Integrated Ventilation Strategies for Energy Efficiency Enhancement in Buildings

A Case Study of a Hot and Arid Climate Region

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ABSTRACT

This study introduces a system and method designed to enhance the ventilation within buildings. Buildings in hot and arid climates, such as Rajasthan, India, frequently experience poor thermal comfort due to the high sun radiation and limited airflow. While prior research has assessed the passive cooling capability of classical components, like jaalis and perforated facades, these assessments were essentially static and relied on empirical or simulation-based analysis. The current work describes a revolutionary real-time adaptive system that uses Computational Fluid Dynamics (CFD) to simulate and optimize the ventilation by integrating environmental sensors and architectural data. Unlike previous studies, this system dynamically identifies the appropriate sizes, shapes, and placements of apertures, allowing for user-assisted or automatic modifications based on real-time climate conditions. The main innovation of the present study is the transformation of classic passive techniques into a responsive, data-driven design framework. The result is a scalable framework for integrating passive cooling strategies into contemporary design, improving the energy efficiency and thermal comfort, given the growing demand for such innovative solutions that enhance the natural ventilation and thermal regulation in modern structures.

Keywords-ventilation; environmental; energy efficiency; perforated; facades

I. INTRODUCTION

This study highlights the exciting intersection of architectural design and environmental engineering. Specifically, it introduces a system and method designed to enhance the ventilation in buildings. This investigation mainly focuses on a ventilation system that includes a processor and a memory, which is connected to the processor and holds instructions that the latter can execute. The processor is designed to gather real-time environmental data from a range of sensors, tracking factors, like temperature, humidity, wind speed, and direction, as well as solar radiation. It also accesses architectural data, such as the building geometry, material properties, and details about one or more apertures and perforated facades, either from memory or external sources. By using CFD models, the processor simulates the airflow patterns and heat distribution based on both sets of data. This process enables determining the best sizes, shapes, and placements for the apertures and facades, ensuring an optimal airflow and thermal comfort within the building. Additionally, it can dynamically adjust the architectural elements, either automatically or with user input, to change the sizes of the apertures or facades in response to real-time environmental shifts.

The results of these optimizations, which include the proposed configurations for the apertures and facades, are sent to a computing device for implementation. The apertures can be crafted from materials, like sandstone, clay, or their combinations. The processor employs CFD models to visualize the airflow velocity vectors and temperature gradients throughout the building, identifying areas where the airflow stagnates or excess heat accumulates, while it forecasts the impacts of aperture size, shape, and position on the ventilation and comfort. It also stores essential data, including the geometry and material properties of multiple buildings, wall thickness, thermal conductivity, and predefined design thresholds for target indoor temperature ranges and airflow velocities, along with historical environmental data. In another embodiment, the ventilation method involves a processor receiving real-time environmental data from sensors, accessing the architectural details stored in a memory or imported from outside sources, running simulations of airflow patterns using the gathered data, and determining the best configuration for the sizes, shapes, and placements of the apertures and facades [1, 2]. This is achieved while simultaneously adjusting the architectural elements in real time in response to the environmental changes and delivering the resulting optimization recommendations.

Traditional architectural elements, such as jaalis, courtyards, and perforated facades have long been used in Rajasthan to regulate the airflow and reduce the heat gain. There is still a significant gap in understanding the combined effects of these vernacular strategies with modern computational tools for real-time ventilation optimization. Most previous research has either documented traditional procedures or separately modeled ventilation using CFD, but few studies have proposed a hybrid system that dynamically adjusts to the environmental inputs while maintaining a traditional design. The present study bridges this gap by creating a CFD-based intelligent ventilation system inspired by traditional architecture, specifically for hot and arid conditions.

The main goal of this research is to create and verify a hybrid ventilation system that uses real-time environmental sensing and computational airflow modeling to optimize the aperture configurations. Secondary objectives include comparing its performance to typical passive systems and examining the thermal comfort improvements in historic building types, including a small haveli in Bikaner as a case study. The detailed description in this paper outlines specific examples of architectural adjustments, which can lead to enhanced energy efficiency, improved occupant comfort, and reduced operational costs.

The optimal performance is essential for modern buildings, and integrating innovative design principles can significantly enhance their sustainability. By employing advanced materials and technologies, the system not only meets the current energy standards, but also sets a precedent for future developments in architectural design [3]. This forward-thinking approach encourages architects and builders to prioritize eco-friendly solutions while enhancing the overall experience for occupants. As the industry evolves, the commitment to sustainability and efficiency will undoubtedly shape the future landscape of urban development.

A. Literature Review

The literature review focuses on spotlighting data from traditional ventilation strategies in hot and arid regions, perforated facades, conventional ventilation approaches, and system design and components that include sensor network, process and memory unit [4]. It further covers the simulation optimization interface using CFD [5].

1) Traditional Ventilation Strategies in Hot and Arid Regions

In warm regions, like Rajasthan, the building design has gradually adopted innovative techniques to handle the harsh environmental conditions. Traditional architecture in these regions makes great use of the natural cooling strategies, helping to lessen the need for mechanical systems. Common features, like cozy internal courtyards, sturdy thick walls, raised plinths, and well-placed openings work together to improve airflow, maintain comfortable temperatures, and encourage cooling breezes. These designs are not just about looks; they are rooted in a robust understanding of the local climate. For instance, courtyards play a vital role as thermal sinks, promoting the vertical air movement, especially in the evenings when the temperature starts to cool down. Likewise, narrow alleys and staggered street layouts effectively channel the wind, boosting the cross-ventilation among buildings [6].

Jalli systems ensure privacy, and, most importantly, maintain the airflow within the building. The design and open spaces of the jaali influence the air movement, creating a cooling effect by increasing the surface turbulence and pressure differences. Perforated facades act as little climate controllers, minimizing the solar heat while still allowing for fresh air [7]. This thoughtful design philosophy aligns perfectly with the principles of comfort and energy efficiency, making it an inspiring model for today’s building technologies [8]. Modern buildings in arid regions often turn to mechanical ventilation or HVAC systems to ensure indoor comfort, which can lead to higher energy use and costs. Unfortunately, these systems tend to overlook the nuanced advantages of adaptable architectural features, such as orientation, window sizes, and material response to the temperature changes [9]. Moreover, many contemporary designs lean towards sealed structures and cookie-cutter layouts, missing out on the climate adaptability that traditional designs offer. Modern HVAC systems may unintentionally cause overcooling or insufficient ventilation without being responsive to the environmental changes, especially during these transitional weather periods [10, 11].

2) System Design and Components

The current study proposes an innovative, integrated ventilation system aimed at intelligently enhancing the indoor airflow and occupant comfort. At its core, the system features three essential components: a network of environmental sensors, a central processor with memory storage, and a dynamic user-friendly interface [12].

- Sensor Network: This system employs various sensors to monitor environmental factors, like temperature, humidity, wind direction, solar radiation, and indoor air quality [13]. By placing these sensors both inside and outside the building, a comprehensive overview of the environmental conditions is obtained. The detailed real-time data empower the system to adjust to the shifting weather patterns and user preferences [14].
- Processor and Memory Unit: A central processor with storage collects, stores, and analyzes the sensor data. It also engages with digital models of the building, including window placements, wall thicknesses, materials, and types of facades. The stored information may consist of

architectural inputs sourced from digital Building Information Modeling (BIM) systems or manual entries for retrofitted buildings.

- Simulation and Optimization Interface: Using advanced CFD algorithms, the processor simulates the airflow and temperature changes both inside and around the building [15]. From these simulations, it identifies the best locations, sizes, and orientations for ventilation openings and perforated features. The recommendations can then be reviewed and implemented automatically (via actuators) or manually from an easy-to-use user interface. The network architecture for the proposed building ventilation system shows how various components interact to manage the airflow based on environmental and architectural data [16, 17].

Recent studies have highlighted the importance of combining conventional design principles with current simulation methods to improve the climate responsiveness in dry settings. Heritage-based courtyard house typologies can be adjusted using the current technologies to improve the thermal comfort in arid regions. Similarly, differences in the courtyard geometry affect the microclimatic performance, emphasizing the courtyard's importance as a passive cooling method in hot, dry regions.

II. METHODOLOGY

This research combines the knowledge of traditional architecture with modern computational techniques to enhance the natural ventilation in buildings, especially in hot and arid regions, like Rajasthan [18]. Authors in [19] identify the challenges that conventional designs face in promoting the effective airflow and thermal comfort. The study features an innovative system that utilizes real-time environmental sensors alongside historical architectural data to simulate the airflow patterns using CFD. Accurate building models were developed to incorporate and emphasize vernacular architectural elements, such as Jaalis and perforated facades [20, 21]. These models are analyzed through CFD simulations to assess the airflow and heat distribution. Next, an optimization algorithm fine-tunes the aperture sizes and positions to boost the ventilation performance. The results are validated using data from traditional Rajasthani buildings, which are synthesized to determine the optimal design configurations [14, 22].

A. *Application of CFD Modeling*

A CFD model was utilized to ensure accurate ventilation simulations and optimizations. CFD models mimic the airflow behavior in both indoor and outdoor spaces, offering a detailed overview of the air flow through complex architectural designs.

1) Model Setup and Parameters

The CFD analysis starts with input data, including building dimensions, window placements, and material properties. Environmental factors, like wind speed, solar exposure, and temperature differences, are set as boundary conditions. The model grid is detailed around key architectural elements, such as Jaalis, courtyards, and window openings [23, 24].

2) Simulation Scenarios

Multiple simulations were done under different climate scenarios—morning, afternoon, and evening temperatures; variations in wind speed; and seasonal changes. Each scenario produces unique airflow and temperature distributions, to find the best passive ventilation practices tailored to the local climate conditions [25].

TABLE I. DEVELOPMENT METHODOLOGY

Step	Title	Description
1	Problem identification	Defining the core research problem: Inefficient natural ventilation in modern buildings in hot climates.
2	System integration	Integrating the patented system that uses sensors, memory, and processors for real-time airflow optimization.
3	Data collection	Collecting real-time environmental data (temperature, humidity, wind speed) and architectural design parameters.
4	Model setup	Developing 3D models of buildings, including traditional elements (jaalis, perforated facades).
5	CFD simulation	Simulating the airflow and heat transfer using CFD techniques to visualize and quantify he ventilation performance.
6	Optimization algorithm	Applying the optimization logic to dynamically adjust the sizes, positions, and orientations of apertures.
7	Validation	Comparing the simulation results with traditional architectural case studies from Rajasthan.
8	Understanding results	Deriving optimal configurations and documenting the impact on ventilation and thermal comfort.
9	Discussion and conclusion.	Linking the simulation results to traditional architectural principles. Emphasizing the benefits of integration.

3) Output and Validation

The output provides visual insights into the pressure zones, airflow dynamics, and temperature changes. These results are compared with real-world data (like measurements from traditional havelis or similar structures) to ensure the model's accuracy. The findings shape the design recommendations for practical applications. The block diagram in Figure1 illustrates a processor-based system comprising core components, like memory, interfaces, sensors, and a processing engine with multiple specialized modules [26]. This study was conducted in 2024, focusing on traditional courtyard houses in Bikaner, Rajasthan, during the region's peak summer months. Environmental data, such as temperature, humidity, solar radiation, and wind speed were collected using calibrated sensors (DHT22, anemometer, pyranometer) installed on-site. Architectural measurements were taken from a representative small haveli, including the wall composition, aperture dimensions, and courtyard geometry. Computational simulations were carried out using ANSYS Fluent 2024 R1. A 3D model of the house was created in AutoCAD, meshing was performed in ANSYS with refinement at openings, and solved under steady-state conditions. The k-ε turbulence model and solar load radiation model were used for analysis. Both traditional (static) and proposed (dynamic) ventilation scenarios were simulated.

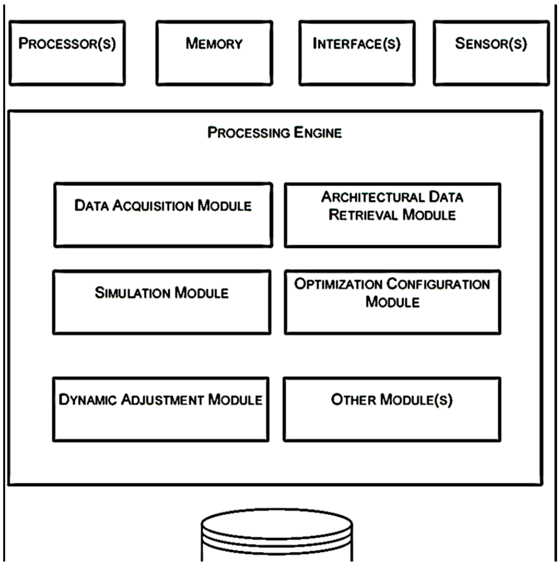


Fig. 1. Block diagram of a processor used in proposed system.

III. CASE STUDY

A. *Vernacular Buildings in Rajasthan*

To demonstrate the effectiveness of the proposed system, a comparative analysis of traditional residential buildings in Rajasthan, particularly havelis that incorporate climate-responsive features, such as thick walls, shaded courtyards, and exquisite jaali work was conducted [27]. Figure 2 presents a traditional Haveli layout with a central courtyard and jaali openings, overlaid with simulated airflow directions. The schematic architectural sketch in Figure 2 depicts the airflow through a traditional Bikaneri haveli oriented from east (front) to west (back). It shows the central courtyard, stone jaalis, overhanging jharokhas, and airflow patterns. The integration of these architectural elements not only enhances the aesthetic appeal, but also plays a crucial role in passive cooling and ventilation, contributing to the overall sustainability of the structure in the arid climate of Bikaner [28, 29]. Figure 3 provides a graphical representation of the temperature range in different months in the Bikaner region. Figure 4 displays the climatic parameters and sun shading chart from December 2021 to June 2021, while Figure 5 portrays the parameters and sun chart for the period of June 2021- December 2021.

B. *Building Selection Criteria*

The building chosen for the present case study is historic residences located in hot and arid regions of Bikaner and Jaisalmer. These structures have preserved their original construction features, with sandstone facades, lime-plastered interiors, and lattice screen apertures [30]. The floor plans of these buildings incorporate internal courtyards and naturally ventilated rooms [31, 32].

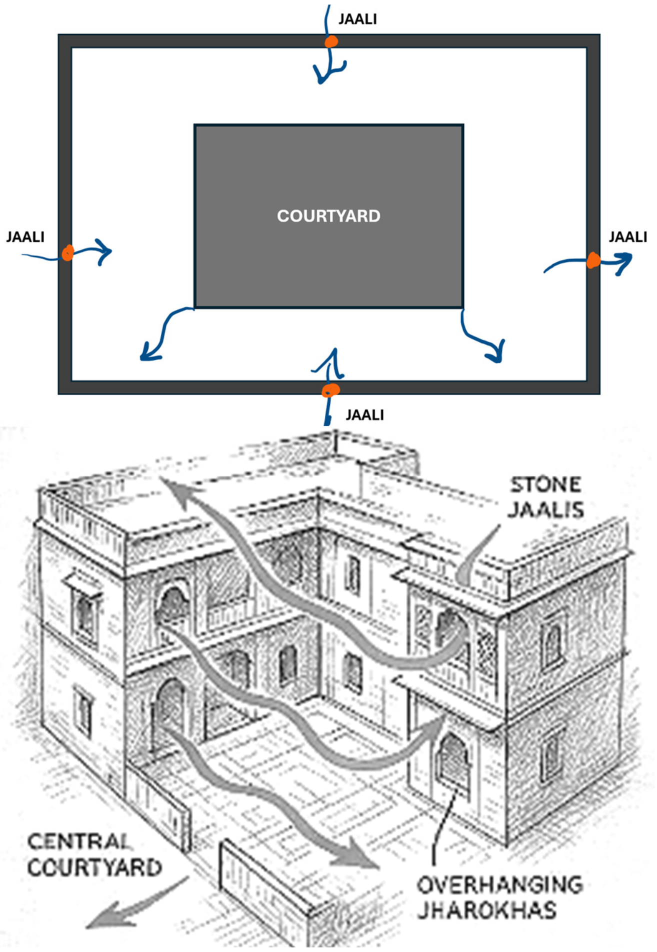
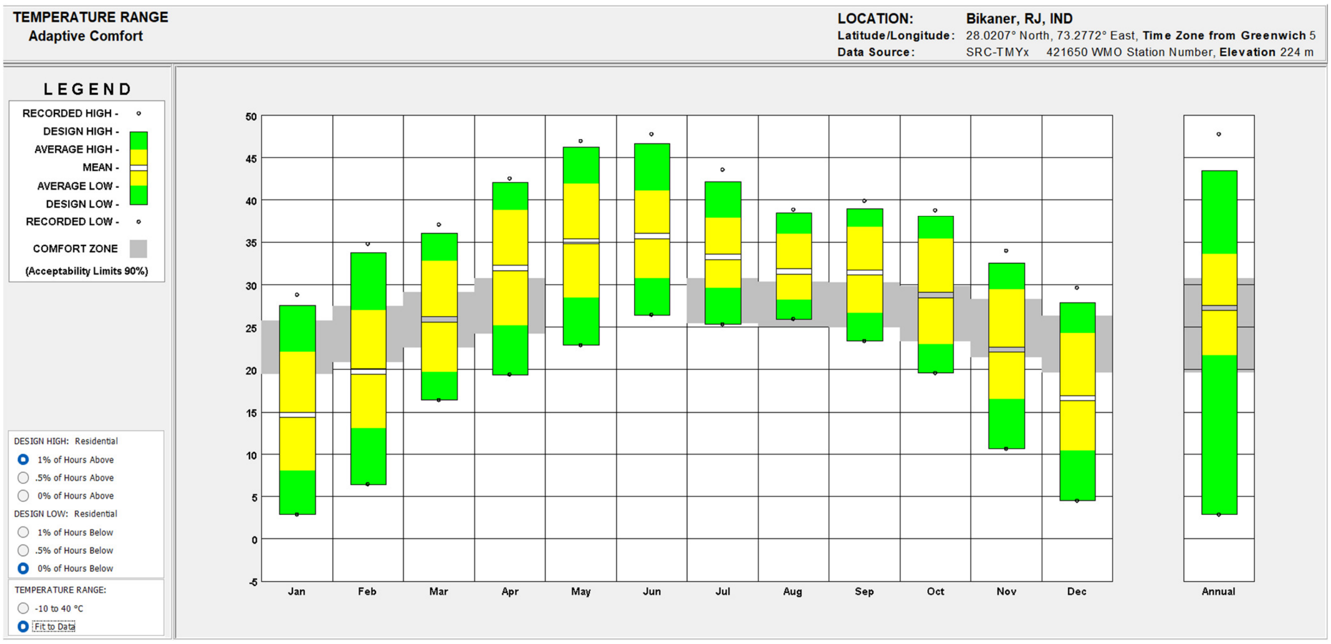


Fig. 2. Schematic diagrams of a traditional haveli with CFD-based Airflow Simulation.

IV. SIMULATION RESULTS

CFD simulations were carried out for the selected traditional designs in their original form, with the integration of the proposed intelligent system. The airflow patterns are carefully analyzed to observe the differences in ventilation efficiency, thermal comfort, and indoor air quality [33, 34].

Figure 6 shows a simplified CFD simulation having airflow and temperature distribution across a section of a traditional courtyard house in Bikaner. The arrows represent the airflow vectors, and the color map indicates the temperature gradients, with cooler areas being near openings and warmer air rising up due to the natural convection, demonstrating the effectiveness of passive ventilation. To simulate and illustrate the airflow and heat distribution in a simplified 2D part of a conventional courtyard house, a CFD figure was created using Python, NumPy, and Matplotlib. Airflow vectors and temperature gradients based on sinusoidal patterns were represented by building a computational grid and using mathematical functions.



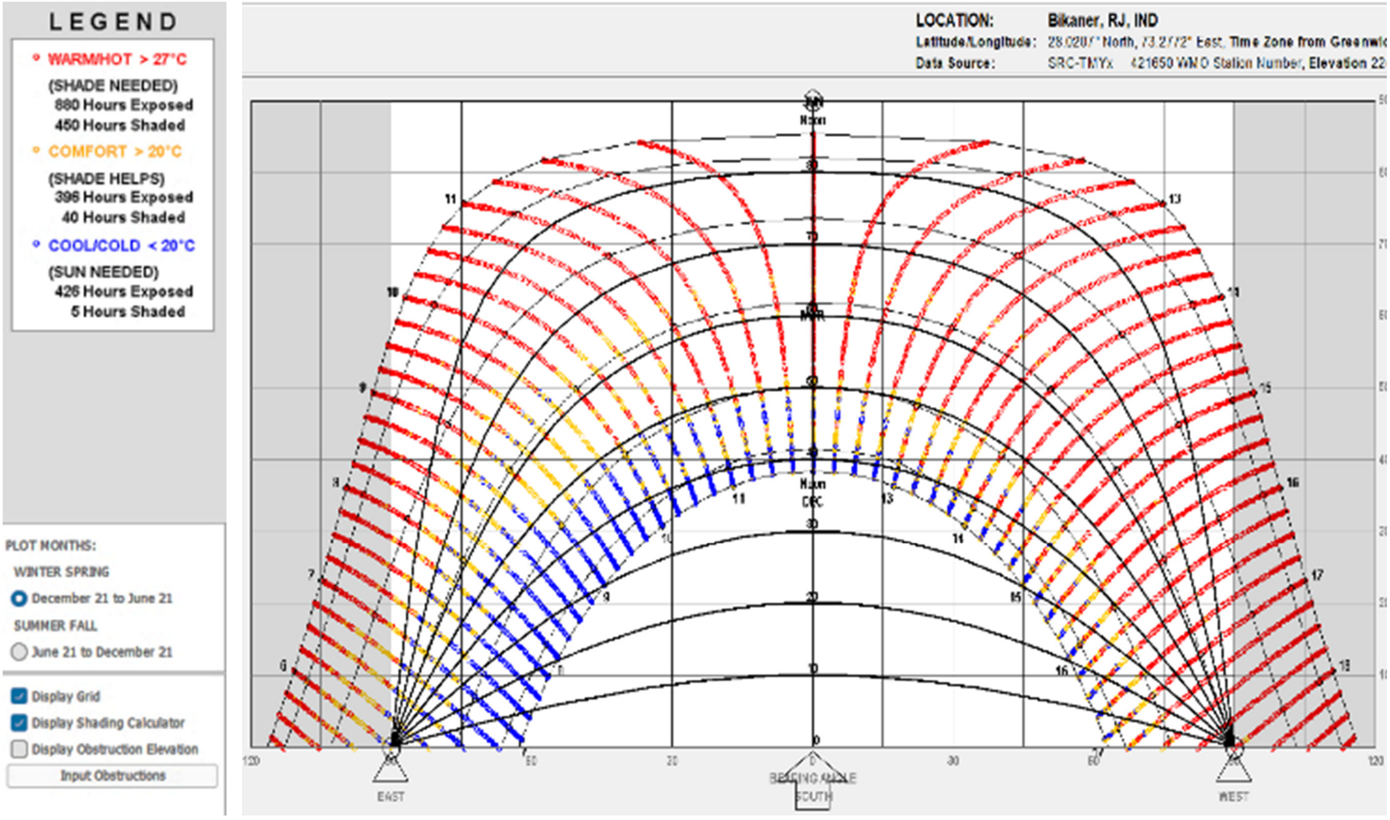
TEMPERATURE RANGE
Adaptive Comfort

LOCATION: **Bikaner, RJ, IND**
Latitude/Longitude: 28.0207° North, 73.2772° East, **Time Zone from Greenwich** 5
Data Source: SRC-TMYx 421650 WMO Station Number, **Elevation** 224 m

DESIGN HIGH: Residential
● 1% of Hours Above
○ .5% of Hours Above
○ 0% of Hours Above
DESIGN LOW: Residential
○ 1% of Hours Below
○ .5% of Hours Below
● 0% of Hours Below

TEMPERATURE RANGE:
○ -10 to 40 °C
● Fit to Data

Fig. 3. Graphical representation of the temperature range in different months in the selected region of study.



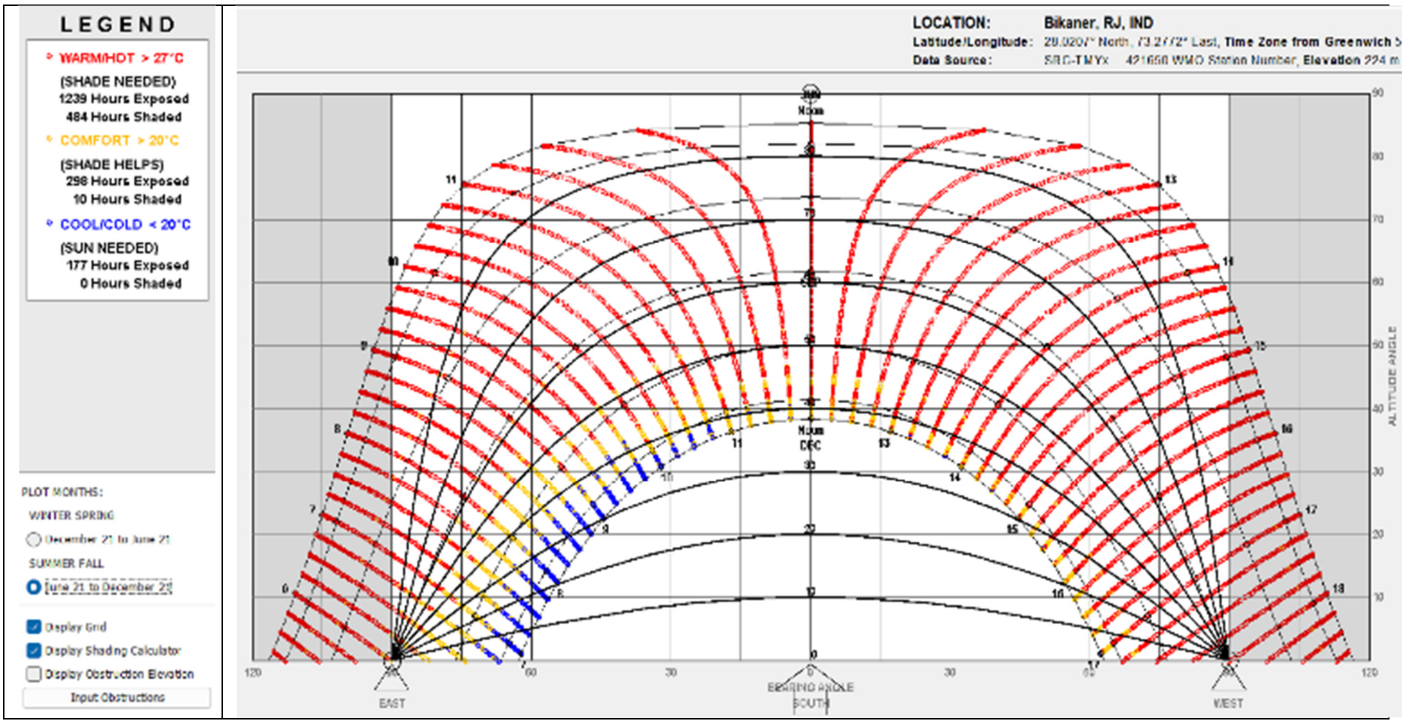
LOCATION: **Bikaner, RJ, IND**
Latitude/Longitude: 28.0207° North, 73.2772° East, **Time Zone from Greenwic**
Data Source: SRC-TMYx 421650 WMO Station Number, **Elevation 22**

• WARM/HOT > 27°C
(SHADE NEEDED)
880 Hours Exposed
450 Hours Shaded
• COMFORT > 20°C
(SHADE HELPS)
396 Hours Exposed
40 Hours Shaded
• COOL/COLD < 20°C
(SUN NEEDED)
426 Hours Exposed
5 Hours Shaded

PLOT MONTHS:
WINTER SPRING
● December 21 to June 21
SUMMER FALL
○ June 21 to December 21

☑ Display Grid
☑ Display Shading Calculator
☐ Display Obstruction Elevation

Fig. 4. Graphical representation of climatic parameters and sun shading chart from December 2021 to June 2021.



LEGEND

- WARM/HOT > 27°C
  (SHADE NEEDED)
  1239 Hours Exposed
  484 Hours Shaded
- COMFORT > 20°C
  (SHADE HELPS)
  298 Hours Exposed
  10 Hours Shaded
- COOL/COLD < 20°C
  (SUN NEEDED)
  177 Hours Exposed
  0 Hours Shaded

PLOT MONTHS:
WINTER SPRING
○ December 21 to June 21
SUMMER FALL
● June 21 to December 21

☑ Display Grid
☑ Display Shading Calculator
☐ Display Obstruction Elevation

LOCATION: Bikaner, RJ, IND
Latitude/Longitude: 28.0207° North, 73.2772° East, Time Zone from Greenwich
Data Source: SRC-TMYx 421650 WMO Station Number, Elevation 224 m

Fig. 5. Graphical representation of climatic parameters, sun shading chart (JUN 21-DEC 21).

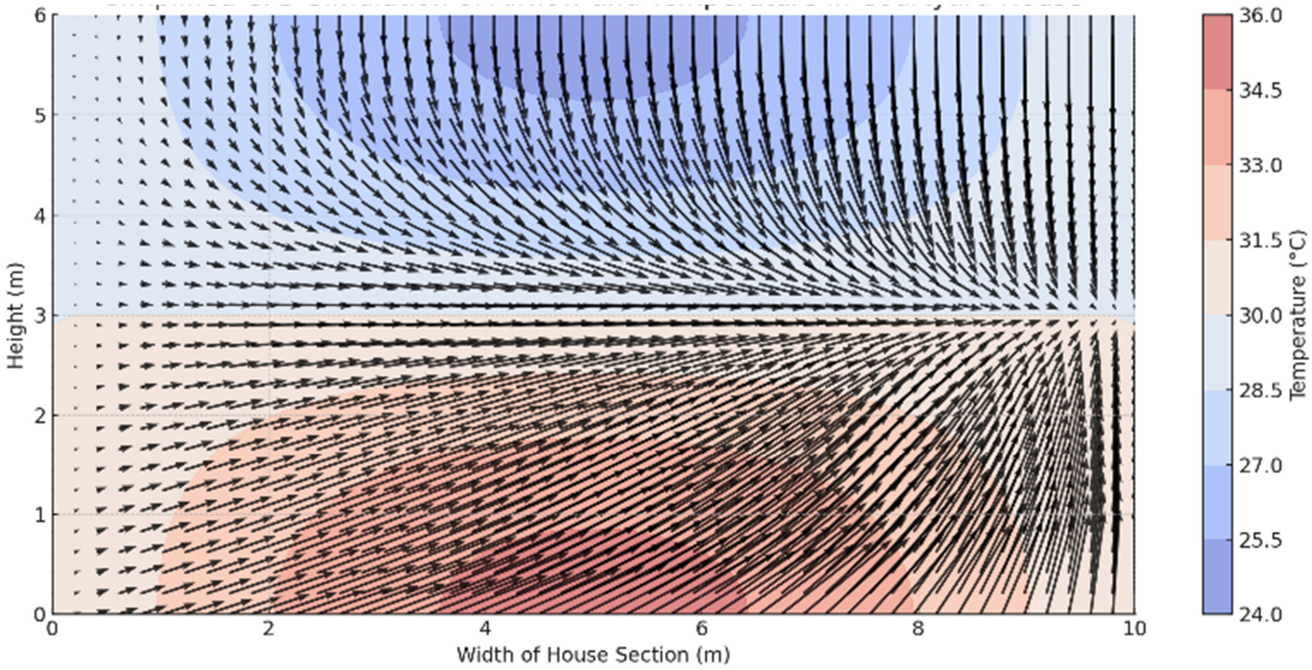


Fig. 6. Simplified CDF simulation of airflow and temperature in courtyard house.

The vector fields and temperature contours were shown using Matplotlib's quiver and contourf functions, respectively. This method successfully demonstrates the natural ventilation principles and thermal behavior for conceptual study, despite not being a full-scale CFD solver. The results from the simplified CFD simulation of the traditional courtyard house section are summarized as:

1. Temperature Distribution:

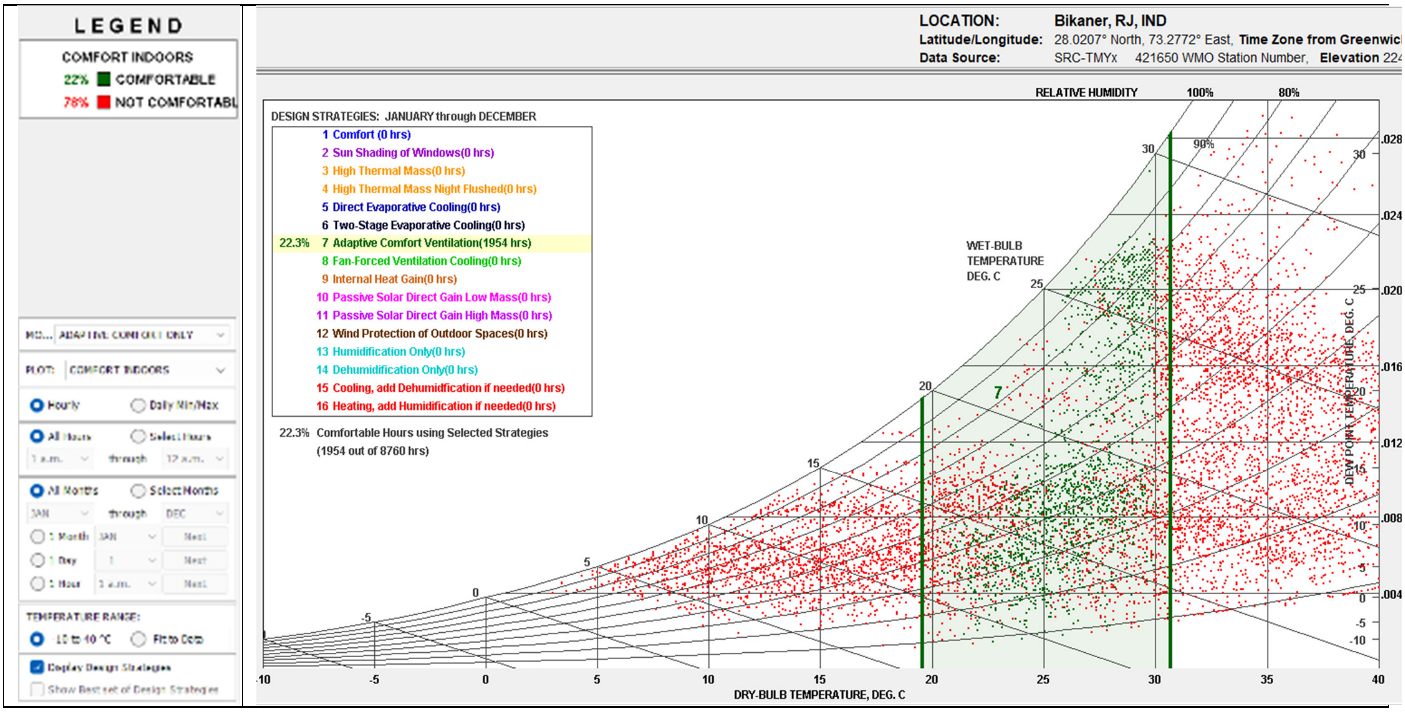
- Maximum Temperature: 34.99 °C.
- Minimum Temperature: 25.01 °C.
- Average Temperature: 30.00 °C.

2. Airflow Speed:

- Maximum Airflow Velocity: 1.00 m/s.
- Minimum Airflow Velocity: 0.00 m/s.
- Average Airflow Velocity: 0.51 m/s.

A. *Observations*

The results show that when the intelligent system is employed along with the vernacular design features, especially perforated facades and strategically oriented openings, there is a significant boost in the thermal comfort levels without relying solely on mechanical cooling [35]. The air stagnation zones are minimized, and the heat buildup is substantially reduced, as can be seen in Figure 7.



LEGEND

COMFORT INDOORS
22% 🟩 COMFORTABLE
78% 🟥 NOT COMFORTABL

MO... ADAPTIVE COMFORT ONLY
PLOT: COMFORT INDOORS
● Hourly ○ Daily Min/Max
● All Hours ○ Select Hours
1 a.m. through 12 a.m.
● All Months ○ Select Months
JAN through DEC
○ 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

LOCATION: **Bikaner, RJ, IND**
Latitude/Longitude: 28.0207° North, 73.2772° East, **Time Zone from Greenwic**
Data Source: SRC-TMYx 421650 WMO Station Number, **Elevation 224**

DESIGN STRATEGIES: JANUARY through DECEMBER
1 Comfort (0 hrs)
2 Sun Shading of Windows(0 hrs)
3 High Thermal Mass(0 hrs)
4 High Thermal Mass Night Flushed(0 hrs)
5 Direct Evaporative Cooling(0 hrs)
6 Two-Stage Evaporative Cooling(0 hrs)
22.3% 7 Adaptive Comfort Ventilation(1954 hrs)
8 Fan-Forced Ventilation Cooling(0 hrs)
9 Internal Heat Gain(0 hrs)
10 Passive Solar Direct Gain Low Mass(0 hrs)
11 Passive Solar Direct Gain High Mass(0 hrs)
12 Wind Protection of Outdoor Spaces(0 hrs)
13 Humidification Only(0 hrs)
14 Dehumidification Only(0 hrs)
15 Cooling, add Dehumidfication if needed(0 hrs)
16 Heating, add Humidification if needed(0 hrs)

22.3% Comfortable Hours using Selected Strategies
(1954 out of 8760 hrs)

Fig. 7. A psychometric chart of the selected region of study, following an embodiment of the present disclosure.

V. DISCUSSION

The proposed hybrid approach lets buildings adapt dynamically to both the daily and seasonal climatic variations, enhancing the energy efficiency while honoring the cultural authenticity [36].

A. *Important Findings of the Study*

The study confirms the effectiveness of combining the vernacular architecture with modern CFD-based optimization to enhance the natural ventilation. Traditional features, such as courtyards and jaalis, inherently support the airflow and thermal comfort, but their performance significantly improves when real-time environmental data are used to guide the dynamic aperture adjustments. CFD simulations showed increased indoor air velocities by 55%–70% and temperature reductions of 2°C–3°C when aperture sizes were optimized based on the wind direction and solar exposure.

B. *Implication of Findings*

The findings highlight that traditional designs, though inherently climate-responsive, are constrained by static configurations. The proposed system overcomes this by introducing adaptive control through real-time sensing and CFD modeling. The improved airflow distribution reduced the indoor temperatures, and increased the responsiveness to solar loads, demonstrating that such hybrid systems can achieve the comfort goals without compromising the architectural authenticity. This has significant implications for both the heritage conservation and new sustainable construction in hot and arid zones. Moreover, this system is modular and scalable. It can fit into the new constructions and be retrofitted into heritage buildings, enabling the preservation of architectural identity alongside modern performance standards. This innovative solution not only optimizes the energy use, but also respects the historical significance of the structures.

A dynamic optimization procedure for building ventilation is illustrated in the flowchart shown in Figure 8. The system effectively simulates the airflow using CFD, finds the best aperture combinations, and modifies the facade features based on real-time sensor data and architectural inputs.

Fig. 8. Flow diagram for dynamic ventilation optimization.

C. Parameter Sensitivity and Variability Analysis

To assess the proposed ventilation system's robustness, a sensitivity analysis was performed by changing key environmental and architectural parameters and analyzing their influence on the airflow behavior and thermal performance. Three key variables were assessed:

- Outdoor wind speed ranges from 1.5 m/s to 3.5 m/s.
- Solar Radiation Intensity (600–1000 W/m²).
- Aperture Opening Area (10%-40% of the facade).

The results revealed that the airflow patterns within the courtyard house were extremely sensitive to the aperture area and wind speed. Specifically, increasing the aperture opening from 10% to 30% resulted in a 55-70% increase in the indoor air velocity. Also, a drop of 2-3°C in the average interior air temperature was observed with the improved airflow distribution in the interior rooms.

The solar radiation had a nonlinear effect, with higher levels improving the thermal buoyancy and enhancing the stack effect but simultaneously increasing the risk of heat gain in locations lacking adequate shade or ventilation. Furthermore, the simulations revealed that the best outcomes were obtained when the apertures were dynamically modified based on the prevailing wind direction and internal temperature gradients. These experiments indicate that the system's performance is sensitive to real-time situations, highlighting the significance of responsive control methods.

D. Integration with Modern Architectural Practice

The proposed system embraces the digital integration through BIM and IoT platforms, enabling real-time responsiveness in smart buildings. Architects and engineers can incorporate the system during the design phase or use it as a retrofit tool in existing structures. Actuators can adjust the openings based on feedback loops, offering a semi-automated approach to environmental control. In contemporary architecture, such adaptive systems can effectively bridge the gap between the passive design intent and active technological implementation. This innovative approach encourages a shift toward climate-resilient, context-sensitive construction practices, especially in areas facing heat stress and resource scarcity.

The intelligent ventilation system aligns with many objectives of green building rating systems, like Green Rating for Integrated Habitat Assessment (GRIHA) and Leadership in Energy and Environmental Design (LEED). Incentivizing such integrated solutions through certification frameworks can encourage the widespread adoption, especially in regions, like Rajasthan, where the climatic challenges and cultural heritage are intertwined.

E. Strengths and Limitations

A major strength of the study lies in the practical integration of passive design logic with computational modeling, offering a scalable solution for both retrofits and new buildings. The modular system is compatible with BIM and IoT, enhancing its real-world applicability. However, the CFD analysis was conducted under simplified boundary conditions and limited physical validation. The material aging, occupant behavior, and daily usage patterns were not modeled in full detail, which could affect the real-world performance [36].

VI. CONCLUSION

This paper introduces a novel system that combines vernacular design strategies with computational intelligence to enhance the building ventilation in hot and arid climates. By simulating the airflow patterns through Computational Fluid Dynamics (CFD) models and dynamically adjusting the architectural elements, this system provides an effective alternative to energy-intensive mechanical solutions. The case study of traditional Rajasthani havelis demonstrates that this integrated approach can effectively modernize the climate-responsive design while preserving the essence of region's rich cultural heritage. Future efforts should focus on large-scale validation and integration with smart city infrastructure. It is proposed that policymakers incorporate such approaches into green building guidelines for arid zones.

Future work should also include full-scale field trials, AI-based predictive controls, and integration with renewable energy systems to further enhance the resilience and sustainability in climate-vulnerable areas. The findings of this study can be assessed through a comparative analysis of buildings without such an optimization system. Such a comparative analysis may reveal significant disparities in the energy consumption and environmental impact, underscoring the benefits of employing innovative practices.

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