

Simulations of Temperature and Wind Speed Contours and Vectors for Thermal Comfort Analysis in Worship Spaces

The Case Study of Baiturrahman Grand Mosque, Indonesia

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ABSTRACT

Thermal comfort in tropical worship spaces is a critical aspect of sustainable design, particularly in densely populated urban centers. This study investigates the thermal environment of the Baiturrahman Grand Mosque in Indonesia, a landmark with significant cultural and architectural value, to assess how traditional design strategies contribute to indoor environmental quality. The purpose of the research is to analyze temperature and wind speed distribution patterns within the mosque using Computational Fluid Dynamics (CFD) simulations, aiming to evaluate its effectiveness in achieving thermal comfort under tropical conditions. The study integrates simulation data with literature on sustainable architectural practices to contextualize the findings. The CFD analysis reveals that the mosque's passive design effectively maintains internal wind speeds between 1-3 m/s and temperatures ranging from 22-30°C, even when external daytime temperatures peak at 29.6°C. Airflow enters through large main entrances and side vents, while the dome structure enhances vertical ventilation. These results reflect traditional Acehese design principles, such as elevated floors and strategic openings, which naturally facilitate cross-ventilation and thermal regulation. The study concludes that integrating CFD with Geographic Information System (GIS) data can significantly enhance the accuracy of thermal comfort assessments, especially in mitigating urban heat island effects. Design interventions, like insulated materials, hybrid ventilation, and green infrastructure are proposed for broader application. Revising the thermal comfort standards for tropical climates and pursuing multidisciplinary, data-driven design approaches are essential for future development. This research supports the potential of culturally rooted, passive design strategies in creating thermally comfortable and sustainable worship environments.

Keywords-thermal comfort; CFD; natural ventilation; tropical architecture; urban heat island

I. INTRODUCTION

The quality of air in indoor environments plays a crucial role in the health, comfort, and overall well-being of occupants. As many people spend most of their time indoors, thermal comfort has become a prominent topic across various types of facilities, including educational buildings, residential spaces, and places of worship. Consequently, it is imperative to seek solutions that can maintain the indoor thermal comfort while simultaneously minimizing the energy consumption within

buildings. For structures with historical value, energy efficiency becomes a particularly significant objective, as restrictions on applicable energy solutions are often imposed to preserve their aesthetic. Architectural constraints, frequently compounded by economic limitations, hinder the adoption of advanced technical solutions. This often results in high energy consumption and poor indoor environmental quality.

Thermal comfort within places of worship, particularly mosques, is a critical factor that significantly influences the

well-being and concentration of congregants during prayer. The Baiturrahman Grand Mosque in Indonesia, as one of the nation's iconic religious landmarks, faces challenges in maintaining thermal comfort due to the hot and humid tropical climate. Temperature contour and vector simulations, along with wind speed analysis were conducted, in order to evaluate the indoor temperature distribution and airflow dynamics.

Previous studies have demonstrated that passive cooling systems, such as wind catchers, can effectively reduce the energy consumption while enhancing natural ventilation and thermal comfort, particularly in places with hot climate, like Iran [1]. To support such design strategies, CFD has been widely employed to model the airflow and temperature distribution, with the $k-\omega$ turbulence model proving to be accurate in predicting air velocity patterns. Furthermore, research introduced a coordinated fan control system aimed at optimizing the thermal comfort in densely occupied indoor environments. The findings highlight that simulation-based approaches can significantly improve user satisfaction, reinforcing the value of integrated modeling in the design and management of indoor climate systems [2].

The integration of CFD modeling with spatial analysis using GIS has also been applied to assess the vertical and horizontal variability of temperature and wind speed in urban environments [3]. This approach reveals that neglecting such variability can lead to significant errors in estimating the surface temperature and thermal comfort indices, thereby emphasizing the need for more comprehensive and integrated modeling frameworks. Moreover, an outdoor thermal comfort prediction model that incorporates the solar radiation, sky view factor, and airflow patterns has been developed, and could potentially be adapted for indoor environmental analysis [4].

In the context of religious buildings, research demonstrated that the size and aspect ratio of window openings significantly influence the temperature distribution and the extent of comfort zones within indoor spaces [5]. Various wind simulation techniques, including Reynolds-Averaged Navier-Stokes (RANS) and Large-Eddy Simulation (LES) offer an accurate evaluation of thermal comfort at the pedestrian level. These simulation approaches can similarly be applied to the analysis of the thermal comfort in mosques, where a detailed mapping of the airflow patterns and temperature distribution is essential for achieving optimal indoor environmental conditions [6].

A case study on refugee tents in Aceh-Indonesia revealed that ventilation design and material selection have a significant impact on the thermal comfort [7]. These findings are particularly relevant to the analysis of the Baiturrahman Grand Mosque, where the configuration of natural openings and passive cooling systems can be further optimized to enhance the indoor conditions. Additionally, studies on traditional Acehese houses confirm that local architectural elements, such as roof overhangs, wooden materials, and natural ventilation, play a critical role in maintaining the indoor temperature stability [8, 9].

This study aims to analyze the thermal comfort in the Baiturrahman Grand Mosque through contour and vector simulations of the temperature and wind speed using a CFD

approach. The results are expected to provide optimal design recommendations to enhance congregants' comfort by utilizing natural ventilation and passive cooling strategies, while also contributing to the development of sustainable mosque architecture in tropical climates. Thermal comfort can be achieved through mechanical ventilation systems, such as Heat, Ventilation, and Air Conditioning (HVAC) or by strategically arranging interior furnishings to better utilize thermally comfortable zones. The effectiveness of air ventilation systems is influenced by several variables, including temperature and Air Changes per Hour (ACH). Air infiltration through natural ventilation can be employed to improve the thermal comfort within indoor spaces.

The Baiturrahman Grand Mosque is a historically significant building located in Banda Aceh. It has undergone multiple renovations, including structural repairs and expansions. In the current research, the mosque is digitally reconstructed and simulated using a natural ventilation system to reduce the energy consumption while maintaining the indoor thermal comfort. The study employs a numerical CFD approach, a branch of fluid mechanics that uses numerical methods and algorithms to analyze and solve problems involving the fluid flow. Here, CFD is applied to obtain wind velocity and temperature profiles within the mosque building, allowing for a quantitative assessment of its thermal comfort performance.

II. METHODOLOGY

In this study, the Baiturrahman Grand Mosque has been digitally redesigned using the Computer-Aided Design (CAD) application, as shown in Figure 1. The CFD simulations were employed to generate airflow velocity and temperature profiles within the mosque's interior. To reflect the varying environmental conditions, the simulations incorporate a range of testing parameters, including time of day, temperature, and inlet air velocity.

The temperature and wind speed parameters were recorded at hourly intervals from 08:00 to 16:00 local time (Western Indonesia Time or WIT) to capture temporal variations. Furthermore, the simulation integrates solar load, ambient temperature, and wind speed to closely replicate real-world conditions. The solar radiation and ambient temperature data used in the simulation were based on environmental conditions specific to Banda Aceh, Aceh Province—the actual location of the mosque. Wind speed data were sourced from the official website of the Meteorology, Climatology, and Geophysics Agency (BMKG) for Banda Aceh to ensure accuracy. In addition, geometric measurements of the mosque were conducted to create the detailed 3D model (Figure 1).

The CAD geometry was imported into a CFD application for the meshing process, which involves dividing it into smaller elements. The tetrahedral mesh of the Baiturrahman Grand Mosque consists of 87,604 nodes and 449,715 elements (Figure 2). Each of these elements will be subjected to numerical analysis. Moreover, the boundary conditions for the simulation were determined (Figure 3).

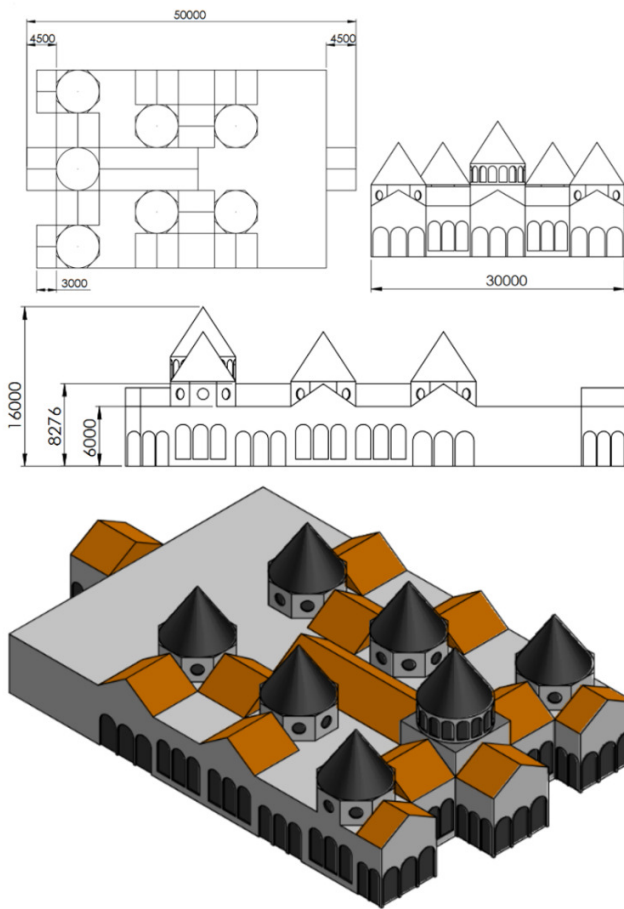


Fig. 1. Dimensions and 3D design of Baiturrahman Grand Mosque.

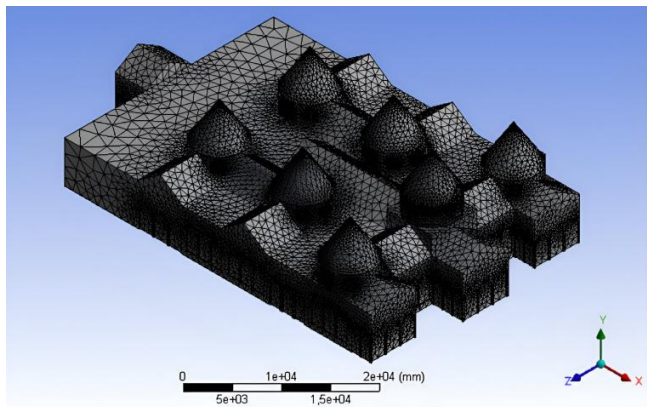


Fig. 2. Meshing of the Baiturrahman Grand Mosque.

The CFD simulation parameters applied to the Baiturrahman Grand Mosque for boundary conditions, initial conditions, and materials are provided in Tables I-III.

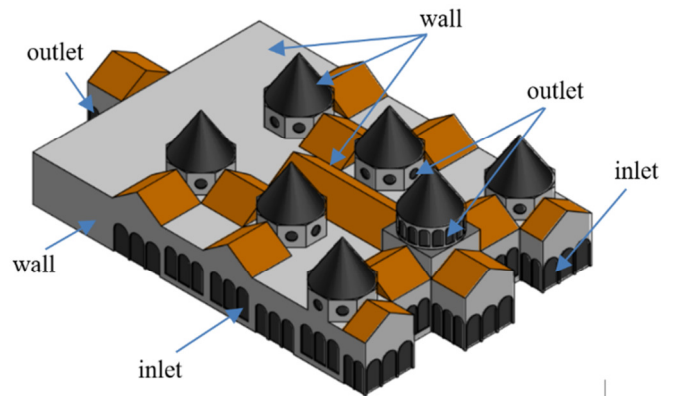


Fig. 3. Boundary conditions of the Baiturrahman Grand Mosque.

TABLE I. BOUNDARY CONDITION PARAMETERS

No.	Boundary conditions	Planning	
1	Inlet	Velocity-inlet	
2	Outlet	Pressure-outlet	
3	Wall	Solid proof against flow of fluid	
4	Wall momentum	Wall motion	Stationary wall
		Shear condition	No slip
		Wall roughness	Standard
5	Thermal condition	Convection	
6	Radiation	Participates in solar ray tracing (opaque)	
7	Solution methods	Simple	
8	Initialization methods	Standard initialization	

TABLE II. INITIAL CONDITION PARAMETERS

No.	Initial conditions	Planning	
1	Flow type	Pressure-based	
2	Time	Steady state	
3	Velocity formulation	Absolute	
4	Viscous models	SST k- ω	
5	Radiation	Roseland	
6	Solar loading (solar calculator: global Position) Banda Aceh	- Longitude (deg)	95.32375
		- Latitude (deg)	5.54829
		- Time zone (+/- GMT)	7
7	Mesh orientation	- North	Z = 1
		- East	X = -1

TABLE III. MATERIAL PARAMETERS

Region	Material	
Fluid	Air	
Solid	Concrete	
	Density	2400 kg/m ³
	Specific heat capacity	880 J/(kg·K)
	Thermal conductivity	1.65 W/(m·K)

The commercial CFD packages incorporate a range of turbulence models, each selected based on the nature and complexity of the flow case under investigation. Among these models, the standard k- ϵ approach is prevalently utilized across many industrial CFD applications. This model is categorized as semi-empirical, relying on transport equations for characterizing both the turbulent kinetic energy (k) and its rate of dissipation (ϵ). While the equation for k is obtained from a precise derivation of the governing equations, the ϵ equation is

constructed through physical insights, which, despite certain simplifications, maintains a degree of consistency with the theoretical framework. In this study, the simulation of turbulence applies the k and ϵ transport relations, as expressed in [10]:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k + G_b - \rho \epsilon - Y_M + S_k \quad (1)$$

$$\frac{\partial}{\partial t}(\rho \epsilon) + \frac{\partial}{\partial x_i}(\rho \epsilon u_i) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_\epsilon} \right) \frac{\partial \epsilon}{\partial x_j} \right] + C_{1\epsilon} \frac{\epsilon}{k} (G_k + G_{3\epsilon} G_b) - C_{2\epsilon} \rho \frac{\epsilon^2}{k} + S_\epsilon \quad (2)$$

The representation of convective heat and mass transfer within the k - ϵ turbulence framework is formulated in [10]:

$$\frac{\partial}{\partial t}(\rho E) + \frac{\partial}{\partial x_i} [U_i(\rho E + p)] = \frac{\partial}{\partial x_j} \left[\left(k + \frac{c_p \mu_t}{Pr_t} \right) \frac{\partial T}{\partial x_j} + U_i(\tau_{ij})_{eff} \right] + S_h \quad (3)$$

In this research, the thermal comfort conditions of the Baiturrahman Grand Mosque, are evaluated by combining on-site measurement data with numerical simulations performed through CFD tools [10].

The skewness analysis method is used for determining the mesh quality. The results indicate that the generated grid has good quality, ensuring the reliability of the simulation [11]. Assuming the room is adiabatic, contains no internal heat sources, occupants, or furniture, and has a uniform temperature, then the energy equation can be neglected. This means that the analysis focuses solely on the continuity and momentum equations. The key boundary conditions include the inlet and outlet air velocities, wall conditions (no-slip), and possibly the outlet pressure [12].

III. RESULTS AND DISCUSSION

In this study, the thermal comfort analysis of the mosque was not only based on the obtained values, but also on contours and vectors of temperature and wind speed. The simulation results are presented through several wind speed and temperature contours at specific areas or planes within the building. In this study, the inlet air velocity was adjusted according to the time variations set for the analysis, which ranged from 08:00 to 16:00 local time (WIT). At 08:00, the inlet air velocity was set to 1.67 m/s. The XY, XZ, and YZ planes were used within the building, with distances of 0 m for the XY plane, 2 m for the XZ plane, and 0 m for the YZ plane. The plane distances were determined based on the conditions experienced by individuals inside the mosque.

The wind speed contours of the mosque's interior exhibit varying speeds at different times (Figure 4). At 08:00, the wind speed ranges from 0 to 3 m/s. The highest wind speeds are observed at the entrance and the rear terrace of the mosque, while the wind speed in the middle of the room ranges from 1.2 to 2.1 m/s. At 12:00, the wind speed ranges from 0 to 3.1 m/s. The highest speeds occur starting from the entrance, flowing towards the center of the room, and accumulating in the middle, extending to the rear terrace of the mosque. In the

middle of the room, wind speeds range from 2.4 to 3 m/s. This phenomenon occurs due to the convergence of airflows from three directions: the front, left, and right of the room. At 16:00, the wind speed contours indicate a decrease to 2.5 m/s. The results at 16:00 and 12:00 are similar, due to the slight decrease in the incoming wind speed. As a result, the airflow pattern remains consistent until 16:00 WIT.

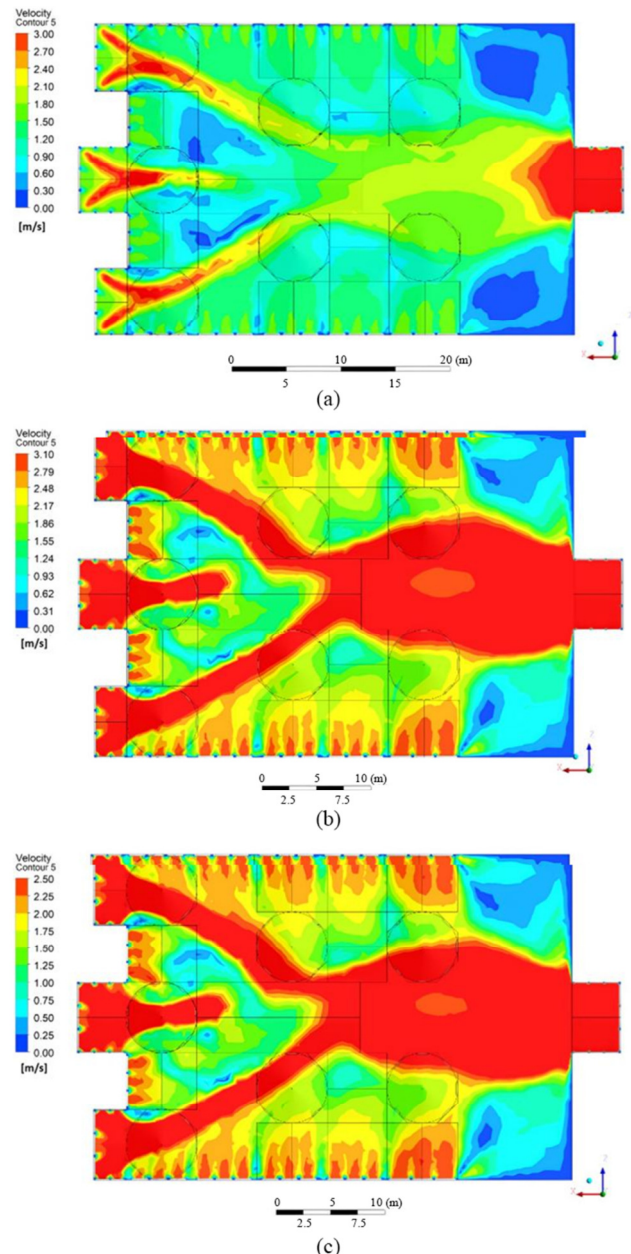


Fig. 4. Wind speed distribution contours on the XZ plane inside Baiturrahman Grand Mosque at: (a) 08:00, (b) 12:00, and (c) 16:00 WIT.

The airflow at the center of the room, on the YZ plane, is depicted in Figure 5. In all three images, the highest wind speeds occur at the entrance of the mosque, where the airflow moves upward towards the front dome, and towards the rear terrace of the mosque.

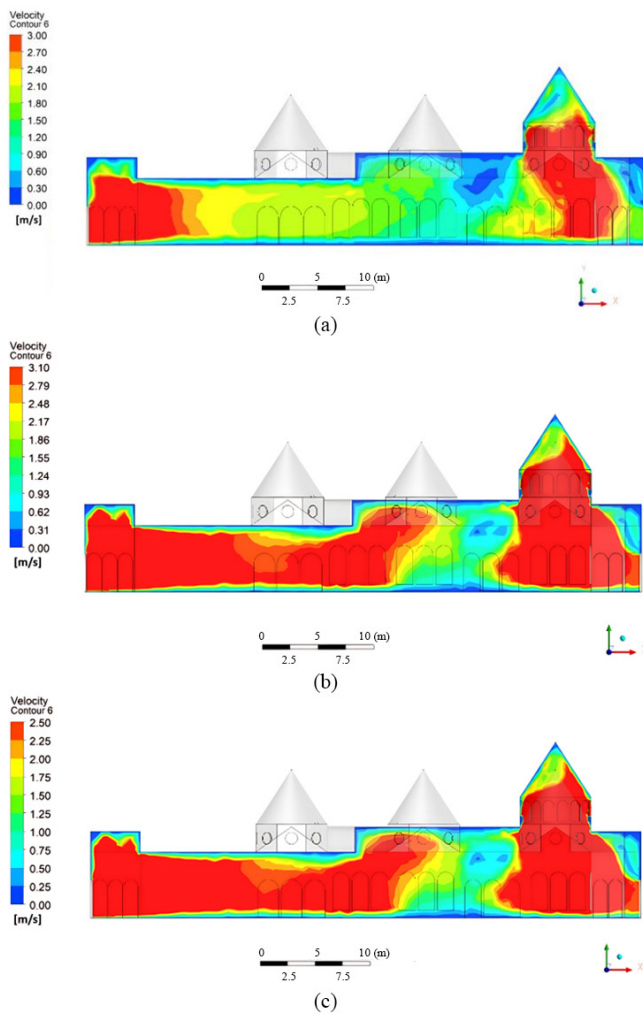


Fig. 5. Wind speed contours on the YZ plane inside the Baiturrahman Grand Mosque at: (a) 08:00, (b) 12:00, and (c) 16:00 WIT.

Figure 6 indicates that the wind enters the room not only from the front entrance of the mosque, but also through the side ventilation of the building. The airflow pattern is consistent across all three images; however, the wind speeds at different times vary. At 08:00, the incoming wind speed is approximately 1.61 m/s, at 12:00 it is around 3.2 m/s, and at 16:00 it is approximately 2.61 m/s.

The temperature distribution inside the mosque at different times is illustrated in Figure 7. At 08:00, the temperature inside the mosque ranges from approximately 22.5 to 25°C. At 12:00, during midday, the room temperature rises to about 26.8-29.6°C. By 16:00, the temperature inside the room is around 26.8-28.6°C. These findings indicate that the Baiturrahman Grand Mosque maintains a relatively comfortable temperature, owing to its design, which incorporates direct or natural ventilation.

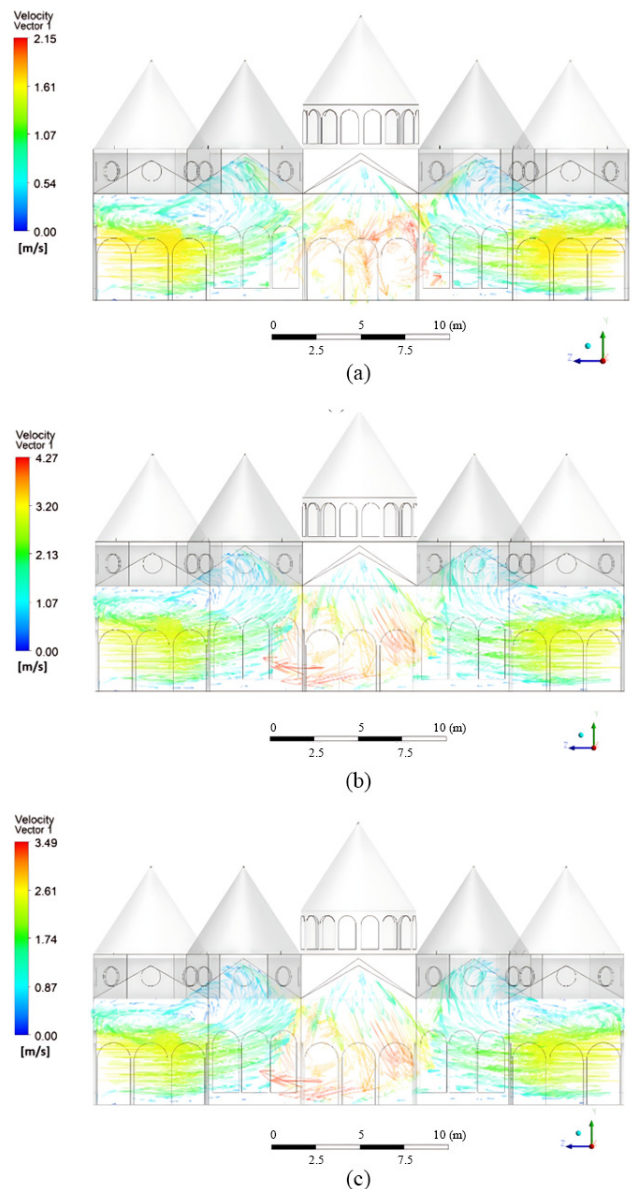


Fig. 6. Wind velocity vectors on the XY plane inside the Baiturrahman Grand Mosque at: (a) 08:00, (b) 12:00, and (c) 16:00 WIT.

The CFD-GIS simulation results for the Baiturrahman Grand Mosque indicate that both vertical and horizontal variability in wind speed patterns and air temperature play a critical role in the thermal comfort [3]. This study confirms that integrated modeling can more accurately identify urban heat distribution compared to surface temperature-based approaches alone. In the case of the mosque, wind speed contours of 1–3 m/s and temperatures ranging from 22–30°C align with tropical comfort standards; however, the temporal variation observed from 08:00 to 16:00 stresses the need for adaptive design solutions to address daily climate fluctuations [4].

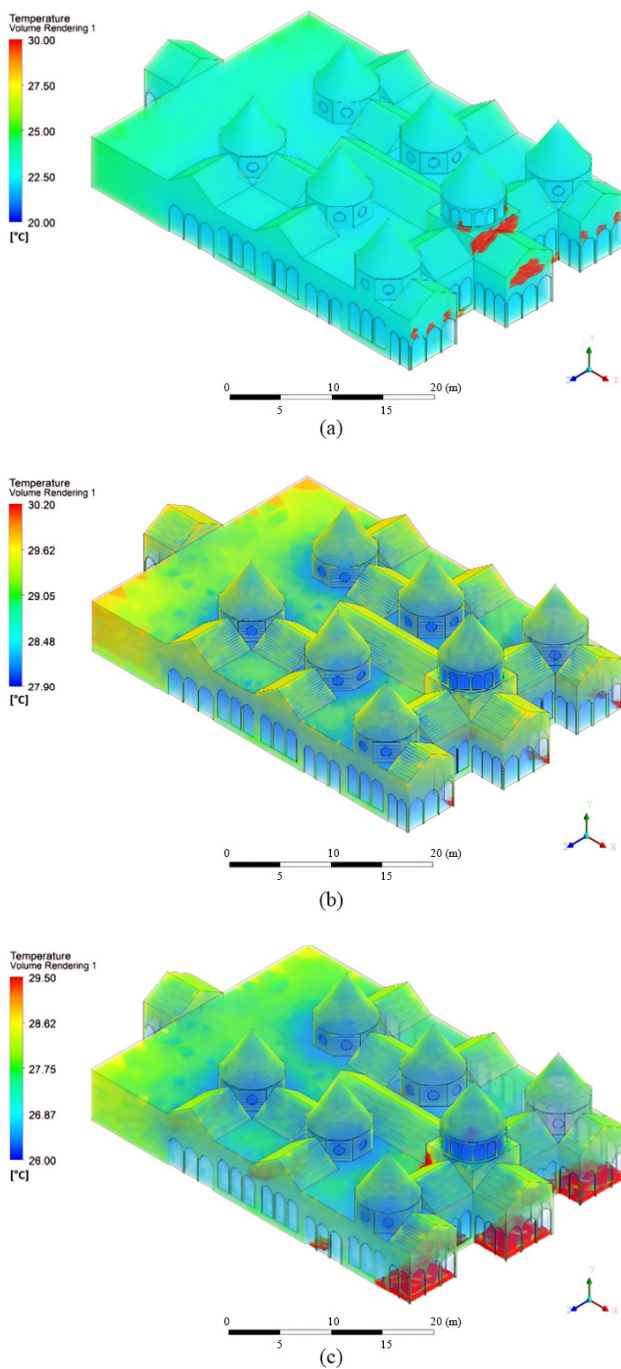


Fig. 7. Temperature inside the Baiturrahman Grand Mosque at: (a) 08:00, (b) 12:00, and (c) 16:00 WIT.

The analysis of the traditional Acehese houses and refugee tents reveals that passive strategies, such as cross-ventilation and local materials, can maintain stable temperatures (23–29°C) with optimal wind speeds (0–2.7 m/s) [9, 10]. However, challenges arise in modern buildings, such as skycourts and windcatchers, where urban landscape irregularities reduce the airflow efficiency by up to 30%. These findings emphasize the

importance of contextually adapting designs based on microclimatic conditions [13, 14].

The massive urbanization increases the surface sealing, triggering the heat island effect [15]. Pedestrian-Level Wind (PLW) simulations show that areas with an amplification factor greater than 1 (wind speeds higher than average) tend to be more comfortable, although RANS simulation techniques have a limited accuracy for factors below 1. Solutions, like skycourt vegetation or hybrid ventilation, can mitigate this impact; nevertheless, they need to be optimized for humid tropical climates, like Aceh, where shading and airflow must be balanced to prevent moisture stagnation [16].

The combination of CFD-GIS is essential for microclimatic analysis to avoid surface temperature bias [17]. High-rise buildings should adopt skycourts with vertical openings, while low-rise buildings should prioritize cross-ventilation, as seen in traditional houses [18]. The use of air gap insulation (such as in refugee tents) and reflective roofs can reduce the thermal loads by up to 2.9°C [9]. Indices, such as Standard Effective Temperature (SET) and Predicted Mean Vote (PMV), must be recalibrated for humid tropical climates, considering the higher wind speed tolerance of local populations [19]. Research on the effects of surrounding vegetation and buildings on the wind flow remains limited [20, 21], highlighting the need for participatory research to understand the local comfort preferences. This study reinforces the importance of a multidisciplinary approach to thermal planning, combining local wisdom (such as the Acehese stilt houses) with advanced technologies (CFD-GIS). Design solutions should be contextual, taking into account the microclimatic variability and user needs, in order to create sustainable built environments in the era of urbanization and climate change.

The numerical solution in this study was considered converged when the residuals of the continuity and momentum equations decreased below 10^{-4} , while the temperature residuals fell below 10^{-6} . Furthermore, key monitoring parameters, such as airflow velocity and temperature at critical locations, exhibited minimal variation between successive iterations, confirming the numerical stability and accuracy of the simulation [22]. CFD modeling has proven to be a powerful tool in evaluating and optimizing various ventilation strategies across indoor environments. For example, CFD has been successfully applied to assess the performance of upper-room Ultraviolet Germicidal Irradiation (UVGI) systems in managing localized airflow, temperature distribution, and airborne bacterial concentrations, contributing to an improved indoor air quality and energy efficiency [23]. Similarly, the CFD simulations have been used to validate analytical models for predicting the airflow and CO₂ distribution in Underfloor Air Distribution (UFAD) systems, thereby supporting the design of ventilation configurations that enhance both the thermal comfort and air quality [24]. In the context of displacement ventilation, CFD modeling enables the optimization of supply conditions to maintain acceptable CO₂ levels in the breathing zone, minimize the draft discomfort, and reduce the temperature stratification, while achieving significant energy savings, up to 44% in some cases, through careful parameter tuning [25]. Additionally, CFD has been

effectively utilized to determine optimal UFAD configurations by adjusting variables, such as diffuser size, supply air temperature and velocity, and the return air ratio. These optimizations aim to meet the thermal comfort criteria and indoor air quality standards, with minimal energy consumption, making CFD a valuable asset in sustainable ventilation design [26]. Thermal comfort in indoor environments is generally achieved when relative humidity ranges between 30% and 65%, and ambient temperatures are maintained between 20°C and 26°C.

The CFD simulations conducted for the Baiturrahman Grand Mosque indicate that the implementation of passive ventilation strategies effectively sustains optimal wind speeds between 1 and 3 m/s across the primary spatial planes. These airflow patterns remain consistent throughout the day, contributing to stable indoor air movement. Despite the natural fluctuations in outdoor temperature, the internal thermal conditions remain within an acceptable comfort range of 22°-30°C, with peak temperatures recorded at approximately 29.6°C around 12:00 WIT. The dome architecture, in conjunction with strategically placed entrance and side ventilation openings, enhances the vertical airflow, thereby promoting an effective air circulation and supporting natural cooling processes within the mosque interior [27].

IV. CONCLUSION

- This study contributes several key findings related to the thermal comfort in tropical buildings, particularly the Baiturrahman Grand Mosque, and their implications for sustainable design in both urban and rural areas. The CFD simulations demonstrate that the passive ventilation design is capable of maintaining optimal wind speeds (1–3 m/s) in the main areas (XY, XZ, YZ), with a consistent airflow pattern throughout the day. The temperature remains within a comfortable range (22–30°C), despite an increase in temperature during midday (up to 29.6°C at 12:00 WIT). An effective air distribution through the entrance and side vents, supported by the dome structure, facilitates vertical airflow.
- Recommendations for architectural practice and microclimate-based design policies include the integration of CFD in the early stages of design to predict the thermal performance. Additionally, adapting elements of Acehese houses (e.g., overhanging roofs, stilt houses) into modern buildings should be explored. The development of local guidelines for thermal indices, which consider the physiological adaptations of tropical populations, is also proposed.
- The incorporation of skycourt vegetation and living walls to enhance shading and evaporative cooling should be prioritized. For future research, there is a need to develop more advanced Computational Fluid Dynamics - Geographic Information System (CFD-GIS) computational models, conduct field validation using Internet of Things (IoT) sensors, and implement adaptive design solutions, like phase-change materials and hybrid ventilation. Studies should also focus on urban solutions, such as green infrastructure, and promote multidisciplinary collaboration

to address the challenges posed by the climate change. The implementation of pilot projects, such as smart mosques and refugee shelters based on research findings, could serve as strategic steps toward creating sustainable built environments in tropical climates.

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