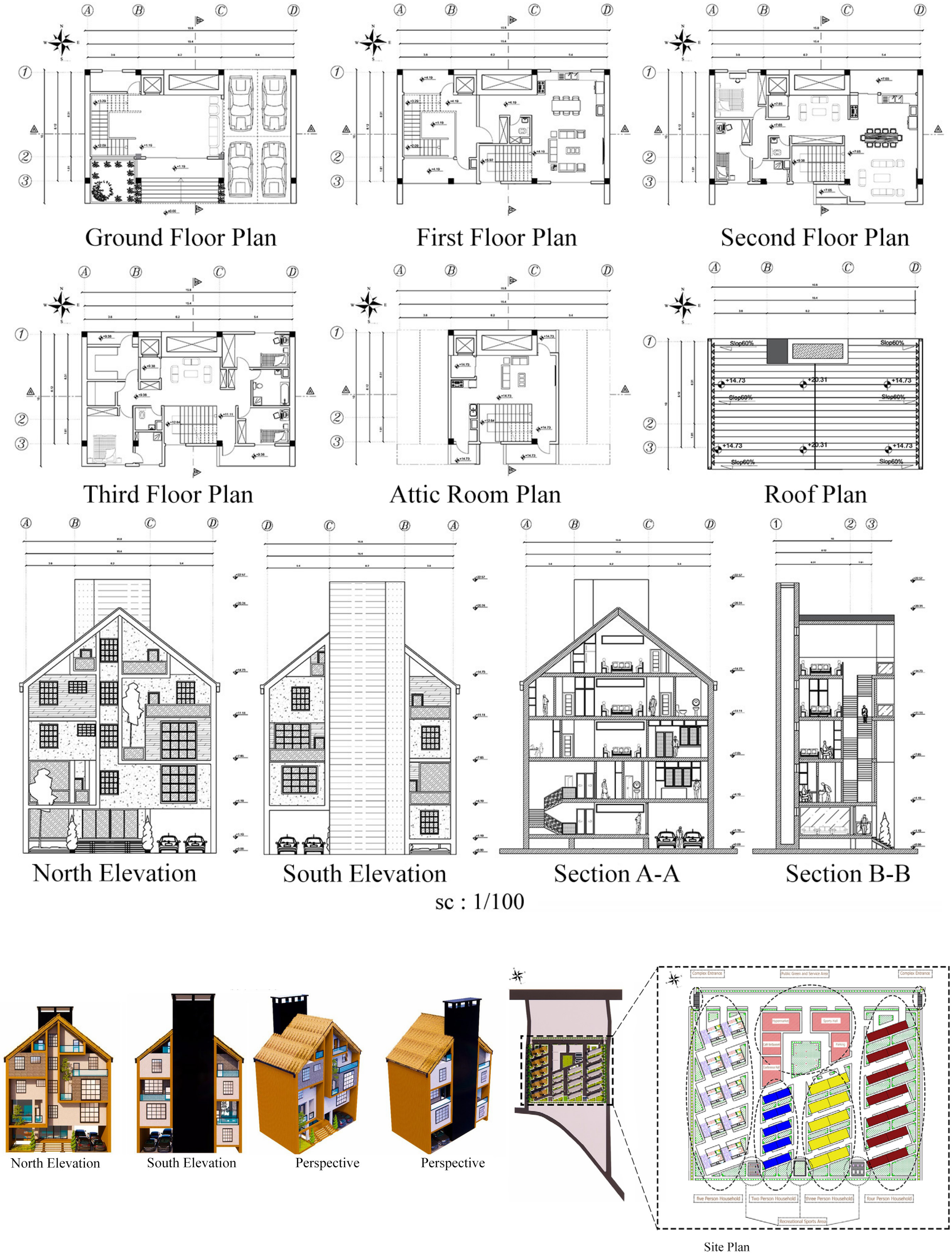
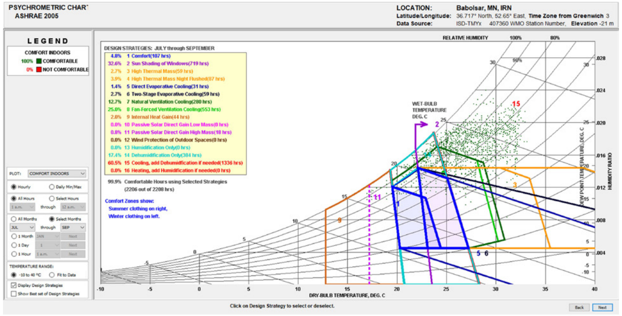


Fig. 4. Architectural drawings of the case study building. Source: Authors.



DESIGN STRATEGIES: JULY through SEPTEMBER

4.8% 1 Comfort(107 hrs)
32.6% 2 Sun Shading of Windows(719 hrs)
2.7% 3 High Thermal Mass(59 hrs)
3.9% 4 High Thermal Mass Night Flushed(87 hrs)
1.4% 5 Direct Evaporative Cooling(31 hrs)
2.7% 6 Two-Stage Evaporative Cooling(59 hrs)
12.7% 7 Natural Ventilation Cooling(280 hrs)
25.0% 8 Fan-Forced Ventilation Cooling(553 hrs)
2.0% 9 Internal Heat Gain(44 hrs)
0.0% 10 Passive Solar Direct Gain Low Mass(0 hrs)
0.8% 11 Passive Solar Direct Gain High Mass(18 hrs)
0.0% 12 Wind Protection of Outdoor Spaces(0 hrs)
0.0% 13 Humidification Only(0 hrs)
17.4% 14 Dehumidification Only(384 hrs)
60.5% 15 Cooling, add Dehumidification if needed(1336 hrs)
0.0% 16 Heating, add Humidification if needed(0 hrs)

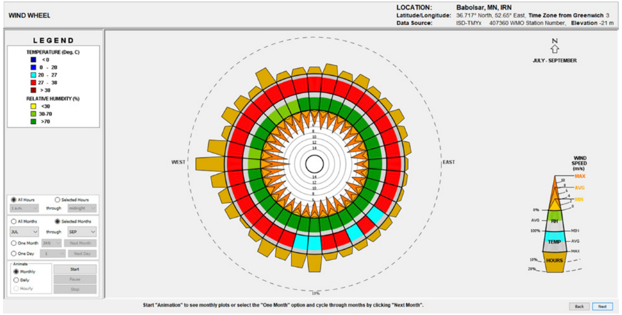
99.9% Comfortable Hours using Selected Strategies (2206 out of 2208 hrs)

Comfort Zones show:
Summer clothing on right,
Winter clothing on left.

PLOT: COMFORT INDOORS
● Hourly ○ Daily Min/Max
● All Hours ○ Select Hours 1 a.m. through 12 a.m.
○ All Months ● Select Months JUL through SEP
○ 1 Month JAN Next
○ 1 Day 1 Next
○ 1 Hour 1 a.m. Next
TEMPERATURE RANGE: ● -10 to 40 °C ○ Fit to Data
☑ Display Design Strategies
☐ Show Best set of Design Strategies

Click on Design Strategy to select or deselect.

Wind Rose Diagram



● All Hours ○ Selected Hours 1 a.m. through midnight
○ All Months ● Selected Months JUL through SEP
○ One Month JAN Next Month
○ One Day 1 Next Day
Animate ● Monthly ○ Daily ○ Hourly

Start "Animation" to see monthly plots or select the "One Month" option and cycle through months by clicking "Next Month".

Psychrometric Chart

Fig. 5. Climate analysis outputs from climate consultant software. Source: Authors.

38°C; these conditions are generally unfavorable for direct natural ventilation cooling. However, secondary wind patterns originating from the south and southeast exhibit more promising characteristics, with air temperatures between 20°C and 27°C and wind speeds of 4-6m/s. These conditions fall within the desirable range for effective natural ventilation, aligning with thermal comfort criteria.

- **Software validation procedure**

To rigorously evaluate the accuracy of the energy simulation component of this research, the ASHRAE Standard 140 / BESTEST Case 600□ benchmark model was simulated. Geometric parameters and boundary conditions were meticulously defined within the simulation software, adhering strictly to the specifications outlined in the standard. An annual simulation was executed using the standard EnergyPlus weather data file. The Case 600 model comprises a simple rectangular volume (8.2m×6.2m×2.7m high) with a wall thickness of 0.17m. Two windows (3m×2m) are situated on the southern facade, featuring a sill height of 0.2m and an external recess depth of 0.5m. Material properties for walls, roof, floor, and glazing were assigned according to ASHRAE specifications. A constant air infiltration rate of 0.5ACH 5 was applied. Internal environmental conditions were defined with a heating setpoint of 20°C and a cooling setpoint of 27°C, both maintained continuously. The HVAC[6] system was modeled using the 'Simple' approach, with a COP[7] set to 1.0, and other passive systems configured as per the standard. Validation focused on comparing simulated outputs for outdoor dry-bulb temperature and incident solar radiation on the south facade against the benchmark results. Deviations were consistently less than 1%, thereby confirming the high fidelity and accuracy of the simulation setup. Table 1 provides a comparative summary of the simulation results against the ASHRAE standard values for Case 600.

- **Simulation modeling and input parameters in design builder**

For a detailed simulation of the case study's thermal performance, boundary conditions were established in DesignBuilder as outlined in Table 2. The building occupancy was defined as residential, with thermostat setpoints configured at 22°C for heating and 26°C for cooling initiation (reset point), alongside an air infiltration rate of 0.7ACH. External wall assemblies consist of 10cm concrete blockwork and 5cm insulation, yielding a composite thermal conductivity (k-value) of 0.892 W/m·K. Internal partition walls are constructed from 10cm concrete blocks (k = 1.097 W/m·K). The thatched roof assembly (spanning 10m×16.5m) features a total thickness of 45cm, resulting in an effective k-value of 0.226 W/m·K. The comparative tile roof assembly comprises 2.5cm ceramic tiles, a 2cm air gap (insulation), and a 5mm roofing felt, with a combined k-value of 2.93W/m·K. The solar chimney construction includes a 10cm cast iron metal layer and 5cm of insulation, contributing to a k-value of 3.219 W/m·K for these primary components, with other layers also meticulously modeled. The window-to-wall ratio (WWR) was set at 30%, with a standard window height of 2.5m and a sill height of 0.8m from the floor. The operational schedule for the HVAC system during the warmer months (approximately April to September) involved a combined strategy: mechanical cooling (air conditioning) operating from 8 AM to 8 PM, supplemented by natural ventilation (including solar chimney effect) activated from 8 PM

Table 1. Comparative validation results. Source: Authors.

Solar incident (kw)	Outside dry-bulb temperature (C)	Date/Time	Source
0	20.70833	7.27.2002 01:00	Ashrae, 2017
0	19.65	7.27.2002 02:00	
0	19.10833	7.27.2002 03:00	
0	18.55	7.27.2002 04:00	
0.041237	18.3	7.27.2002 05:00	
0.72812	18.94167	7.27.2002 06:00	
1.912095	21.38333	7.27.2002 07:00	
2.953853	24.43333	7.27.2002 08:00	
5.582846	27.525	7.27.2002 09:00	
8.246233	29.54167	7.27.2002 10:00	
9.891035	30.35	7.27.2002 11:00	
10.3255	31.88333	7.27.2002 12:00	
10.13706	33.09167	7.27.2002 13:00	
8.815766	33.94167	7.27.2002 14:00	
6.731585	34.4	7.27.2002 15:00	
3.949468	34.10833	7.27.2002 16:00	
1.805119	33.55	7.27.2002 17:00	
1.159304	31.025	7.27.2002 18:00	
0.353594	28.46667	7.27.2002 19:00	
0.017426	27.15833	7.27.2002 20:00	
0	26.05833	7.27.2002 21:00	
0	24.60833	7.27.2002 22:00	
0	23.9	7.27.2002 23:00	
0	20.70833	7.27.2002 01:00	Authors
0	19.65	7.27.2002 02:00	
0	19.10833	7.27.2002 03:00	
0	18.55	7.27.2002 04:00	
4.123747E-02	18.3	7.27.2002 05:00	
0.7281203	18.94167	7.27.2002 06:00	
1.912095	21.38333	7.27.2002 07:00	
2.953852	24.43333	7.27.2002 08:00	
5.582847	27.525	7.27.2002 09:00	
8.246233	29.54167	7.27.2002 10:00	
9.891035	30.35	7.27.2002 11:00	
10.3255	31.88333	7.27.2002 12:00	
10.13706	33.09167	7.27.2002 13:00	
8.815766	33.94167	7.27.2002 14:00	
6.731585	34.4	7.27.2002 15:00	
3/949468	34/10833	7/27/2002 16:00	
1/805119	33/55	7/27/2002 17:00	
1/159304	31/025	7/27/2002 18:00	
0/353594	28/46667	7/27/2002 19:00	
0/017426	27/15833	7/27/2002 20:00	
0	26/05833	7/27/2002 21:00	
0	24/60833	7/27/2002 22:00	
0	23/9	7/27/2002 23:00	

Table 2. Summary of key input parameters for designbuilder simulation (activity, openings, lighting, hvac, construction). Source: Authors.

Activity			
Activity pattern	**Residential space**		**Data**
Environmental control (°C)	Heating setpoint		22
	Heating setback		28
	Cooling setpoint		22
	Cooling setpoint		26
Construction			Data
Infiltration	Constant Rate		0.7
Materials (Heat transfer coefficient)	Exterior wall	Concrete block	0.892
	Interior wall	Concrete block	1.097
	Roof	Thatch	0.226
		Tile	2.93
	Solar chimney	Metal	3.219
Lighting			
Lighting type		LED	
Openings			
Glazing Type	Double glazing, 6mm air gap		Data
Dimensions	Window-to-wall ratio (%)		30
	Window height (m)		2.5
	Sill height (m)		0.8
HVAC			
HVAC strategy		Simple HVAC Combined mechanical cooling and natural ventilation	
Mechanical cooling		Air conditioner	
Natural ventilation		Outdoor air, solar chimney, and thatched roof	
Schedule	Mechanical cooling	8 AM - 8 PM (April to September)	
	Natural ventilation	8 PM - 8 AM (April to September)	
	Solar chimney	8 PM - 8 AM (April to September)	
	Thatched roof	Continuous (24.7 April to September)	

to 8 AM. The thatched roof's thermal properties were considered active continuously (24/7). Internal lighting loads were simulated based on an energy-efficient LED lighting scheme. Meteorological data was sourced from the validated EnergyPlus weather file for Babolsar (the closest representative station) covering the period 2004-2018. The geometric configuration and material specifications for the solar chimney design were carefully considered. The optimal aspect ratio (width-to-height) for solar chimney air cavities is influenced by factors including the neutral pressure level, indoor-outdoor temperature differentials, and the effective areas of intake and exhaust openings (Ashrae, 2017). Research specific to Algerian conditions suggests an optimal cavity width-to-height ratio of approximately H/10(Bouchair, 1994). Similar studies conducted within the Iranian context have corroborated this finding, indicating that the same ratio is generally optimal for local conditions (Fakhari & Heidari, 2013). Based on these precedents, the solar chimney in this model was designed with a height (H) of 20m and an air cavity width (depth) of 2m. The separating wall between the occupied space and the chimney cavity, serving as the primary solar absorber surface, was modeled with 5cm of insulation adjacent to a 10cm concrete layer. The insulation layer is critical for preventing undesirable heat transfer from the chimney back into the occupied spaces, thus avoiding overheating and minimizing parasitic heat loss. Ventilation openings connecting the solar chimney to each floor were sized at 4m length × 0.7m width, positioned 2.40m above the finished floor level. Fig. 6 provides detailed drawings

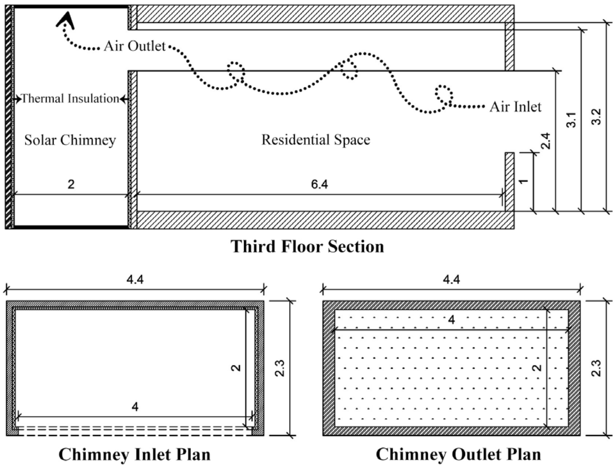


Fig. 6. Detail drawings of the solar chimney configuration. Source: Authors.

of the solar chimney configuration, while Fig. 7 illustrates the complete building model within the DesignBuilder environment. It is imperative to acknowledge that all simulation modeling entails inherent limitations. In this study, the representation of complex phenomena such as solar radiation dynamics, intricate natural airflow patterns, and certain environmental variables involved necessary simplifications dictated by the nature of numerical modeling and software capabilities. These simplifications may introduce discrepancies compared to real-world performance. However, DesignBuilder is recognized as a robust and validated tool for building energy and ventilation analysis. Despite the unavoidable simplifications, the key parameters governing natural ventilation performance were simulated with appropriate fidelity, and it is assessed that the inherent limitations of the software do not substantially compromise the validity or conclusions of this research.

Findings

• Comparative evaluation: combined system vs. separate ventilation. Cooling strategies

The thermal performance and energy consumption associated with the building's environmental control system during the six warmer months (approx. April-September) were analyzed under three distinct operational scenarios. Thermal comfort was assessed using the criteria defined in ASHRAE Standard 55, requiring the PMV[8] to remain within the range of -0.5to + 0.5, and the PPD[9] to be below 15%. Scenario 1 (Natural Ventilation Only): Relying solely on natural ventilation strategies resulted in an estimated energy consumption of 23.03kWh.m². However, this scenario failed to consistently maintain thermal comfort conditions, with PMV values frequently falling outside the acceptable range and PPD levels exceeding the 15% threshold. Scenario 2 (Mechanical Cooling Only): Employing only mechanical cooling successfully maintained thermal comfort throughout the six months, with both PMV and PPD indices remaining within the prescribed limits. However, this was achieved at a significant energy cost, estimated at 212.59kWh.m², which contravenes the objective of energy conservation. Scenario 3 (Combined Natural Ventilation & Mechanical Cooling): This integrated strategy maintained thermal

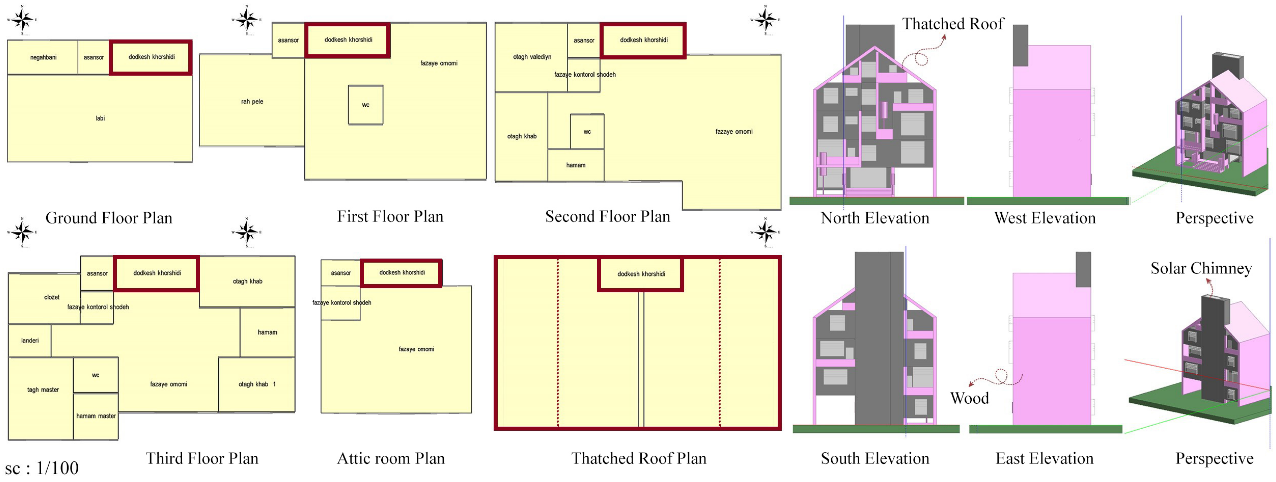


Fig. 7. Rendered views of the building model in designbuilder software. Source: Authors.

comfort levels comparable to Scenario 2 but achieved this with substantially lower energy consumption, estimated at 164.20kWh.m². This represents a 23% reduction in energy use compared to the mechanical-cooling-only scenario. Based on these findings, the combined strategy (Scenario 3), integrating natural ventilation during cooler periods and mechanical cooling during peak heat periods, was identified as the optimal operational approach for the warmer months and adopted for subsequent detailed analyses.

• Impact of the solar chimney on thermal balance and air exchange

This section analyzes the contribution of the solar chimney to the building's thermal balance and total fresh

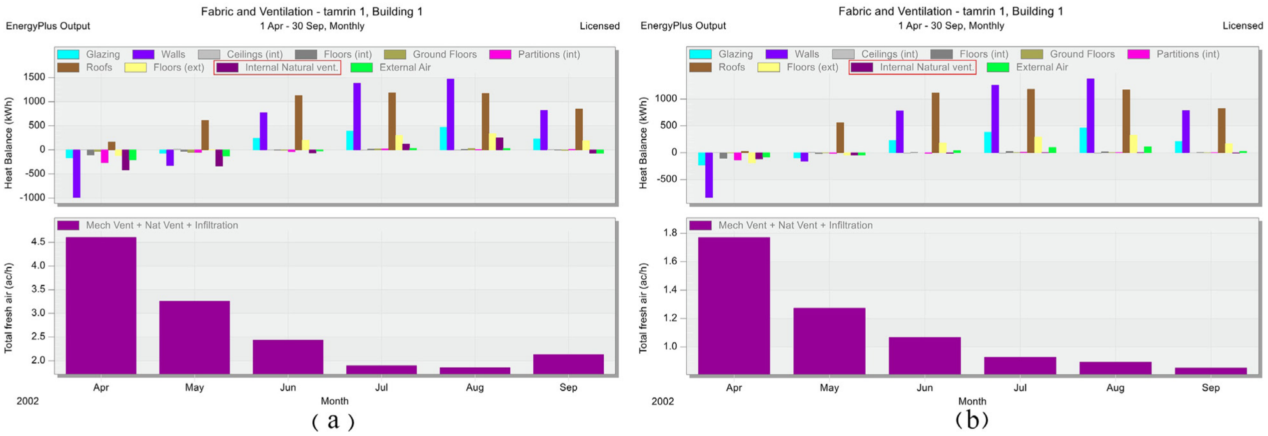
air introduced. The analysis utilizes graphical outputs from the simulation. The thermal balance chart disaggregates monthly heat gains and losses attributed to building components and heat transfer mechanisms (negative values denote heat loss, positive values denote heat gain, in kWh). The component representing heat transfer via internal natural ventilation[10] (highlighted in purple) reflects the thermal impact attributable to the solar chimney-driven airflow. A separate chart illustrates the total fresh air supply, quantified in air ACH, accounting for contributions from mechanical ventilation, natural ventilation (including chimney effect), and background infiltration. Fig. 8 presents these two charts, comparing thermal balance (via natural ventilation) and total fresh air rates for the building under the combined strategy (all floors included), with and without the solar chimney, over the six warm months. Comparison between the two configurations reveals that incorporating the solar chimney enhances heat removal via natural ventilation during four of the six months (April, May, June, and September), reducing the building's net heat gain by an average of 707 kWh during these months compared to the baseline without the chimney. Conversely, during the two hottest months (July and August), the increased ventilation from the chimney results in a slightly higher net heat gain, averaging 307 kWh more than the baseline. Overall, the solar chimney improves the building's thermal balance through enhanced ventilation during most (4.6) warm months. Crucially, the solar chimney substantially increases the building air exchange rate, providing an average of 9.9ACH compared to the configuration without the chimney over six months. Table 3 provides a quantitative breakdown of the monthly differences in thermal balance (due to natural ventilation) and total fresh air rates between the scenarios with and without the solar chimney.

• Impact of the thatched roof on thermal balance and air exchange

This section evaluates the thermal contribution of the thatched roof, focusing on its influence on heat exchange via both natural ventilation and direct conduction through the roof assembly (exterior roof[11]), and its effect on overall fresh air rates. A comparative analysis is performed against a conventional tile roof, chosen as a baseline due to its prevalence in contemporary construction within the Babol region. In the thermal balance charts (Fig. 9), the contributions of internal natural ventilation (purple) and heat transfer through the exterior roof (brown) are specifically examined. Fig. 9 displays the thermal balance components (natural ventilation and roof conduction) and total fresh air rates for the building operating under the combined HVAC strategy (all floors), comparing the performance of the thatched roof against the tile roof over the six warm months. The analysis indicates that the thatched roof configuration facilitates slightly greater heat rejection via natural ventilation, averaging 38.4kWh more per month compared to the tile roof scenario. More significantly, the thatched roof demonstrates substantially lower heat absorption through direct conduction; over six months, it absorbs 3613 kWh less heat compared to the tile roof. The difference in the overall building air change rate between the two roof types was found to be negligible. Table 4 presents the quantified monthly differences in thermal balance attributable to natural ventilation and exterior roof conduction when comparing the thatched roof versus the tile roof.

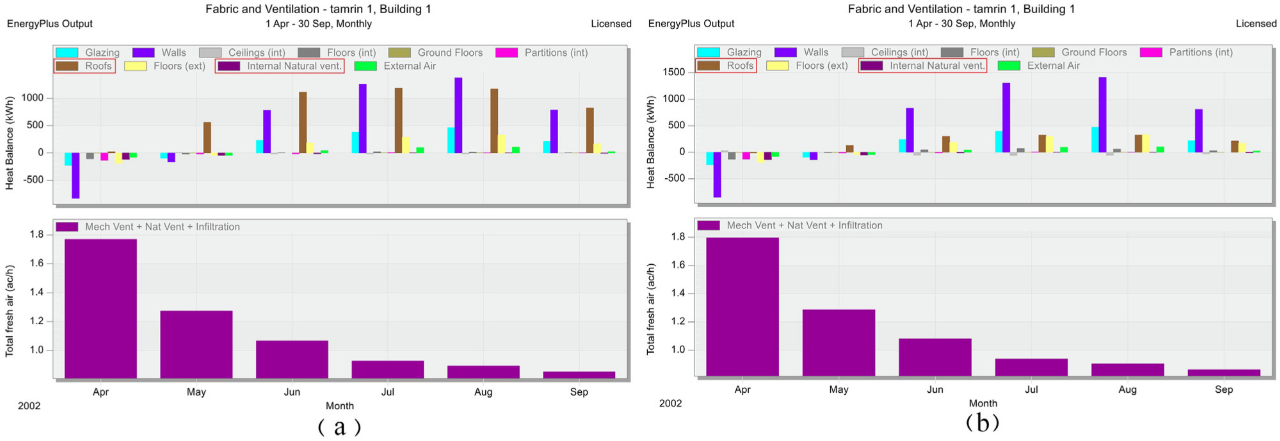
• CFD analysis: solar chimney influence on natural ventilation patterns

To investigate the detailed airflow dynamics induced by the solar chimney, CFD simulation was conducted focusing on the second floor of the building. The simulation period represented conditions typical of early morning hours



(a) (b)

Fig. 8. Graphical comparison of thermal performance, (a) With solar chimney vs, (b) Without solar chimney. Source: Authors.



(a) (b)

Fig. 9. graphical comparison of roof performance , a) Tile roof vs, b) Thatched roof. Source: Authors.

Table 3. Difference in building thermal balance via natural ventilation and total fresh air difference, associated with the presence or absence of solar chimney ventilation. Source: Authors.

Indicator type	Specification of Conditions	Month					
		Apr	May	Jun	Jul	Aug	Sep
Heat transfer (kWh)	Heat gain/loss via solar chimney ventilation	-415	-338	-64	119	253	-70
	Heat gain/loss without solar chimney ventilation	-116	-44	-13	1	0.7	-7
	Difference in heat gain/loss with vs. without solar chimney	-299	-294	-51	118	252	-63
Air change rate (ACH)	Total air changes with solar chimney	4.6	3.2	2.4	1.9	1.8	2.1
	Total air changes without solar chimney	1.7	1.2	0.9	0.8	0.7	0.8
	Difference in air change rate with vs. without solar chimney	2.9	2	1.5	1.1	1.1	1.3

Table 4. Quantified impact of roof type on the difference in building thermal balance via natural ventilation and via the external roof. Source:Authors.

Indicator type	Specification of Conditions	Month					
		Apr	May	Jun	Jul	Aug	Sep
Heat transfer (kWh)	Heat gain/loss via ventilation with thatched roof	-137	-53	-14	-0.9	-0.8	-11
	Heat gain/loss via ventilation with tile roof	-116	-44	-13	1	0.7	-7
	Difference in heat gain/loss via ventilation thatched vs. tile roof	-21	-9	-1	-1.9	-1.5	-4
Roof heat transfer (kWh)	Heat gain/loss through thatched roof	-15	126	296	323	325	211
	Heat gain/loss through tile roof	24	561	1113	1184	174	823
	Difference in heat gain/loss tile roof vs. thatched roof	39	435	817	861	849	612

(3AM) during a specific period in May (4th-10th). The computational domain was discretized using a structured mesh[12] composed of uniform cubic cells with a base dimension of 20cm and a refinement tolerance[13] of 5cm. For the second-floor domain, this resulted in a total cell count of 115,444, with a maximum-to-minimum cell edge length ratio of 9.600. Within the refined zone representing the solar chimney itself, the mesh comprised 15,876 cells with a maximum-to-minimum edge length ratio of 2.901, indicating appropriate mesh quality for resolving the flow features. The simulation employed the standard k-ε turbulence model[14] to account for turbulent flow characteristics, utilizing a hybrid[15] numerical differencing scheme. Convergence was achieved after 10,000 iterations. Fig. 10 visually presents key outputs from the CFD simulation. The results clearly demonstrate that airflow exiting the solar chimney vents effectively assists the natural ventilation process on the second floor, promoting a relatively uniform distribution of fresh air throughout the space. Simulated indoor air temperatures remain comfortably within the 20-22°C range, conducive to thermal comfort. The analysis reveals a condition of positive pressure within the space, ensuring that the volume of incoming fresh air exceeds the volume of outgoing air, thereby guaranteeing effective ventilation exchange. The 'age of air' metric, indicating the average time air resides within the space, reached a maximum of approximately 300 seconds. This suggests a complete turnover of indoor air roughly every 3 to 4 minutes, contributing to the maintenance of good indoor air quality. Collectively, these conditions foster a favorable thermal equilibrium on the second floor. Additionally, the thermal performance of the solar chimney itself was analyzed via CFD across the warmer months (April to September) at the 3 AM time point. This analysis revealed average air temperatures within the chimney cavity to be approximately 18°C (Apr), 21°C (May), 24°C (Jun), 26°C (Jul), 27°C (Aug), and 23°C (Sep). The lowest temperatures were observed in April, while the peak occurred in August, reflecting the influence of variations in incident solar radiation, solar angles, and ambient outdoor temperatures during these months. Fig. 11 provides visualizations of the simulated air temperature distribution within the solar chimney across these months.

• CFD analysis: thatched roof influence on natural ventilation patterns

To examine the airflow characteristics within the attic space directly beneath the thatched roof, a separate CFD simulation was performed. This simulation mirrored the setup used for the second-floor analysis, focusing on the same representative period in May (4th-10th) at 3 AM. Meshing parameters, the turbulence model, iteration count, and other numerical settings were kept consistent. The computational mesh for the attic volume consisted of 49,938 cells, with a maximum-to-minimum cell edge length ratio of 8.699, confirming adequate mesh resolution for the analysis. Fig. 12 presents the key outputs from this CFD simulation focused on the attic space. The results illustrate that airflow permeates effectively through or around the thatched roof assembly, distributing relatively uniformly within the attic volume and facilitating natural ventilation of this buffer space. Simulated air temperatures within the attic generally remain within the 20-23°C range, close to the comfort zone, indicating the roof's effectiveness in moderating temperature extremes. Similar to the floor below, a condition of positive pressure is observed, indicating a net inflow of fresh air and efficient ventilation exchange. The maximum age of air within the attic is again around 300 seconds, implying rapid air turnover (every 3-4minutes) and contributing to maintaining air quality within this space. These findings suggest the thatched roof contributes positively to the overall thermal balance of the building by effectively ventilating the attic space.

Conclusion

Within the temperate and humid climate characterizing Babol, indigenous architectural elements, and practices – including optimized east-west building orientation, the incorporation of ventilated crawl spaces and raised floor platforms, strategically sized and placed window openings, the use of pitched roofs, the inclusion of semi-open transitional spaces like verandas and terraces, and the predominant use of natural building materials – exert a significant positive influence on natural ventilation effectiveness and occupant thermal comfort. When integrated with passive ventilation strategies, these

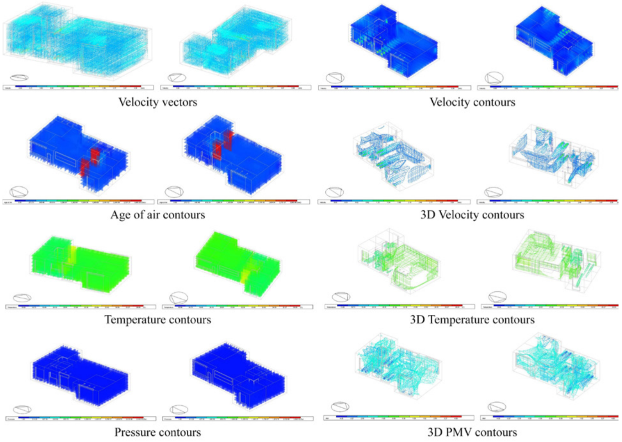


Fig. 10. CFD simulation results visualizing solar chimney impact on second floor ventilation. Source: Authors.

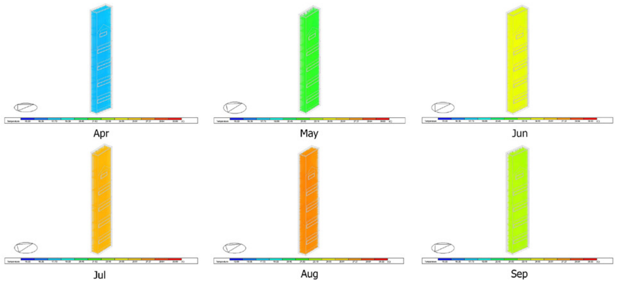


Fig. 11. CFD Simulation results showing solar chimney air temperature distribution (cross-section) for spring.summer months. Source: Authors.

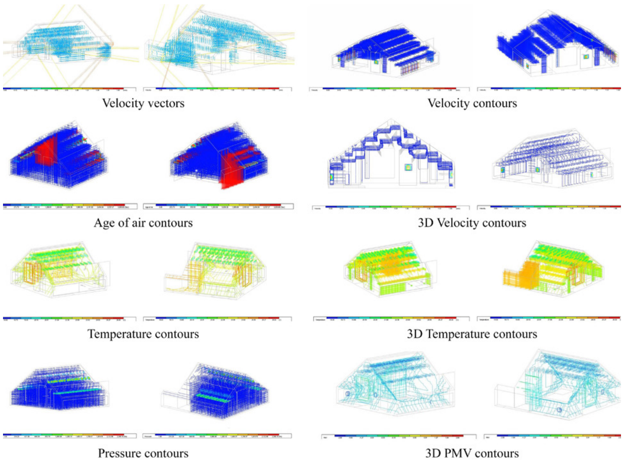


Fig. 12. CFD simulation results visualizing thatched roof impact on attic space ventilation. Source: Authors.

vernacular features contribute substantially to improving the building's thermal equilibrium during warmer periods, consequently reducing the dependence on mechanical conditioning systems and lowering operational energy consumption. This study specifically demonstrates that passive systems like solar chimneys and thatched roofs actively enhance this thermal balance. The solar chimney, operating primarily during nighttime hours (8PM - 8 AM), was found to improve thermal balance by increasing heat rejection via ventilation during four out of the six evaluated warm months (Apr, May, Jun, Sep), reducing net heat gain by an average of 707 kWh during these months compared to a baseline without the chimney. While it led to a minor increase in heat gain during the two peak summer months (Jul, and Aug), its overall contribution across the six months resulted in an average net reduction in heat gain attributable to ventilation by approximately 400 kWh. Critically, the solar chimney significantly boosted the overall building air exchange rate by an average of 9.9ACH throughout the period. Similarly, the thatched roof demonstrated consistent thermal benefits throughout the spring and summer. Operating continuously, it facilitated slightly enhanced heat rejection through natural ventilation pathways (average 38.4kWh.month more than a tile roof) and, more importantly, dramatically reduced conductive heat gain through the roof assembly itself, absorbing 3613 kWh less heat over the six months compared to the tile roof baseline. The core finding of this research lies in the synergistic effect of combining these two systems. The integrated application of the solar chimney (nighttime operation) and the thatched roof (continuous operation) yields a substantial improvement in the building's thermal balance during the spring and summer months. Compared to a conventional configuration with a tile roof and no solar chimney, this combined strategy results in an average reduction of 438.4kWh in heat gain managed via natural ventilation, elevates the average air change rate by 9.9ACH and decreases direct heat absorption through the building envelope by 3613 kWh. These results underscore the tangible benefits of integrating solar chimneys and thatched roofs for enhancing energy performance, improving thermal regulation, and promoting better indoor air quality in relevant climates. While this study focused on a single case study, the building typology and climatic context are representative of common residential construction in the temperate and humid regions of northern Iran, particularly Babol. Therefore, the findings possess qualitative generalizability to similar scenarios and offer a valuable foundation for future research and climate-responsive design practices in the region. It is recommended, however, that subsequent investigations explore a broader range of case studies and parametrically analyze variables such as solar chimney dimensions (height, width), thatched roof characteristics (material type, thickness, slope), overall building geometry and massing, material selection, and orientation effects relative to solar paths and wind patterns. Such studies would enable the refinement of the findings and facilitate the development of optimized design guidelines for integrating these passive strategies effectively.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Endnotes

1. Computational Fluid Dynamics
2. A low-height space between the ground and the ground floor, for natural ventilation.
3. An elevated floor structure raising the main living level above the ground, primarily for moisture protection.
4. A single residential unit distributed over three floors.
5. Air Changes per Hour
6. Heating, Ventilation, and Air Conditioning
7. Coefficient of Performance
8. Predicted Mean Vote
9. Predicted Percentage Dissatisfied
10. Heat transfer component associated with Nat Vent
11. Heat transfer component through the roof assembly
12. Computational grid for CFD
13. Mesh generation parameter
14. E.g., k-ε model used in CFD
15. Numerical schemes used in CFD solver

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