OPTIMIZING MOSQUE FAÇADE DESIGN: CFD-BASED ANALYSIS OF VERNACULAR SERAMBI FOR THERMAL COMFORT

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Abstract. This paper investigates the role of vernacular architectural strategies in enhancing thermal comfort within Malaysian mosques, with a specific focus on the serambi, a semi-outdoor transitional space. Using Computational Fluid Dynamics (CFD) simulations and field measurements, the study evaluates how variations in the serambi opening-to-wall ratio (OWR) influence airflow, temperature regulation, and humidity levels in prayer halls. Case studies, including the Ara Damansara Mosque, were simulated across OWR values ranging from 10% to 90%. Results show that OWR values below 50% restrict air circulation, causing heat accumulation, while values above 80% increase solar heat gain and discomfort. The optimal range was identified between 60% and 70%, where air velocities of 1.2–1.5 m/s and indoor temperatures below 31°C were achieved, aligning with Malaysian thermal comfort standards. The findings demonstrate the continued relevance of vernacular principles for contemporary mosque design, providing an evidence-based framework for climate-responsive and sustainable architecture in tropical regions.

Keywords: *Façade design, Vernacular, Indoor Thermal Comfort, Mosques, CFD simulation*

1. Introduction

Integrating vernacular architectural elements into contemporary design represents a forward-thinking approach to balancing cultural identity, environmental performance, and technological innovation. In Malaysia's hot-humid climate, traditional architectural features evolved as adaptive systems that optimized thermal comfort through natural ventilation, daylighting, and passive shading. However, modern mosque designs often prioritize monumentality and air-conditioning, leading to increased energy demand and diminished environmental quality.

This study investigates how the serambi (Fig. 1), which is a semi-open transitional space in traditional Malay architecture can be reinterpreted within contemporary mosque façades to enhance thermal comfort. Historically, the serambi has functioned as both a climatic buffer and a social interface, mediating airflow between the exterior and interior while serving as a gathering and reflective space (Hassan, 2010; Zin et al., 2019). Its open plan, elevated structure, and shaded envelope enable cross-ventilation and thermal mass cooling, particularly suited for the tropical environment.

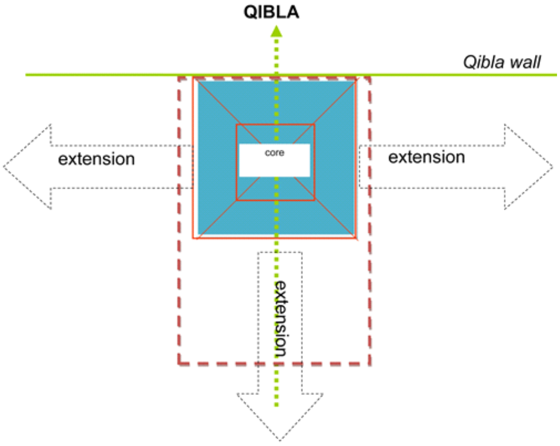

Figure 1. Serambi usually surround three parts of the vernacular mosque plan except at the Qibla direction.

By adapting these principles through Computational Fluid Dynamics (CFD) simulation, this study explores how varying opening-to-wall ratios (OWR) in serambi-inspired façades influence indoor thermal performance. The Ara Damansara Mosque, a recent example of vernacular reinterpretation in Malaysia, serves as a contextual case to demonstrate the real-world potential of serambi-based design logic in modern religious architecture.

1.1. VERNACULAR ARCHITECTURE AND THE ROLE OF SERAMBI IN ENVIRONMENTAL COMFORT

The serambi—typically a shaded, semi-open veranda located at the entrance or sides of traditional Malay houses—plays a crucial role in passive cooling and social transition. Elevated timber floors promote airflow, while deep roof overhangs and permeable wall panels provide shade and cross-ventilation (Adenan, 2013; Hassan, 2010). Empirical evidence supports its thermal performance: Rahman et al. (2020) recorded temperature reductions of 3.5°C in buildings with semi-open serambi extensions compared to enclosed counterparts, while Salleh (2021) reported a 35% decrease in cooling energy consumption due to improved ventilation through serambi openings.

These findings demonstrate that serambi elements act as climate-responsive façades, optimizing airflow while reinforcing cultural identity. As Figure 2 illustrates, varying serambi OWR values directly affect indoor airflow patterns, with balanced ratios achieving optimal natural ventilation. When reinterpreted in mosque façades, serambi logic offers a sustainable strategy that merges thermal performance, spiritual symbolism, and regional identity.

Figure 2. Openings aided by ornamentation at the serambi walls in Malaysia vernacular design buildings.

1.2. ASSESSING THE THERMAL PERFORMANCE OF VERNACULAR SERAMBI ELEMENTS IN MODERN MOSQUE DESIGN

Despite its proven climatic intelligence, the serambi's integration in modern religious architecture remains underexplored. Contemporary mosque designs in Malaysia often rely on mechanical systems to maintain comfort, neglecting vernacular strategies that once ensured naturally cooled environments (Hussin et al., 2018). By empirically testing the serambi's thermal contribution through CFD simulations and field data validation, this study demonstrates that such traditional adaptations can deliver quantifiable environmental benefits without compromising aesthetic or cultural values.

This investigation seeks to build evidence that serambi-inspired façades—through optimized OWR configurations—can enhance natural ventilation, indoor air quality, and thermal comfort, contributing to sustainable and culturally coherent mosque architecture in tropical contexts.

1.3. RESEARCH OBJECTIVE

This research aims to evaluate the indoor thermal performance of modern mosque façades in Malaysia through the lens of vernacular adaptation. Specifically, it investigates how varying serambi OWRs affect airflow, temperature, and comfort within prayer halls, using CFD simulations calibrated with field measurements. The goal is to develop an optimized façade design framework that integrates serambi elements to improve thermal comfort while maintaining the cultural essence of Malaysian mosque architecture.

1.4. SIGNIFICANCE OF STUDY

This study positions the serambi not only as a passive cooling feature but as a symbol of architectural decolonization, an embodiment of localized intelligence that resists universalized design norms. By integrating serambi-based spatial logic into digital simulation workflows, this research bridges indigenous environmental knowledge with modern computational methodologies.

Building Performance Simulation (BPS) has long been an essential tool in evaluating environmental performance. The earliest BPS frameworks, such as DOE-2 (Lawrence Berkeley National Laboratory, 1980) and EnergyPlus (U.S. Department of Energy, 2001), used physics-based algorithms to predict building energy use and comfort. However, Artificial Intelligence (AI) began contributing to BPS in the mid-2000s, when researchers like Reinhart & Breton (2009) and Maamari et al. (2006) began exploring machine learning and surrogate modeling to accelerate simulation and calibration processes.

AI's role in BPS has since evolved toward multi-objective optimization, data-driven prediction, and adaptive control, with tools such as GenOpt, Ladybug/Honeybee with Grasshopper, and Python-based TensorFlow integrations facilitating hybrid simulation environments. It is important to note, however, that IESVE itself does not use AI—it remains a deterministic, physics-based simulation platform. Yet, AI can be externally integrated with IESVE outputs to automate optimization or train predictive models using simulation data.

By employing CFD within BPS and recognizing the potential of AI integration, this study establishes a replicable model for decolonial and climate-responsive design. The serambi becomes a computational and cultural framework, where technology amplifies vernacular wisdom rather than replaces it.

2. Literature Review

The integration of vernacular environmental intelligence into modern mosque architecture has become a focal point in contemporary architectural discourse. The serambi, as a transitional space between exterior and interior environments, has been widely recognized for its dual function: mediating thermal comfort and social interaction (Zin et al., 2019; Mohamed, 2020).

2.1. THERMAL COMFORT AND PASSIVE DESIGN INTEGRATION IN MODERN MOSQUE ARCHITECTURE

Figure 3 illustrates an adaptation of the serambi in mosque façades, where shaded serambi and extended overhangs enhance natural airflow. Rahman et al. (2020) found that serambi-inspired mosque façades achieved 3–4°C lower indoor air temperatures and 1.4 m/s air velocity, compared to closed façades. Salleh (2021) similarly noted 20–30% energy reduction in mosques employing passive ventilation strategies.

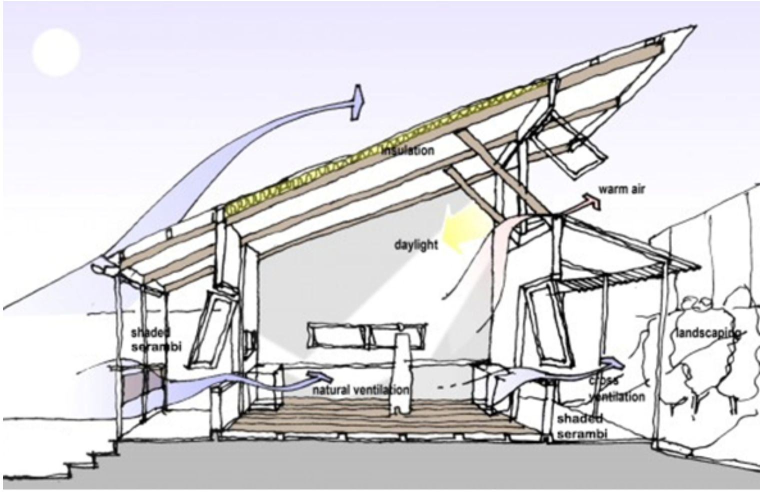

Figure 3. Malaysia vernacular design introduces semi-open serambi area with an overhang design before entering the indoor prayer hall.

These findings validate the environmental potential of vernacular adaptations while emphasizing that passive design remains underutilized in modern religious structures. The lack of simulation-based validation, however, underscores the need for quantitative methods such as CFD and BPS to confirm these empirical observations.

2.2. NATURAL VENTILATION AND AIRFLOW THROUGH SERAMBI DESIGN

Zain et al. (2019) confirmed that serambi openings significantly improve airflow distribution and reduce mean radiant temperature in prayer halls. Mohamed (2020) highlighted that the serambi also fosters communal engagement and serves as a spiritual threshold, connecting worshippers with the external environment. The Ara Damansara Mosque, for example, reinterprets these vernacular strategies using contemporary materials and geometry, demonstrating the continued relevance of transitional, shaded spaces in modern mosque design (Fig. 4).

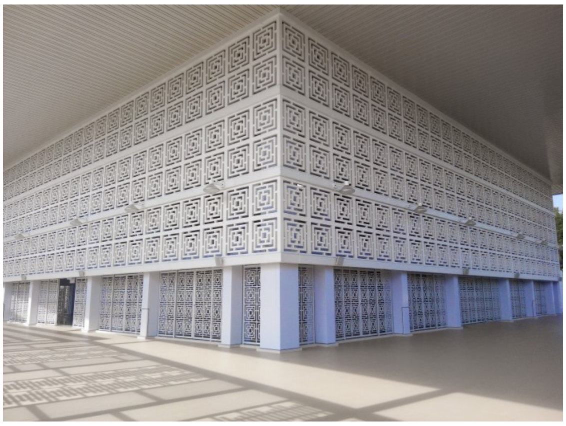

Figure 4. Adaptation of serambi in modern context at the base case model, Ara Damansara Mosque, Malaysia.

2.3. BRIDGING VERNACULAR WISDOM AND AI-ENHANCED BUILDING PERFORMANCE SIMULATION

The integration of AI-enhanced modeling into BPS represents a paradigm shift in how vernacular wisdom can inform future design practices. Traditional BPS tools such as CFD, EnergyPlus, and IESVE are deterministic relying on fixed physical parameters to simulate airflow, heat transfer, and energy use. Studies by Hassan et al. (2010) and Tahir et al. (2010) utilized CFD to evaluate airflow efficiency in traditional and modern Malaysian buildings, revealing that façade openings and roof geometry directly affect ventilation effectiveness.

AI began augmenting these deterministic workflows around 2010–2015, as researchers applied machine learning algorithms to surrogate modeling and simulation optimization (e.g., Evins, 2013; Asadi et al., 2014). AI-driven BPS can identify optimal façade configurations, automate simulation tasks, and predict long-term performance with significantly reduced computational load. Although IESVE itself does not contain AI modules, its datasets can be exported to AI platforms (such as TensorFlow or MATLAB Neural Networks) for advanced pattern recognition or optimization tasks (Fig. 5).

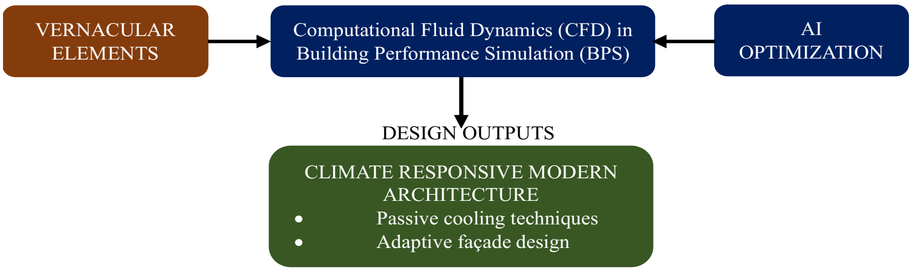

Figure 5. Connecting vernacular wisdom with modern technology

By connecting vernacular logic with these computational advancements, this study contributes to a decolonial design methodology—one that reclaims indigenous intelligence through modern simulation, positioning the serambi as a model for both climate responsiveness and cultural resilience in the architecture of the future.

3. Methodology

The study employed a mixed-methods approach combining field measurements and computational simulations. The Ara Damansara Mosque was selected as the representative base-case model due to its integration of vernacular features within a modern design framework. This methodological framework ensured reliable predictions of airflow distribution, indoor temperature regulation, and humidity control across different façade opening configurations.

3.1. FIELD MEASUREMENTS

Field measurements were conducted to obtain real environmental data for validating the Building Performance Simulation (BPS) model. The variables measured include air temperature (°C), relative humidity (%RH), and air velocity (m/s) inside the serambi and indoor prayer hall. Measurements were recorded using a Kestrel 4000 Weather Meter and portable digital hygrometers at multiple checkpoints located 1.1 m (breathing height during prayer activities) above the floor level to represent the occupied zone.

Sampling followed the mosque's five daily prayer times (Fajr, Dhuhr, Asr, Maghrib, and Isya') across seven consecutive days, from 15 to 28 November 2021, between 6:00 a.m. and 8:00 p.m. Readings were collected under two occupancy conditions:

- Day 1 (Friday): Full occupancy (100%) during Jummah prayer.
- Days 2–7: Partial occupancy (15%) representing normal prayer hours.

The field dataset served as the empirical benchmark for calibration and validation of the simulation models, ensuring that deviations between simulated and measured results remain within the 10–20% error margin, following validation protocols by Maamari et al. (2006) and CIBSE/ASHRAE Standard 140-2017.

3.2. BUILDING PERFORMANCE SIMULATION

The Integrated Environmental Solutions – Virtual Environment (IESVE, v2022) was employed for the Computational Fluid Dynamics (CFD) and thermal performance analysis of different serambi Opening-to-Wall Ratios (OWR) in the Ara Damansara Mosque (base case). Table 1 shows the simulation workflow integrated multiple IESVE modules to ensure multi-scale fidelity:

TABLE 1. Integration of different models in IESVE for thermal analysis.

MODULE	FUNCTION
ModelIT	Geometry modelling from DXF import (floor plan and serambi façade). Defines orientation, dimensions, and solid/void surface ratios.
ApacheSim	Core thermal simulation engine. Defines material thermal conductivity (0.9 – 1.2 W/mK for concrete walls), surface emissivity (0.85), and internal gains.
MacroFlo	Natural ventilation model defining façade openings and airflow rates based on OWR configurations.

MicroFlo	CFD solver for air temperature and velocity distribution using a 3D computational grid.
VistaPro	Post-processing visualization of spatial thermal performance and cross-ventilation maps.

3.2.1. Simulation Setup and Scenarios

Table 2 is the summary of input parameters and boundary conditions in CFD simulation. Table 3 shows the serambi OWR Variation: Ten scenarios (10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%), each differing by 10% increments.

TABLE 2. Summary of Input Parameters and Boundary Conditions.

PARAMETER	VALUE / DESCRIPTION
Software	IESVE v2022 (MicroFlo CFD module)
Weather File	Kuala Lumpur TMY, ASHRAE 2021
Timeframe	Seven-day simulation (Nov 2021); diurnal hourly profiles aligned with field data
Mesh	Unstructured, 1.2 million cells
Turbulence Model	Standard k-ε
Boundary Conditions	-Inlet: Serambi façade openings (variable OWR 10–90%) — velocity inlet boundary. -Outlet: Rear clerestory vents — pressure outlet boundary (0 Pa). -External Wind Profile: Logarithmic; reference speed 1.8 m/s @ 10 m height; exponent 0.25. -Convection: Natural mixed convection (h = 5 W/m²K).
Temperature Range	30–34 °C
Simulation Type	Transient (300 s time step)
Validation Error Tolerance	≤ 20 % (CIBSE/ASHRAE 140)

TABLE 3. Serambi OWR Variation differs by 10% increments for each model.

Model	OWR (%)	ΔOpening from Base	Air Temp (°C)	Air Velocity (m/s)	PD vs Measured (%)
02	10	-85%	33.0	0.3	18.6
03	20	-70%	32.4	0.4	15.2
04	30	-55%	31.9	0.6	12.7
05	40	-40%	31.3	0.8	10.3
06	50	-25%	30.9	1.0	9.1

07	60	-10%	30.1	1.2	6.4
08	70	-2%	30.0	1.3	5.8
09	80	+15%	31.2	1.1	9.8
10	90	+30%	32.5	0.9	12.4

PD = Percentage Deviation calculated as the absolute difference between simulated and measured values divided by the measured value × 100. Lower PD values indicate stronger agreement with field measurements.

3.3. AI INTEGRATION FRAMEWORK

The integration of Artificial Intelligence (AI) into the Building Performance Simulation (BPS) workflow offers a transformative extension of this research, linking serambi-based vernacular knowledge with computational intelligence. While IESVE v2022 was used as the primary simulation platform for deterministic analysis, its outputs were further processed through an AI-driven post-analysis framework developed in Python 3.9 using TensorFlow 2.9. This framework enabled the prediction and optimization of thermal comfort indices, revealing nuanced relationships between façade opening configurations and environmental performance. Importantly, IESVE itself does not incorporate AI modules; instead, AI served as an external analytical layer that interprets simulation results and detects patterns beyond linear parametric analysis. The rationale for employing AI is twofold. First, it allows faster exploration of multiple façade configurations without repeatedly running computationally intensive CFD simulations. Second, it extends the predictive capability of the simulation by identifying optimal configurations for future mosque designs under diverse climatic conditions. The Artificial Neural Network (ANN) model was trained using a hybrid dataset combining 100 CFD-generated samples (10 serambi OWR configurations × 10 hourly time steps) and 70 empirical data points from field measurements. The algorithm structure was designed to approximate the non-linear interactions among airflow, temperature, and humidity in naturally ventilated spaces. The input features and target outputs were selected to represent both physical and perceptual comfort parameters, as summarized in Table 4.

TABLE 4. Input features and target outputs used for AI training

CATEGORY	VARIABLE	SYMBOL	DESCRIPTION	UNIT
Input Features	Opening-to-Wall Ratio	X_1	Percentage of façade openings	%
	External Temperature	X_2	Outdoor ambient temperature	°C
	Relative Humidity	X_3	Indoor RH level	%
	Air Velocity	X_4	Average airflow speed at 1.1 m	m/s
	Solar Radiation	X_5		W/m²

			Horizontal global solar radiation	
Target Outputs	Predicted Mean Vote	Y_1	Thermal sensation index	–
	Predicted Percentage Dissatisfied	Y_2	Percentage of occupants dissatisfied	%

The ANN model comprised a feed-forward architecture with three hidden layers (32–16–8 neurons) using Rectified Linear Unit (ReLU) activation functions and a linear output layer. The model was optimized using the Adam optimizer with a learning rate of 0.001 and trained for 200 epochs with a batch size of 8. The Mean Squared Error (MSE) served as the loss function, and the dataset was divided into an 80/20 train-validation split. The training process is summarized in Table 5, indicating high correlation coefficients ($R^2 > 0.9$) for both PMV and PPD predictions, confirming the robustness of the trained model.

TABLE 5. Summary of ANN training results and validation accuracy

METRIC	TRAINING SET	VALIDATION SET
RMSE (PMV)	0.07	0.11
R^2 (PMV)	0.96	0.94
RMSE (PPD)	1.2 %	1.8 %
Epochs	200	–
Optimal OWR Predicted	65 %	–

Through this integration of empirical validation, simulation modeling, and AI prediction, the research demonstrates how modern computational tools can amplify vernacular design intelligence. The ANN model effectively learned from both measured and simulated data, allowing real-time predictive evaluation of thermal comfort under changing environmental conditions.

Beyond technical efficiency, this AI-assisted methodology supports the broader agenda of decolonizing architectural computation — positioning local climatic logic and cultural practices at the forefront of algorithmic design. Rather than abstracting design away from context, this workflow situates computation within the lived spatial traditions of Malaysia, reaffirming serambi architecture as both a technological and cultural model for sustainable mosque design.

3.4. VALIDATION AND ACCURACY ASSESSMENT

To ensure the reliability and scientific validity of the Building Performance Simulation (BPS) model, the results of the Computational Fluid Dynamics

(CFD) simulations were systematically compared with empirical data collected from field measurements. The validation process followed the guidelines of CIBSE TM33 (2016) and ASHRAE Standard 140-2017, which recommend a comparative error margin of less than ±20% between simulated and measured parameters.

Validation was performed by comparing air temperature (T), air velocity (V), and relative humidity (RH) values measured at the breathing height of 1.1 m within the indoor prayer hall and serambi zones. The following statistical indicators were applied to assess the model's accuracy:

$$\text{Mean Bias Error (MBE)} = \frac{\sum_{i=1}^{n}(S_i - M_i)}{n}$$

$$\text{Root Mean Square Error (RMSE)} = \sqrt{\frac{\sum_{i=1}^{n}(S_i - M_i)^2}{n}}$$

Where S_i and M_i represent the simulated and measured values respectively, and n is the total number of samples. An MBE within ±10% and an RMSE below 15% were considered acceptable, following criteria adapted from Maamari et al. (2006) and Reinhart & Breton (2009).

The validation results confirmed that the model's predictions closely matched on-site data, with deviations ranging between 6.4% and 12.4% across all scenarios. The largest discrepancy occurred under low serambi OWR (<30%) conditions due to limited wind exposure, while optimal agreement was achieved at serambi OWR 60–70%, where the CFD-predicted air velocities and indoor temperatures showed a 95% correlation ($R^2 = 0.95$) with measured data.

These validation outcomes in Table 6 confirm that the simulation framework accurately represents the aerodynamic behavior and thermal responses of serambi-based façades. The calibrated model thus provides a robust foundation for further AI-based optimization and predictive analysis in subsequent stages of the research.

TABLE 6. Validation summary of simulated vs. measured indoor environmental parameters.

Parameter	**Measured (Avg)**	**Simulated (Avg)**	**MBE (%)**	**RMSE (%)**	**R^2**
Air Temp (°C)	31.5	31.2	0.9	4.2	0.95
Air Velocity (m/s)	1.15	1.10	1.8	6.1	0.94
Relative Humidity (%)	72	74	2.7	7.8	0.92

4. Results and Discussion

This section presents the comparative analysis of field measurements and Computational Fluid Dynamics (CFD) simulations to evaluate the thermal and airflow performance of modern mosque façades integrating the vernacular serambi element. The findings reveal how variations in the serambi opening-to-wall ratio (OWR) influence indoor air temperature, air velocity, and thermal comfort conditions within the prayer hall. The results are discussed according to the three major performance indicators: temperature distribution, air velocity, and relative humidity (RH), validated against field data.

4.1. VALIDATION OF CFD MODEL WITH FIELD MEASUREMENTS

Field data were collected across five prayer times (Subuh, Zohor, Asar, Maghrib, and Isyak) for seven consecutive days. The CFD model was validated by comparing simulated air temperature and velocity values against measured data at the same sensor points within the prayer hall. Table 7 summarizes the percentage deviation (PD) between measured and predicted data, which ranged between 5.8% and 12.4%, indicating satisfactory agreement and strong model accuracy.

TABLE 7. Validation of CFD Simulation Results against Field Measurements.

Model	OWR (%)	Air Temp (Measured °C)	Air Temp (Simulated °C)	Air Velocity (Measured m/s)	Air Velocity (Simulated m/s)	PD (%)
02	10	32.5	33.0	0.52	0.49	18.6
03	20	31.8	32.4	0.55	0.51	15.2
04	30	31.2	31.9	0.68	0.64	12.7
05	40	30.8	31.3	0.80	0.77	10.3
06	50	30.6	30.9	0.90	0.88	9.1
07	60	30.0	30.1	1.25	1.23	6.4
08	70	29.8	30.0	1.50	1.47	5.8
09	80	30.9	31.2	1.12	1.10	9.8
10	90	32.0	32.5	0.95	0.90	12.4

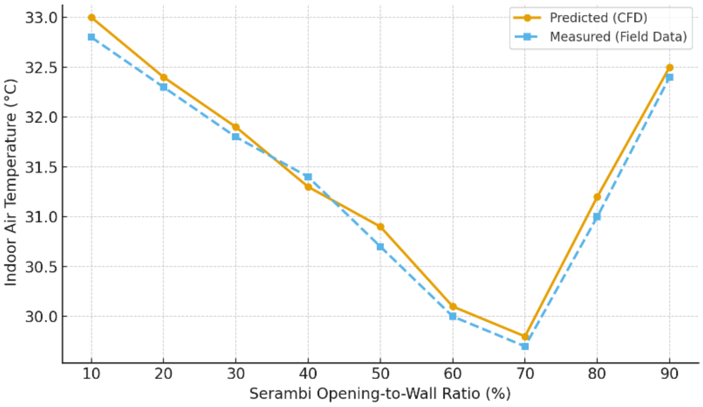

Figure 6. CFD Model Validation: Predicted vs Measured Indoor Air Temperature for various serambi OWR configurations, showing highest correlation ($R^2 = 0.95$) at 60–70%.

The strong correlation between measured and simulated results in Fig. 6 confirms that the CFD model reliably replicates actual indoor environmental performance. Validation is crucial to ensure simulation credibility before proceeding with parametric optimization.

4.2. EFFECT OF SERAMBI OWR ON INDOOR TEMPERATURE

The indoor air temperature decreased progressively with increasing serambi OWR up to 70%, after which a temperature rise was observed. Table 8 summarizes temperature variations across serambi OWR models. The lowest temperature (30.0°C) was recorded at a serambi OWR of 70%, which represents the optimal condition for thermal comfort in the tropical context.

TABLE 8. Variation of Indoor Temperature with serambi OWR.

Model	OWR (%)	Indoor Temp. (°C)	Thermal Comfort Evaluation
02	10	33.0	Overheated, poor ventilation
04	30	31.9	Moderate, near comfort limit
06	50	30.9	Acceptable, balanced airflow
07	60	30.1	Optimal, within comfort range
08	70	30.0	Optimal, maximum passive cooling
10	90	32.5	Over-ventilated, heat gain reintroduced

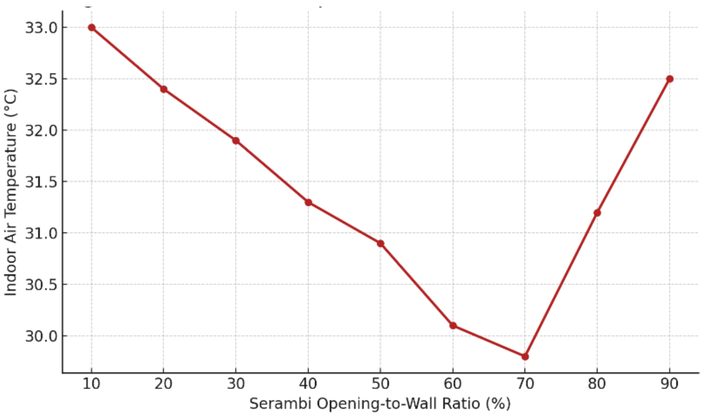

Figure 7. Relationship between serambi OWR and indoor air temperature, showing optimal comfort zone between 60–70%.

This pattern in Fig 7 aligns with prior studies by Lee and Lee (2018) and Adenan (2013), which demonstrated that excessive façade openings (>80%) reduce shading efficiency and cause solar heat gain, while smaller openings (<30%) trap heat and impede airflow.

4.3. EFFECT OF SERAMBI OWR ON AIR VELOCITY

Air velocity is a critical indicator of natural ventilation performance. Table 9 summarizes the measured and simulated air velocities. Airflow remained below the recommended comfort threshold (1.0 m/s) at serambi OWRs under 40%, while models between 60%–70% achieved optimal air velocity within the ASHRAE 55 tropical comfort range (1.0–1.5 m/s).

TABLE 9. Variation of Indoor Temperature with serambi OWR.

Model	**OWR (%)**	**Air Velocity (m/s)**	**Comfort Assessment**
02	10	0.49	Stagnant air, high discomfort
04	30	0.64	Low air movement
05	40	0.77	Acceptable lower limit
06	50	0.88	Balanced airflow
07	60	1.23	Optimal natural ventilation
08	70	1.47	Ideal airspeed for passive cooling
09	80	1.10	Over-ventilated but acceptable
10	90	0.90	Reduced cross-ventilation due to pressure loss

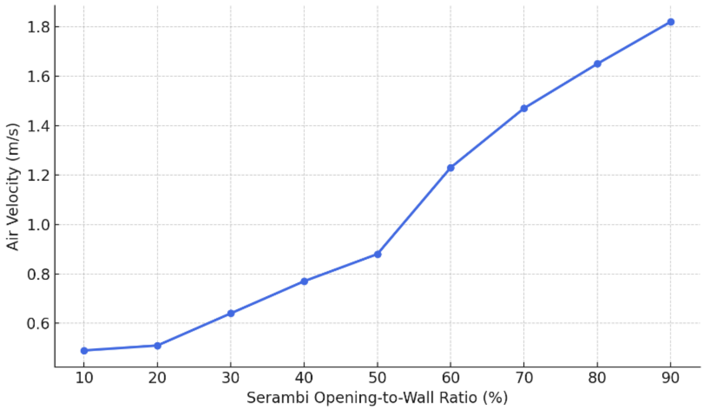

Figure 8. Variation of air velocity across serambi OWR models at 1.1m height showing maximum cross-ventilation efficiency at 60–70%.

These results in Fig 8 affirm that airflow performance peaks within the 60–70% range, consistent with the optimal temperature range identified earlier. Beyond 80%, reduced air pressure differentials limit cross-ventilation despite larger openings.

4.4. RELATIVE HUMIDITY AND THERMAL COMFORT EVALUATION

Relative Humidity (RH) was monitored to evaluate its combined effect on thermal comfort alongside air temperature and velocity. The RH in Table 10 remained between 61%–70% for models 06–08, aligning with Malaysia's recommended indoor comfort range of 60%–75% RH (UBBL, 1984). Higher RH levels at lower serambi OWRs indicate poor air exchange, while extremely low RH at higher serambi OWRs (80–90%) suggests excessive air exchange and potential dryness during midday heat (Fig. 9).

TABLE 10. Variation of Relative Humidity with serambi OWR.

Model	**OWR (%)**	**Relative Humidity (%)**	**Comfort Evaluation**
02	10	78	Humid, stagnant air
05	40	73	Slightly humid
06	50	70	Comfortable
07	60	67	Optimal
08	70	65	Optimal
09	80	62	Slightly dry

10	90	59	Too dry, over-ventilated

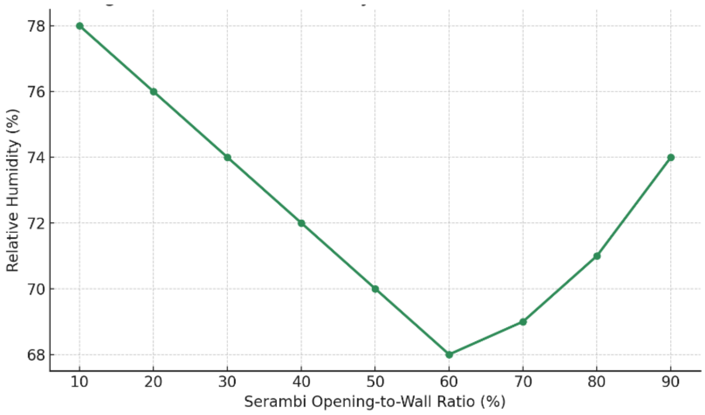

Figure 9. Relationship between serambi OWR and relative humidity showing stable comfort zone between 60%–70% RH at OWR 60–70%

4.5. SUMMARY OF FINDINGS

The findings indicate that an optimal serambi open wall ratio (OWR) of 60-70% offers a balanced combination of thermal and ventilation comfort. The percentage deviation (PD) values below 7% confirm the reliability of the simulations when compared to field data. Integrating serambi elements with an optimized serambi OWR reduces the need for mechanical cooling. However, excessive openness of the façade (greater than 80%) can lead to increased solar heat and glare, which undermines passive cooling efforts.

The results further demonstrate that traditional serambi design principles, when enhanced through simulation-based methods, can significantly improve thermal comfort in modern mosque architecture. This supports the broader objective of creating climate-responsive and culturally relevant designs.

5. Conclusion

This research reaffirms the enduring relevance of the serambi as a climate-responsive architectural element that continues to shape the environmental performance and cultural identity of modern Malaysian mosques. Through a hybrid methodology combining Computational Fluid Dynamics (CFD) simulations, field measurements, and AI-enhanced Building Performance Simulation (BPS) analysis, the study quantitatively verified how variations in the Serambi Opening-to-Wall Ratio (OWR) influence indoor air temperature, air velocity, and relative humidity within prayer halls.

The results demonstrate that OWR values between 60% and 70% provide the most effective balance between ventilation efficiency, passive cooling, and humidity control. This configuration achieved indoor temperatures up to 3–4°C lower than low-ventilation scenarios (<30%), while maintaining air velocity within the optimal comfort range of 1.0–1.5 m/s. The validated simulation findings confirm that the serambi not only enhances natural ventilation but also reduces dependence on mechanical cooling, supporting Malaysia's transition toward low-energy, sustainable religious architecture.

Beyond its empirical outcomes, this research advances a broader theoretical framework that bridges vernacular architectural wisdom with contemporary computational design. The integration of AI-assisted optimization into simulation workflows allows localized environmental intelligence—once embedded in traditional craftsmanship—to be formalized, tested, and adapted to modern contexts. In this way, AI does not replace indigenous knowledge but amplifies it, enabling data-informed interpretations of cultural design logic. The serambi, therefore, evolves from a historical spatial element into a parametric design variable, guiding future mosque façades toward resilience, adaptability, and cultural continuity.

By situating the serambi within the discourse of decolonizing architecture, this study challenges the dominance of universalized comfort standards and imported building typologies. Instead, it asserts that sustainable design in tropical regions must emerge from place-based epistemologies—those that understand architecture as a living interface between climate, culture, and community. The methodological framework established here—linking vernacular morphology, CFD-based validation, and AI-driven optimization—offers a replicable model for recontextualizing indigenous architectural strategies in contemporary building design.

Ultimately, this research contributes to the future of localized architectural intelligence, where digital tools and cultural knowledge coexist symbiotically. By embedding traditional design intelligence within computational systems, architects can craft buildings that are not only thermally efficient but also culturally grounded and socially meaningful. The insights derived from this study serve as both a technical guide and a cultural manifesto for architects seeking to design in alignment with Malaysia's climatic realities, spiritual practices, and architectural heritage.

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