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Numerical analysis of thermal comfort behavior in Acehnese traditional houses in Indonesia

Muslimsyah[1*], Husni Husin[2], Akhyar[3]

[1] Department of Architecture and Planing, Universitas Syiah Kuala, Banda Aceh 23111, Indonesia
[2] Department of Chemical Engineering, Universitas Syiah Kuala, Jl. Syech Abdurrauf 7, Darussalam, Banda Aceh 23111, Indonesia
[3] Department of Mechanical Engineering, Universitas Syiah Kuala, Jl. Syech Abdurrauf No. 7, Darussalam, Banda Aceh 23111, Indonesia
* Corresponding author's e-mail: muslimsyah@usk.ac.id

ABSTRACT

To achieve sustainability amid the limited global energy resources, it is crucial to minimize energy consumption and enhance economic efficiency by utilizing local and recycled materials. In the Aceh Peninsula, Indonesia, various local building construction techniques have evolved over centuries, adhering to these principles. The diverse climate and cultural influences in Aceh (Indonesia) have led to the development of rich and varied building construction solutions. Traditional houses are considered to exhibit better thermal behavior compared to modern houses. The passive design features in traditional houses, such as natural ventilation and the use of local materials, can serve as a reference for passive system design. This study aims to analyze the thermal comfort of Acehnese traditional houses using CFD simulations and direct measurements to evaluate the effectiveness of passive design in maintaining temperature stability in a tropical climate. Based on CFD simulations and direct measurements, the study reveals that Acehnese traditional houses exhibit good thermal performance in maintaining thermal comfort. The wind speed distribution profile inside the building at 08:00 ranges from 0 to 1.6 m/s, with incoming air speeds of approximately 1–1.4 m/s. At 12:00, wind speed increases to a range of 0–2.7 m/s, with incoming air speeds around 1.9–2.5 m/s. At 16:00, wind speed varies between 0 and 2.5 m/s, with incoming air speeds of about 1.5–2 m/s. Additionally, the initial temperature at 08:00 is around 23 °C, indicating relatively cool conditions in the morning. The temperature gradually increases, reaching a maximum of approximately 29 °C between 12:00 and 14:00 before decreasing again. By 16:00, the temperature drops to around 27 °C, indicating gradual heat release. This study confirms that the passive design of traditional houses, including natural ventilation and the use of local materials, plays a significant role in maintaining indoor temperature stability. By maintaining indoor temperatures within the thermal comfort range for 80% of the time, Acehnese traditional houses can serve as a reference for the development of sustainable architecture in tropical regions. Future research should further analyze the impact of extreme weather changes and design adaptations to enhance the thermal efficiency of traditional houses in addressing evolving climate challenges.

Keywords: numerical analysis, computational fluid dynamics, thermal comfort, Acehnese traditional houses

INTRODUCTION

In an era of global energy resource limitations, improving energy efficiency and utilizing local materials have become key strategies for achieving sustainability. The construction sector is one of the main contributors to energy consumption, particularly in building cooling and heating systems. Therefore, the development of architectural solutions that optimize thermal efficiency without relying on additional energy sources is crucial. Traditional houses worldwide have evolved with passive design principles that allow them to adapt to local environmental conditions. One such example is the Acehnese traditional house, which has endured for centuries in the Aceh Peninsula, Indonesia.

The diverse climate and cultural influences present in the Aceh region have led to the development of rich and varied construction solutions, tailored to the environmental and socio-cultural needs of the local community. The Acehnese traditional house is known for its adaptive design to tropical climates, incorporating natural ventilation, the use of local materials, and spatial arrangements that facilitate optimal airflow. This makes traditional houses more efficient in maintaining thermal comfort compared to modern buildings, which often rely on artificial cooling (Lotfabadi and Hançer, 2019; Dear et al., 2013; Fouseki et al., 2020).

Global climate change and rising environmental temperatures pose challenges in maintaining thermal comfort in buildings located in tropical regions (Latha, et al., 2015). Although traditional house designs have been proven to maintain stable indoor temperatures, there is still a lack of research that quantitatively evaluates their thermal performance using a scientific approach (Borong, et al., 2004). Therefore, a study is needed to analyze the thermal behavior of Acehnese traditional houses using numerical methods and direct measurements to understand the effectiveness of passive systems in maintaining thermal comfort (Li and Zhu, 2022).

Recent studies have highlighted the effectiveness of passive cooling strategies in traditional architecture for improving indoor thermal comfort. Samuel et al. (2017) found that vernacular buildings in India utilizing air cavities, high thermal mass, and induced ventilation significantly reduced indoor temperature fluctuations. Hailu et al. (2021) revealed that 88% of occupants in Ethiopian traditional houses were satisfied with thermal comfort compared to only 22% in modern houses, emphasizing the role of traditional design in thermal regulation. Shaeri et al. (2018) demonstrated that natural ventilation in historic Iranian houses effectively maintained thermal comfort with low occupant dissatisfaction rates. Additionally, Toe and Kubota (2015) analyzed passive cooling techniques in Malaysian vernacular houses, showing that features like small courtyards and night ventilation substantially improved indoor conditions.

These studies explore natural ventilation and passive cooling strategies to improve indoor thermal comfort and reduce energy consumption in different climatic conditions. Aram and Abessi (2020) found that increasing windward-side space, adding roof windows, and using light-colored coatings significantly enhanced ventilation and reduced apparent temperature by up to 10 °C in Iran's humid climate. Kim (2021) and Barbosa and Southall (2015) investigated double-skin façades (DSF), revealing that cavity geometry, opening sizes, and shading devices influence airflow and temperature, improving comfort in Saudi Arabia and Rio de Janeiro, respectively. Mirrahimi et al. (2016) analyzed passive design elements in Malaysia's high-rise residential buildings, emphasizing envelope design, shading, and ventilation as key factors in maintaining thermal comfort between 25–31 °C. Finally, Stavrakakis (2010) used CFD modeling and artificial neural networks to optimize night-time ventilation in rural houses, demonstrating that building orientation and opening sizes significantly impact airflow and thermal comfort.

These studies examine the relationship between climate change, energy consumption, and HVAC strategies in buildings. Ali and Akkaş (2023) highlight the inefficiencies of conventional air conditioning in green buildings, advocating for innovative HVAC solutions that align with sustainability. Wang et al. (2010) project significant increases in heating and cooling energy demands in Australia due to climate change, with energy-efficient homes being particularly sensitive to future temperature changes. Lomas and Ji (2009) demonstrate that advanced natural ventilation strategies outperform single-sided ventilation in maintaining indoor comfort and reducing energy use, especially in hospital buildings under a warming climate. Wan et al. (2012); Wang and Chen (2014) analyze climate change impacts on energy demand in office and residential buildings across China and the U.S., respectively, emphasizing the need for adaptive design measures, such as improved insulation, optimized cooling setpoints, and enhanced natural ventilation.

The research emphasizes the importance of passive and low-energy systems in reducing building energy consumption and enhancing thermal comfort while minimizing environmental impact (Omer, 2008). Mushtaha et al. (2021) conducted a simulation-based study integrating passive design strategies such as shading, natural ventilation, and insulation, achieving a 59% reduction in total energy consumption. Ascione, et al. (2015) optimized the thermal properties of building envelopes for Mediterranean climates using a Genetic Algorithm, demonstrating significant energy savings with high-reflective coatings and proper insulation. Hellwig et al. (2019) explored the adaptive thermal comfort concept, identifying challenges in translating scientific findings into practical building designs. Nguyen and Reiter (2014) applied optimization algorithms to low-cost housing, demonstrating substantial energy savings and improved indoor comfort through adaptive comfort approaches.

Therefore, this study aims to analyze the thermal comfort behavior of Acehnese Traditional Houses in Indonesia using numerical simulations and direct temperature measurements. By applying CFD, this research evaluates the effectiveness of passive design strategies, such as natural ventilation and the use of local materials, in maintaining indoor thermal comfort. The study compares numerical simulation results with field measurements recorded throughout 2022 and validates them with data from the Indonesian Meteorology and Geophysics Agency (Aceh branch). This research is expected to contribute to the development of sustainable architecture, particularly in tropical regions. The findings of this study can serve as a reference for designing more thermally efficient modern buildings by adopting the passive design principles applied in Acehnese traditional houses. Additionally, this study can serve as a foundation for further research exploring the adaptation of traditional house designs in response to extreme climate change in the future.

MATERIALS AND METHODS

This study will be conducted at the locations around Banda Aceh, Indonesia. The Aceh museum, is located on Jalan Sultan Mahmudsyah Nomor 10, Peuniti, Baiturrahman District, with geographic coordinates of 5° 32’ 55.5” North latitude and 95° 19’ 16.0” East longitude. Aceh is a region situated at the western tip of Sumatra Island, surrounded by the Indian Ocean and the Malacca Strait, and is characterized by distinct wind patterns.

In this study, three fundamental equation categories are derived from the principles of mass and energy conservation, namely mass, momentum, and energy conservation. These principles result in the continuity equation, the Navier-Stokes equations, and the energy equation (Norton, & Sun, 2006). In the conducted simulation, the Reynolds number was calculated for each drying case. The results indicate that the Reynolds number exceeds 2000, suggesting that the airflow within the dryer exhibits a turbulent flow pattern (Amanlou & Zomorodian, 2010; Akhyar, et. al., 2022).

Various turbulence models are embedded in commercial CFD software, and their application is tailored to the specific case under analysis (Norton, & Sun, 2006). Among the available turbulence models, the standard k-ε model is one of the most widely applied in industrial settings (Foster, et. al., 2005; Margaris and Ghiaus, 2006). This standard k-ε model is a semi-empirical model based on transport equations, specifically for turbulent kinetic energy (k) and its dissipation rate (ε). The transport equation for k is derived directly from the exact equation, while the transport equation for ε is formulated using physical reasoning, which, although having some limitations, still shows similarities with its mathematical counterpart (Yongson, et. al., 2007). The turbulent kinetic energy (k) and its dissipation rate (ε) in this simulation are determined using the following transport Equations 1–2.

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

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

The convective heat and mass transfer modeling in the k-ε model is represented by Equation 3, as reported by Yongson et al. (2007).

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

This study assesses the thermal comfort of refugee tents in Aceh by integrating field measurements with computational simulations conducted using Ansys Fluent 19.2 (CFD software). Before conducting the simulation, the first step is to collect the necessary data for the simulation, including initial condition data and boundary condition data. The simulation will use time variations starting from 08:00 AM to 04:00 PM, as presented in the Table 1 and Table 2.

In this simulation, the object used is a traditional stilt house from the Aceh region, known as Rumoh Aceh. The dimensional data of the Rumoh Aceh used in this study are presented in the Table 3.

Table 1. Initial conditions (Akhyar, et. al., 2022)

No.	Initial conditions		Planning
1	Flow type		Pressure – based
2	Time		Steady state
3	Velocity formulation		Absolute
4	Viscous models		STT k-ω
5	Radiation		Rosseland
6	Solar loading (solar calculator: Global Position) Banda Aceh	Langitude (deg)	95.32375
		Latitude (deg)	5.54829
		Time zone (+-GMT)	7
7	Mesh orientation	North	Z=1
		East	X=-1
8	Material	Fluid	Air
		Solid	Wood

In this simulation, the geometry of Rumoh Aceh was designed using computer-aided design (CAD) application. Rumoh Aceh has two doors on the lower part of the house, ten windows on the front side, and ten windows on the back side. Additionally, it has windows on both the right and left sides, with 20 windows on each side.

The Rumoh Aceh consists of six separate rooms, divided by walls. This simulation was conducted with a time variation ranging from 08:00 WIB/AM to 16:00 WIB (04:00 PM). The geometric design of Rumoh Aceh can be seen in the Figure 1.

Figure 1 illustrates the geometric design of Rumoh Aceh, showcasing its dimensions as follows: the building has a length of 2000 cm, a width of 920 cm, and a height of 865 cm. The front and rear windows measure 50 cm in width and 100 cm in height, while the side windows have a width of 50 cm and a height of 70 cm. The meshing process was carried out after importing the geometry into DesignModeler. The meshing results for the Rumoh Aceh geometry (Figure 2).

In this meshing stage, a tetrahedron mesh type was used. The tetrahedron mesh was chosen due to its advantages in handling complex and intricate geometries. Additionally, the tetrahedron mesh is significantly better at analyzing fluid flow compared to other mesh types. The shape of the tetrahedron mesh can be seen in the Figure 3.

The initial stage begins with the general setup. In this stage, the solver method to be used is determined. The second stage involves selecting the models for the simulation. In this simulation, the energy equation is activated, the shear stress transport (SST) k-ω model is selected for the viscous model, and the Rosseland model is chosen for radiation.

Next, the material properties used in the simulation are defined. This is followed by setting the boundary conditions, which include input data for velocity, temperature, thermal conditions, and the selection of wall conditions and momentum parameters (Figure 4). The reference values configuration includes determining the method used and the number of initialization steps for the simulation.

The inlet acts as the primary entry point for air circulation within the room, such as through windows, while the walls define the fluid boundary for the simulation. The outlet serves as the air exhaust channel, allowing airflow to exit the structure. In the CFD simulation of Rumoh Aceh, the scale is set in millimeters, and a tetrahedral mesh with a size of 30 mm is applied. The simulation utilizes a pressure-based solver method with double precision and a steady-state approach to ensure a robust and efficient single-phase flow implementation.

The data models incorporated in the simulation include an enabled energy equation, an SST k-ω viscous model with a production limiter option, and a radiation model using the Rosseland approach. Additionally, solar loading is accounted for using a solar calculator, with the global position set to Banda Aceh at a longitude of 95.32375°, a latitude of 5.54829°, and a time zone of GMT+7.

Material properties considered in the simulation include air as the fluid material and wood as the solid material. The properties of wood are defined by a density of 700 kg/m³, a specific heat capacity (Cp) of 2310 J/kg·K, and a thermal conductivity of 0.173 W/m·K (https://help.iesve.

Table 2. Boundary conditions (Akhyar, et. al., 2022)

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	Temperature inlet	Time (WIB)	Temperature (ºC)
		08.00	22
		09.00	25
		10.00	26
		11.00	28
		12.00	28.1
		13.00	29
		14.00	28.9
		15.00	27.5
		16.00	27
6	Free stream temperature	08.00	26
		09.00	29
		10.00	30
		11.00	32
		12.00	32
		13.00	32
		14.00	30
		15.00	31
		16.00	30
7	Velocity	Timen (WIB)	Air velocity (m/s)
		08.00	1.67
		09.00	2.22
		10.00	2.22
		11.00	2.22
		12.00	3.05
		13.00	3.05
		14.00	3.05
		15.00	2.5
		16.00	2.5
8	Thermal condition		Convection
9	Radiation		Participates in solar ray tracing (opaque)
10	Solution methods		Simple
11	Initialization methods		Standard initialization

Tabel 3. Planning data for Rumoh Aceh

No.	Parameter		Value
1	Room dimensions	Length	2000 cm
		Width	920 cm
		Height	860 cm
2	Tent wall (wood)	Thickness	2.5 cm
3	Number of ventilation		60

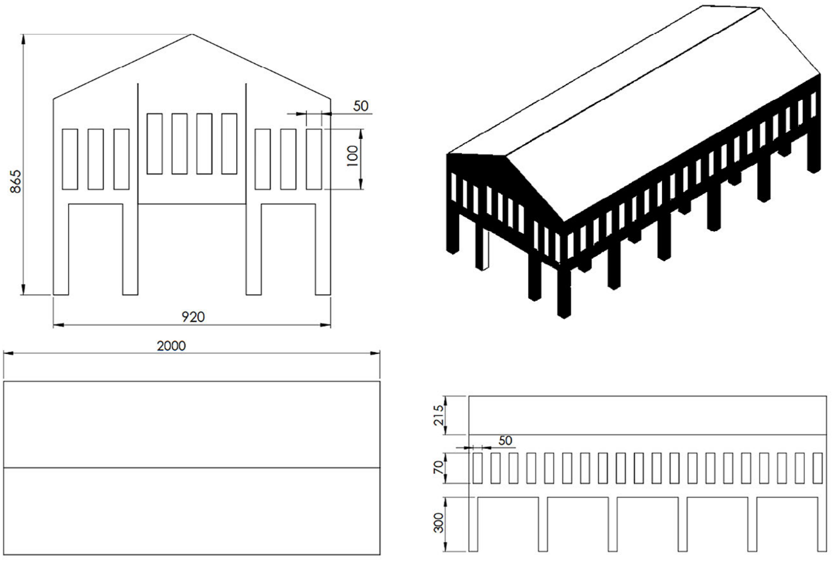

Figure 1. Dimensions of Rumoh Aceh (in cm)

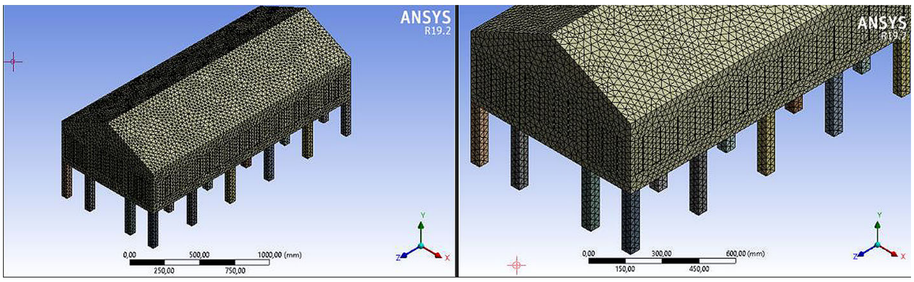

Figure 2. Meshing results of Rumoh Aceh

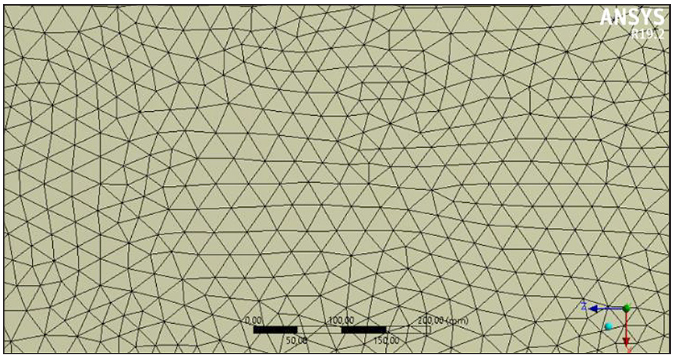

Figure 3. Mesh tetrahedron

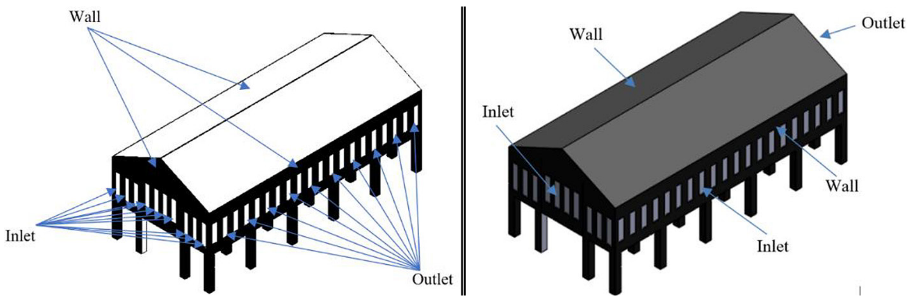

Figure 4. Traditional Rumoh Aceh boundary conditions

com/ve2021/table_6_thermal_conductivity__specific_heat_capacity_and_density.htm).

RESULTS AND DISCUSSION

Since no specific orientation rules are prescribed for Traditional Acehnese Houses, the digital simulation assumes a general orientation with the longitudinal axis of the house aligned either north-south or east-west. The CFD simulation utilizes direct field measurement data along with data from the nearest Indonesian Meteorology and Geophysics Agency station, collected daily over the span of one year. The simulation model is also simplified by removing ornamental details that are deemed insignificant or negligible in influencing airflow and thermal behavior.

In this study, the thermal comfort analysis of traditional Acehnese houses is conducted not only by evaluating numerical values but also by analyzing contours and vectors representing temperature and wind velocity distributions. The simulation results are presented through wind velocity and temperature contours across specific planes. The air velocity at the inlet is adjusted based on predetermined time variations, ranging from 08:00 WIB to 16:00 WIB. At 08:00 WIB, the inlet air velocity is set to 1.67 m/s. The study considers XY, XZ, and YZ planes inside the house, with distances set as follows are XY plane: 0 m; XZ plane: 0.2 m; YZ plane: 0 m. The plane distances are chosen to match human height and experience within the indoor space.

Based on Figure 5, it can be observed that wind velocity ranges from 0 to 1.6 m/s at 12:00 WIB. At 12:00 WIB and 16:00 WIB, wind velocity ranges

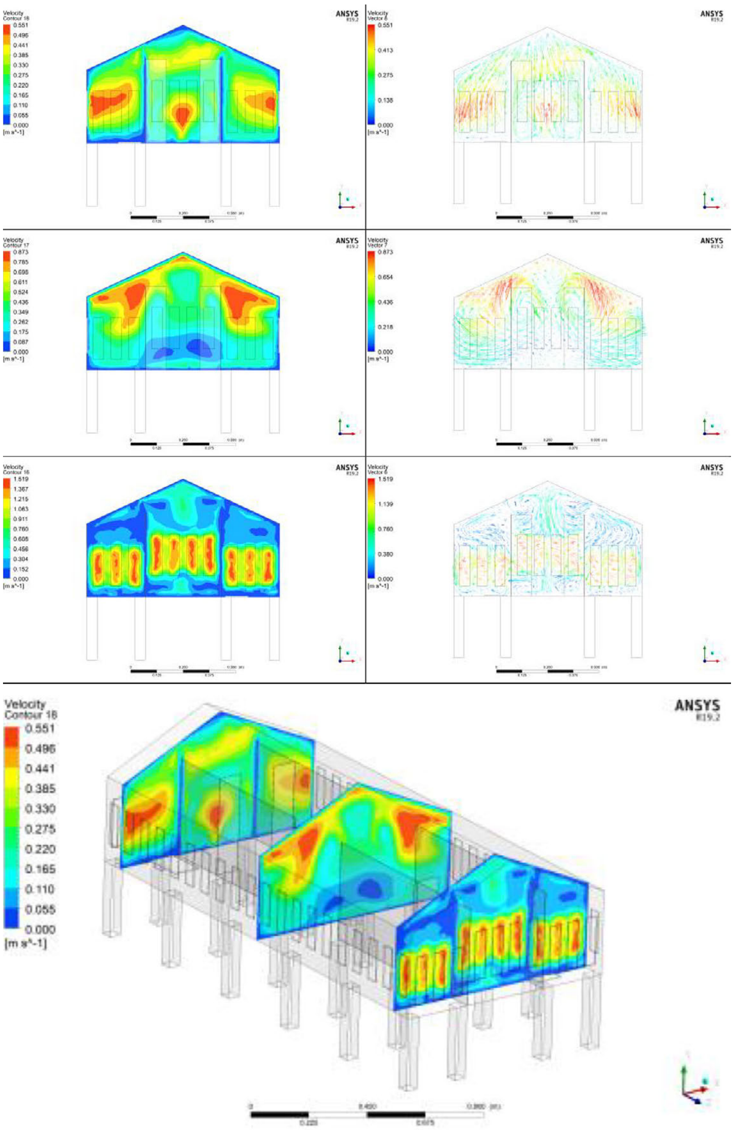

Figure 5. Velocity distribution on the vertical section of traditional Rumoh Aceh (XY plane)

are 0–2.7 m/s and 0–2.5 m/s, respectively, with the highest wind velocity recorded at 12:00 WIB. Figure 5 also shows that the highest wind velocity occurs at the front of the house, which is attributed to wind entering through ventilation openings at the front. This phenomenon leads to an increase in velocity in that region. The direction of airflow can be observed in Figure 6 and Figure 7.

Figure 6 illustrates that the airflow direction remains consistent across three different time periods. The wind flows towards the upper and central areas of the room. The incoming wind velocity is approximately 1–1.4 m/s at 08:00 WIB, 1.9–2.5 m/s at 12:00 WIB, and 1.5–2.0 m/s at 16:00 WIB.

The Figure 17 presents a comparison between experimentally measured and simulated temperature variations over time, spanning from 8:00 to 16:00. The experimental data, represented by red crosses and a dashed line, closely follows the trend of the simulation results, which are depicted by black circles and a solid line. From the graph, the temperature shows a consistent increase in the morning, reaching its peak around 13:00–14:00, before gradually decreasing in the afternoon. This pattern is typical of daily temperature fluctuations influenced by solar radiation and environmental conditions. The agreement between the simulation and experimental results demonstrates that the computational model effectively captures the thermal behavior of the system. However, minor discrepancies between the two datasets can be observed at certain time points, particularly during the warming phase (8:00–10:00) and cooling phase (14:00–16:00). These differences may arise due to factors such as measurement uncertainties, simplifications in the simulation model, or variations in real-world environmental conditions that are not fully accounted for in the numerical approach. The strong correlation between experimental and simulation data validates the reliability of the computational model in predicting temperature variations. This indicates that the model can be used for further analysis and optimization of thermal performance in similar studies.

The data obtained indicates that the indoor temperature gradually increases from 08:00, reaching its peak between 12:00 and 14:00, before gradually decreasing after 15:00. This trend suggests the presence of a heat accumulation effect during the daytime, followed by a gradual release in the afternoon. This characteristic aligns with passive design principles, where natural ventilation and the use of local materials with high thermal capacity contribute to stabilizing indoor temperatures, as shows at Figures 8–17.

Between 09:00 and 11:00, there is a significant increase in temperature, indicating that the house begins to absorb heat from the external environment. However, after reaching approximately 28–29 °C between 12:00 and 14:00, the temperature remains relatively stable with minimal fluctuations. This stability demonstrates the effectiveness of the natural ventilation system and building materials in optimally distributing and storing heat.

Compared to modern houses constructed with materials such as concrete and glass, traditional Acehnese houses exhibit superior thermal performance in maintaining indoor temperatures within a comfortable range. Natural materials, such as wood and thatched roofs, provide excellent insulation properties, reducing the rate of rapid heat transfer. The implementation of cross-ventilation also plays a crucial role in maintaining effective airflow, preventing excessive heat accumulation during the day.

These findings are consistent with previous research, which suggests that traditional house designs in tropical regions offer better thermal comfort than modern constructions that often lack adequate natural ventilation systems (Jegede and Taki, 2022). Additionally, comparisons with data from the Indonesian Meteorology and Geophysics Agency, Aceh branch, confirm consistency between simulation results and field measurements, reinforcing the validity of the findings.

Traditional architecture has long been adapted to local climatic conditions to ensure indoor thermal comfort without relying on modern HVAC systems (Beccali et al., 2018). The design of traditional Acehnese houses, for instance, incorporates passive cooling strategies such as elevated floors, natural ventilation, and the use of thermally efficient materials. These elements help regulate indoor temperatures and maintain comfort even in hot and humid tropical climates. Compared to modern concrete and glass structures, traditional houses demonstrate superior thermal adaptability due to their ability to facilitate air circulation and minimize heat retention (Munir et al., 2024). Studies on traditional architectural designs worldwide have highlighted the effectiveness of vernacular techniques in mitigating extreme weather conditions while ensuring comfort (Hu, 2023). This study evaluates the thermal comfort of refugee tents in Aceh's

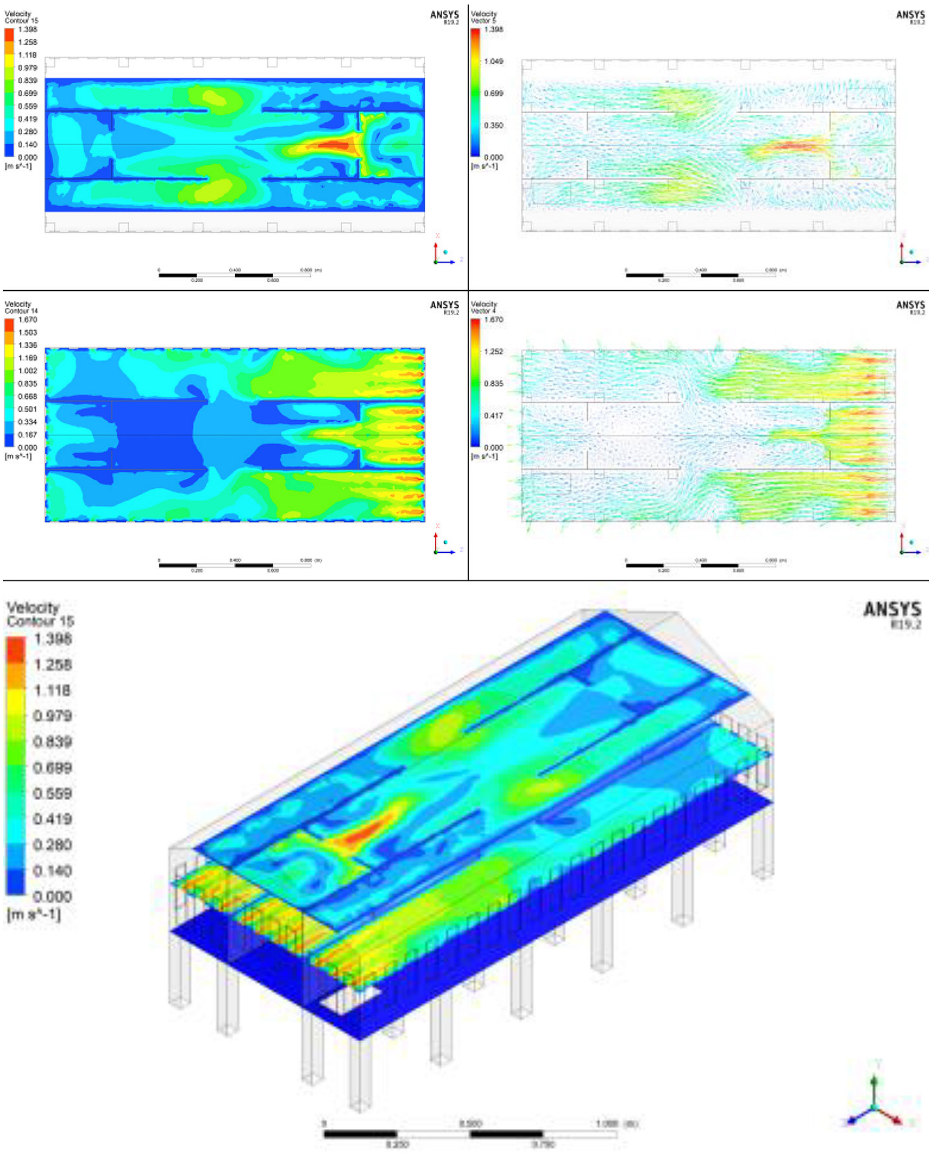

Figure 6. Velocity distribution on the horizontal section of traditional Rumoh Aceh (XZ plane)

tropical climate using field measurements and CFD simulations, proposing improved designs with ventilation and insulation that enhance airflow by 0.18 m/s and reduce indoor temperatures by up to 2.9 K (Haiqal et al., 2025).

The CFD has emerged as a powerful tool for analyzing indoor and outdoor airflow patterns, temperature distribution, and overall thermal comfort (Quang et al., 2024.). In this study, CFD simulations were conducted to assess the airflow and temperature variations inside Traditional Acehnese Houses at different times of the day. The results indicated significant thermal stability due to natural ventilation and material properties. By visualizing air velocity vectors and temperature contours, CFD enables researchers and architects to optimize passive design strategies, improving the effectiveness of traditional and modern sustainable buildings. The integration of CFD in thermal analysis enhances the accuracy of predictions and provides valuable insights for designing energy-efficient structures (Kang et al., 2022).

Climate change has led to rising global temperatures, increased frequency of extreme weather events, and shifts in humidity levels, all of which significantly impact indoor thermal comfort. Traditional building designs, which have historically been well-adapted to local climates, may face challenges in maintaining their effectiveness due to these changing conditions (Juan et al., 2019). The increasing intensity of heat waves, for instance, may necessitate additional passive cooling strategies or material modifications to

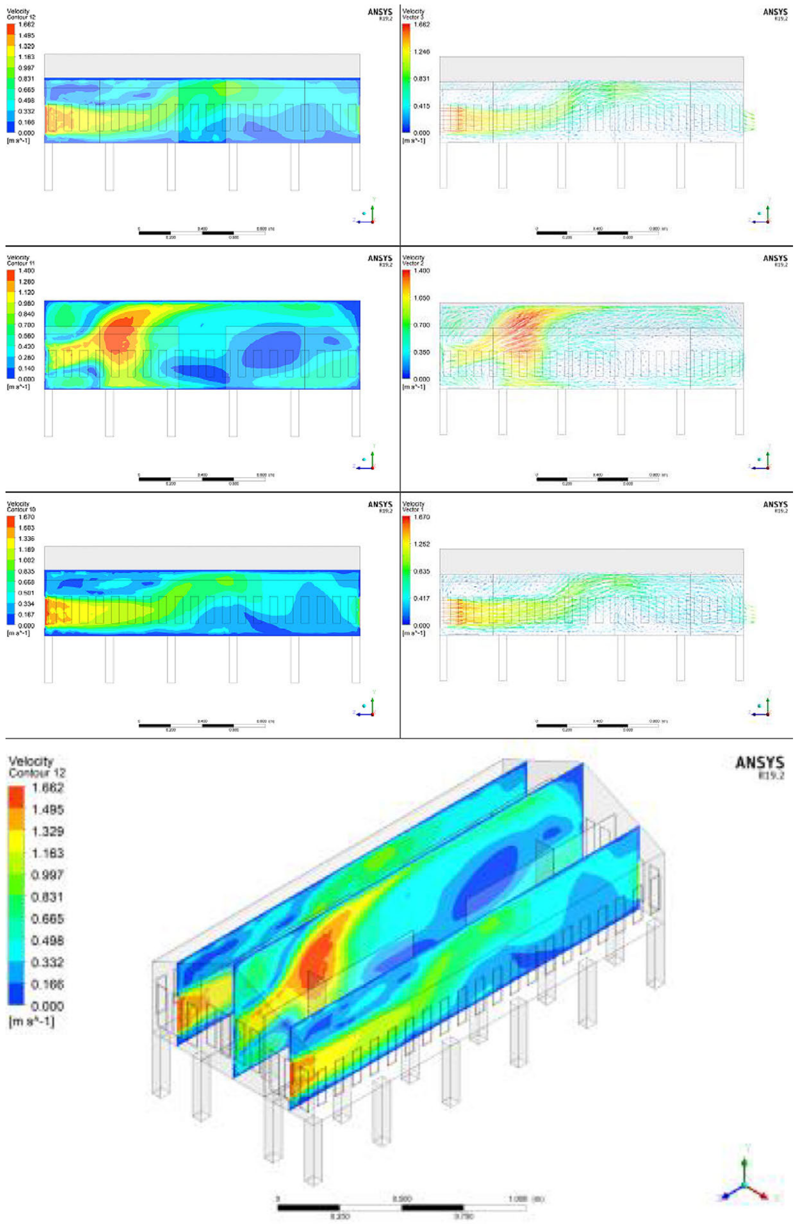

Figure 7. Velocity distribution on the longitudinal vertical section of traditional Rumoh Aceh (YZ plane)

enhance heat dissipation (Attia et al., 2021). Future research should focus on how traditional architectural designs can be adapted to withstand these changes while preserving their inherent sustainability and efficiency.

Sustainable architecture prioritizes energy efficiency, minimal environmental impact, and occupant well-being. The design principles observed in Traditional Acehnese Houses align with modern sustainability goals by reducing dependence on artificial cooling systems and optimizing natural resources for thermal comfort. The combination of natural ventilation, appropriate building orientation, and the use of local materials contributes to lower energy consumption (Chenari et al., 2016). Lessons from traditional architecture can inform contemporary building designs to develop more resilient and energy efficient structures (Amirkhani and Martek, 2024; Oktay, 2017; Cascone et al., 2024). Further exploration of hybrid approaches integrating passive strategies with modern energy efficient technologies can enhance building performance in a changing climate.

Overall, this study confirms that Acehnese traditional houses offer thermal efficiency advantages due to their passive design approach. These findings provide a foundation for the development of sustainable architecture by utilizing proven design principles that effectively adapt to local

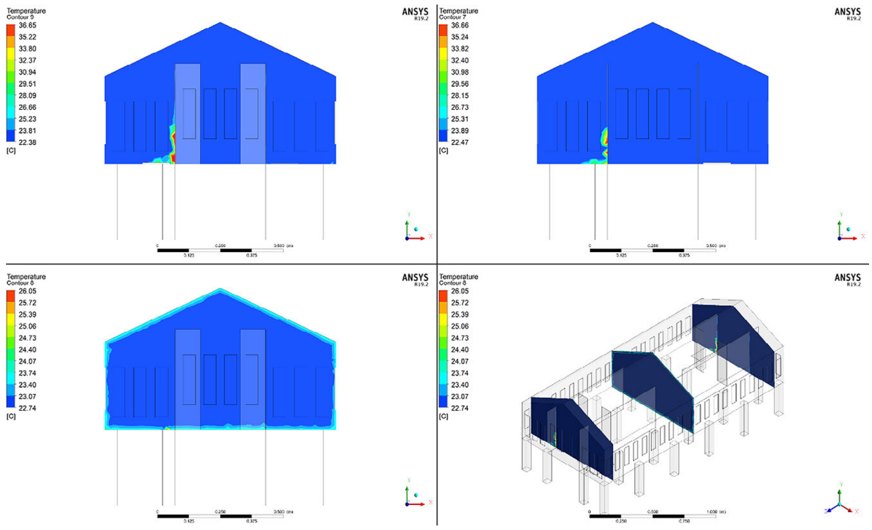

Figure 8. Temperature distribution on the vertical section of traditional Rumoh Aceh (XY plane) at 08:00 WIB

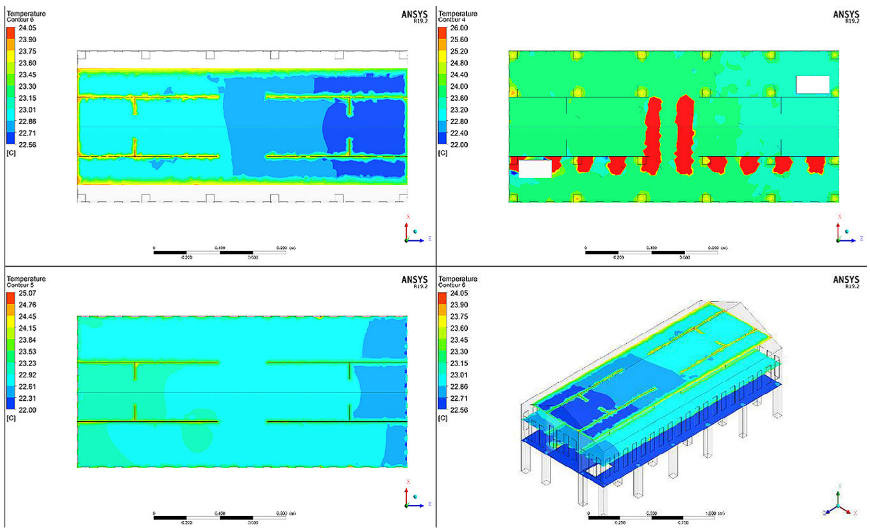

Figure 9. Temperature distribution on the horizontal section of traditional Rumoh Aceh (XZ plane) at 08:00 WIB

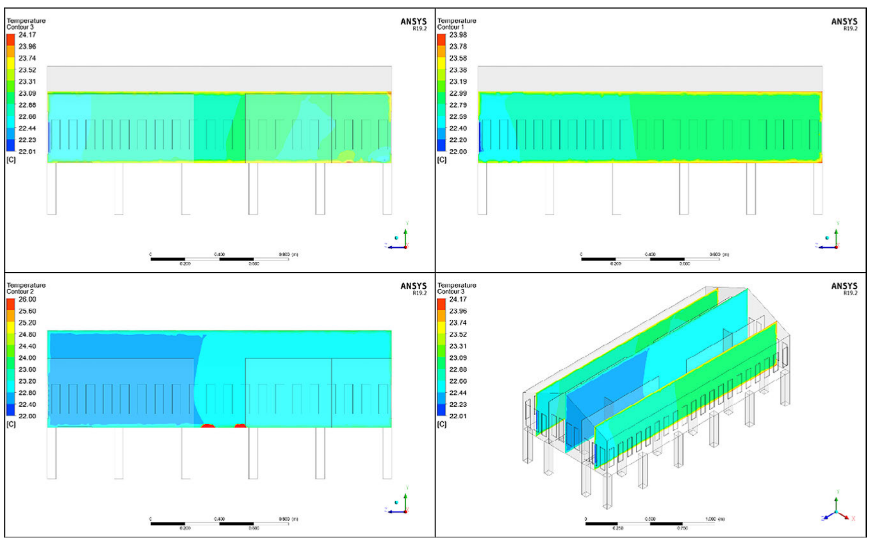

Figure 10. Temperature distribution on the longitudinal vertical section of traditional Rumoh Aceh (YZ Plane) at 08:00 WIB

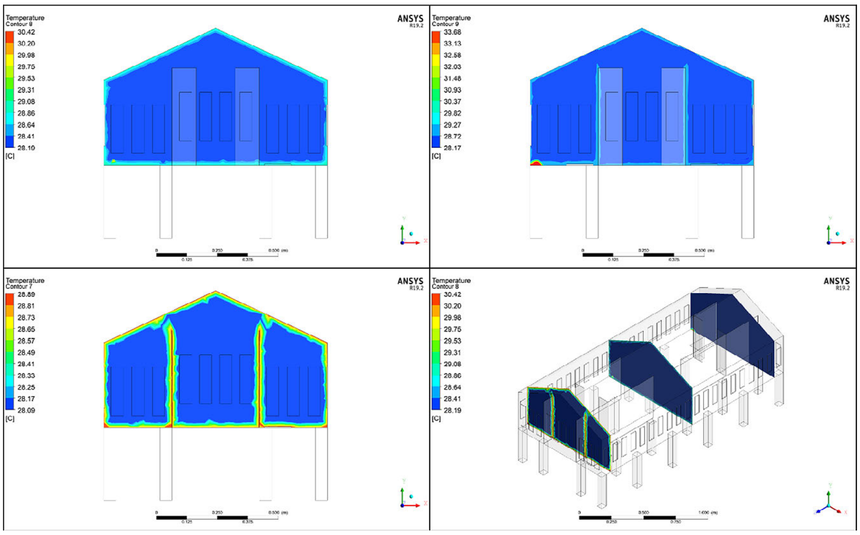

Figure 11. Temperature distribution on the vertical section of traditional Rumoh Aceh (XY plane) at 12:00 WIB

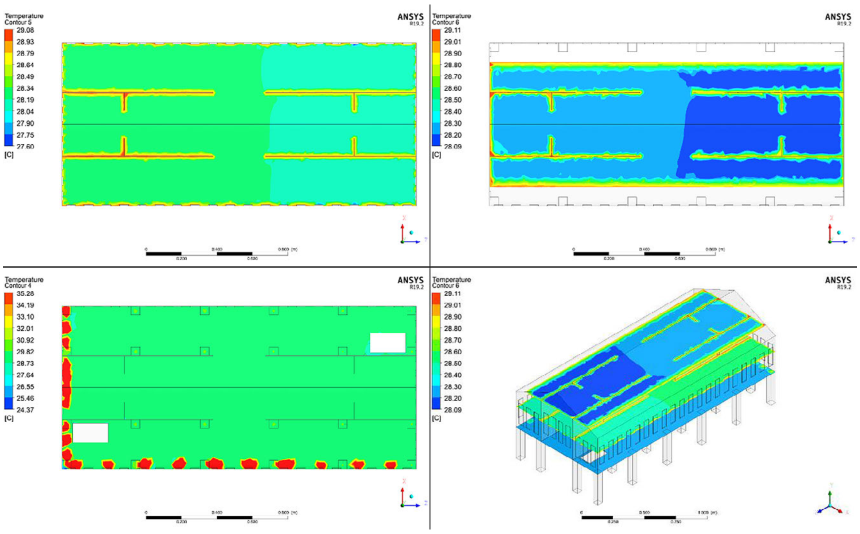

Figure 12. Temperature distribution on the horizontal section of traditional Rumoh Aceh (XZ plane) at 12:00 WIB

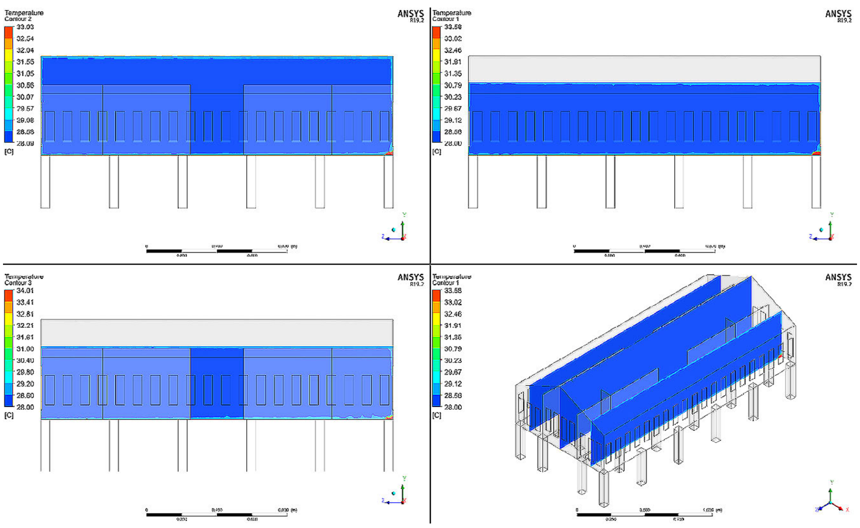

Figure 13. Temperature distribution on the longitudinal vertical section of traditional Rumoh Aceh (YZ plane) at 12:00 WIB

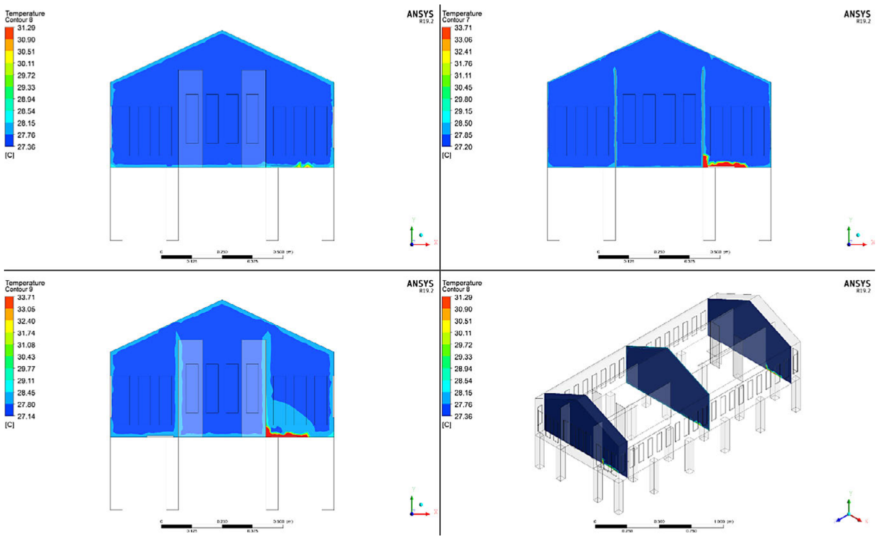

Figure 14. Temperature distribution on the vertical section of traditional Rumoh Aceh (XY plane) at 16:00 WIB

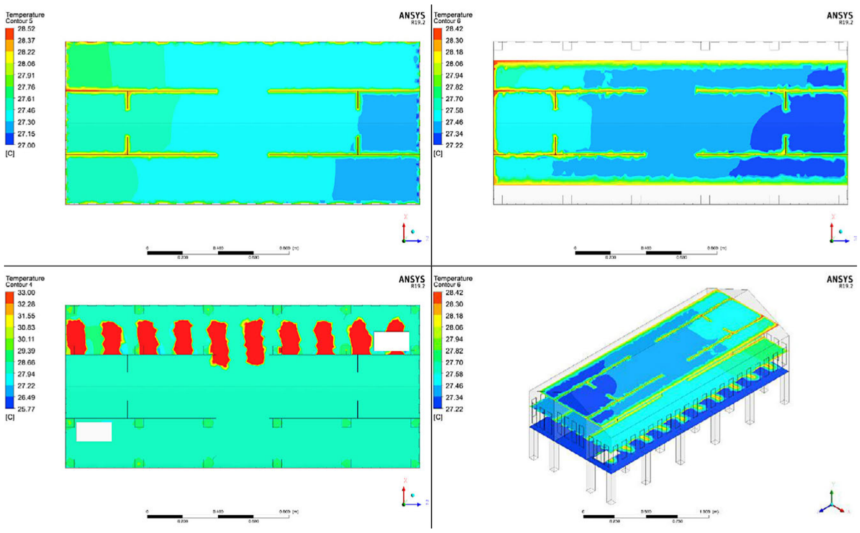

Figure 15. Temperature distribution on the horizontal section of traditional Rumoh Aceh (XZ plane) at 16:00 WIB

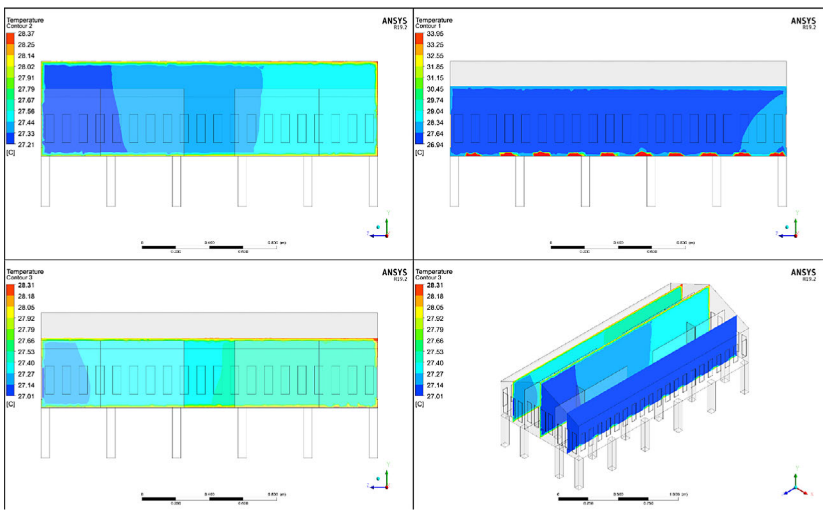

Figure 16. Temperature distribution on the longitudinal vertical section of traditional Rumoh Aceh (YZ plane) at 16:00 WIB

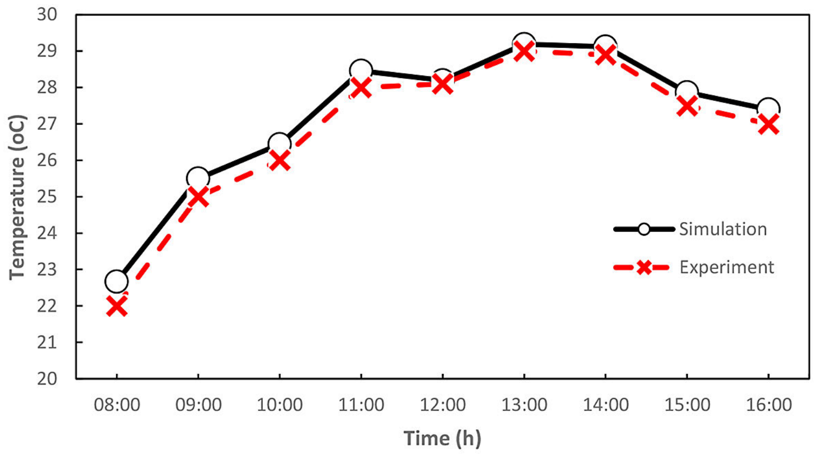

Figure 17. Temperature characteristics experiment and simulation

climatic conditions. Further research is needed to explore the impact of extreme weather variations on the thermal performance of traditional houses and potential design adaptations to enhance energy efficiency in the future.

CONCLUSIONS

Based on CFD simulations and direct measurements, this study demonstrates that traditional Acehnese houses exhibit good thermal performance in maintaining thermal comfort. The wind velocity distribution inside the traditional house varies throughout the day. At 08:00, the wind speed ranges from 0 to 1.6 m/s, with incoming air velocity around 1–1.4 m/s. At 12:00, the wind speed increases to a range of 0–2.7 m/s, with an incoming velocity of approximately 1.9–2.5 m/s. By 16:00, the wind speed is between 0 and 2.5 m/s, with incoming air velocity around 1.5–2 m/s.

At 08:00, the initial indoor temperature is approximately 23 °C, reflecting relatively cool morning conditions. The temperature gradually rises, reaching a peak of around 29 °C between 12:00 and 14:00, before decreasing again. By 16:00, the temperature drops to approximately 27 °C, indicating a gradual heat release.

This study confirms that the passive design of traditional houses, including natural ventilation and the use of local materials, plays a crucial role in maintaining indoor temperature stability. By keeping indoor temperatures within the thermal comfort range for 80% of the time, traditional Acehnese houses serve as a valuable reference for the development of sustainable architecture in tropical regions.

REFERENCES

1. Akhyar, A., Harun, D., Robby, M., Maulana, M.I. & Farhan, A. (2022). Experimental and simulation evaluation of temperature and air flow in tunnel-type dryers: Preliminary study. *Jurnal Polimesin, 20*(1), 55–62. http://dx.doi.org/10.30811/jpl.v20i1.2620
2. Ali, B.M. & Akkaş, M. (2023) The green cooling factor: Eco-innovative heating, ventilation, and air conditioning solutions in building design. *Applied Sciences, 14*(1), 195, 1–25. https://doi.org/10.3390/app14010195
3. Amanlou, Y. & Zomorodian, A. (2010). Applying CFD for designing a new fruit cabinet dryer. *Journal of food engineering, 101*(1), 8–15. https://doi.org/10.1016/j.jfoodeng.2010.06.001
4. Amirkhani, M. & Martek, I. (2024). Latest research on the theme of "Sustainability, challenges, and opportunities to optimize building performance. Sustainability, 16(22), 1–8. https://doi.org/10.3390/su162210040
5. Aram, M. & Abessi, O. (2020). Optimal design of green buildings using computational fluid dynamics and climate simulation tools. *International Journal of Environmental Science and Technology, 17*(2), 917–932. https://doi.org/10.1007/s13762-019-02403-6
6. Ascione, F., Bianco, N., De Masi, R.F., Mauro, G.M. & Vanoli, G.P. (2015). Design of the building envelope: A novel multi-objective approach for the optimization of energy performance and thermal comfort. *Sustainability, 7*(8), 10809–10836. https://doi.org/10.3390/su70810809
7. Attia, S., Levinson, R., Ndongo, E., Holzer, P., Kazanci, O.B., Homaei, S., Zhang, C., Olesen, B.W., Qi, D., Hamdy, M. & Heiselberg, P. (2021). Resilient cooling of buildings to protect against heat waves and power outages: Key concepts and definition. *Energy and Buildings, 239*, 1–12. https://doi.org/10.1016/j.enbuild.2021.110869

8. Barbosa, S., Ip, K. & Southall, R. (2015). Thermal comfort in naturally ventilated buildings with double skin façade under tropical climate conditions: The influence of key design parameters. *Energy and Buildings, 109*, 397–406. https://doi.org/10.1016/j.enbuild.2015.10.029
9. Beccali, M., Strazzeri, V., Germanà, M.L., Melluso, V. & Galatioto, A. (2018). Vernacular and bioclimatic architecture and indoor thermal comfort implications in hot-humid climates: An overview. *Renewable and Sustainable Energy Reviews, 82*, 1726–1736. https://doi.org/10.1016/j.rser.2017.06.062
10. Borong, L., Gang, T., Peng, W., Ling, S., Yingxin, Z. & Guangkui, Z. (2004). Study on the thermal performance of the Chinese traditional vernacular dwellings in Summer. *Energy and Buildings, 36*(1), 73–79. https://doi.org/10.1016/j.buildenv.2024.111634
11. Cascone, S., Parisi, G. & Caponetto, R. (2024). BIM-Based Strategies for the Revitalization and Automated Management of Buildings: A Case Study. *Sustainability, 16*(16), 1–21. https://doi.org/10.20944/preprints202406.1874.v1
12. Chenari, B., Carrilho, J.D. & Da Silva, M.G. (2016). Towards sustainable, energy-efficient and healthy ventilation strategies in buildings: A review. *Renewable and Sustainable Energy Reviews, 59*, 1426–1447. https://doi.org/10.1016/j.rser.2016.01.074
13. de Dear, R.J., Akimoto, T., Arens, E.A., Brager, G., Candido, C., Cheong, K.W.D., Li, B., Nishihara, N., Sekhar, S.C., Tanabe, S. & Toftum, J. (2013). Progress in thermal comfort research over the last twenty years. *Indoor air, 23*(6), 442–461. https://doi.org/10.1111/ina.12046
14. Foster, A.M., Madge, M. & Evans, J.A. (2005). The use of CFD to improve the performance of a chilled multi-deck retail display cabinet. *International Journal of Refrigeration, 28*(5), 698–705. https://doi.org/10.1016/j.ijrefrig.2004.12.009
15. Fouseki, K., Newton, D., Murillo Camacho, K.S., Nandi, S. & Koukou, T. (2020). Energy efficiency, thermal comfort, and heritage conservation in residential historic buildings as dynamic and systemic socio-cultural practices. *Atmosphere, 11*(6), 1–22. https://doi.org/10.3390/atmos11060604
16. Hailu, H., Gelan, E. & Girma, Y. (2021). Indoor thermal comfort analysis: a case study of modern and traditional buildings in hot-arid climatic region of Ethiopia. *Urban Science, 5*(3), 1–35. https://doi.org/10.3390/urbansci5030053
17. Haiqal, M., Sari, L.H., Husin, H., Akhyar, A., Munir, A. & Bilqis, K. (2025). The thermal comfort performance in an Indonesian refugee tent: Existing conditions and redesigns. *Energies, 18*(5), 1249. https://doi.org/10.3390/en18051249
18. Hellwig, R.T., Teli, D., Schweiker, M., Choi, J.H., Lee, M.J., Mora, R., Rawal, R., Wang, Z. & Al-Atrash, F. (2019). A framework for adopting adaptive thermal comfort principles in design and operation of buildings. *Energy and Buildings, 205*. https://doi.org/10.1016/j.enbuild.2019.109476
19. Hu, M. (2023). Exploring low-carbon design and construction techniques: Lessons from vernacular architecture. *Climate, 11*(8). https://doi.org/10.3390/cli11080165
20. Jegede, O.E. & Taki, A. (2022). Optimization of building envelopes using indigenous materials to achieve thermal comfort and affordable housing in Abuja, Nigeria. *International Journal of Building Pathology and Adaptation, 40*(2), 219–247. https://doi.org/10.1108/IJBPA-01-2021-0009
21. Juan, X., Ziliang, L., Weijun, G., Mengsheng, Y. & Menglong, S. (2019). The comparative study on the climate adaptability based on indoor physical environment of traditional dwelling in Qinba mountainous areas, China. *Energy and Buildings, 197*, 140–155. https://doi.org/10.1016/j.enbuild.2019.05.045
22. Kang, K.Y., Wang, X., Wang, J., Xu, S., Shou, W. & Sun, Y. (2022). Utility of bim-cfd integration in the design and performance analysis for buildings and infrastructures of architecture, engineering and construction industry. *Buildings, 12*(5). https://doi.org/10.3390/buildings12050651
23. Kim, D.D. (2021). Computational fluid dynamics assessment for the thermal performance of double-skin façades in office buildings under hot climatic condition. *Building Services Engineering Research and Technology, 42*(1), 45–61. https://doi.org/10.1016/j.enbuild.2005.06.014
24. Latha, P.K., Darshana, Y. & Venugopal, V. (2015). Role of building material in thermal comfort in tropical climates–A review. *Journal of Building Engineering, 3*, 104–113. https://doi.org/10.1016/j.jobe.2015.06.003
25. Li, E. & Zhu, J. (2022). Parametric analysis of the mechanism of creating indoor thermal environment in traditional houses in Lhasa. *Building and Environment, 207*. https://doi.org/10.1016/j.buildenv.2021.108510
26. Lomas, K.J. & Ji, Y. (2009). Resilience of naturally ventilated buildings to climate change: Advanced natural ventilation and hospital wards. *Energy and buildings, 41*(6), 629–653. https://doi.org/10.1016/j.enbuild.2009.01.001
27. Lotfabadi, P. & Hançer, P. (2019). A comparative study of traditional and contemporary building envelope construction techniques in terms of thermal comfort and energy efficiency in hot and humid climates. *Sustainability, 11*(13). https://doi.org/10.3390/su11133582
28. Margaris, D.P. & Ghiaus, A.G. (2006). Dried product quality improvement by air flow manipulation in tray dryers. *Journal of Food Engineering,*

75(4), 542–550. https://doi.org/10.1016/j.jfoodeng.2005.04.037

29. Mirrahimi, S., Mohamed, M.F., Haw, L.C., Ibrahim, N.L.N., Yusoff, W.F.M. & Aflaki, A. (2016). The effect of building envelope on the thermal comfort and energy saving for high-rise buildings in hot–humid climate. *Renewable and Sustainable Energy Reviews, 53*, 1508–1519. https://doi.org/10.1016/j.rser.2015.09.055
30. Munir, A., Away, Y., Arif, T.Y. & Novandri, A. (2024). A model of indoor thermal condition based on traditional acehnese houses using artificial neural network. *Heliyon, 10*(23). https://doi.org/10.1016/j.heliyon.2024.e40644
31. Mushtaha, E., Salameh, T., Kharrufa, S., Mori, T., Aldawoud, A., Hamad, R. & Nemer, T. (2021). The impact of passive design strategies on cooling loads of buildings in temperate climate. *Case Studies in Thermal Engineering, 28*. https://doi.org/10.1016/j.csite.2021.101588
32. Nguyen, A.T. & Reiter, S. (2014). Passive designs and strategies for low-cost housing using simulation-based optimization and different thermal comfort criteria. *Journal of Building Performance Simulation, 7*(1), 68-81. https://doi.org/10.1080/19401493.2013.770067
33. Norton, T. & Sun, D.W. (2006). Computational fluid dynamics (CFD)–an effective and efficient design and analysis tool for the food industry: a review. *Trends in Food Science & Technology, 17*(11), 600–620. https://doi.org/10.1016/j.tifs.2006.05.004
34. Oktay, D. (2017). *Lessons for future cities and architecture: Ecology, Culture, Sustainability*. In Mediterranean Green Buildings & Renewable Energy: Selected Papers from the World Renewable Energy Network's Med Green Forum. 259–273. https://doi.org/10.1007/978-3-319-30746-6_19
35. Omer, A.M. (2008). Renewable building energy systems and passive human comfort solutions. *Renewable and sustainable energy reviews, 12*(6), 1562–1587. https://doi.org/10.1016/j.rser.2006.07.010
36. Quang, T.V., Doan, D.T., Phuong, N.L. & Yun, G.Y. (2024). Data-driven prediction of indoor airflow distribution in naturally ventilated residential buildings using combined CFD simulation and machine learning (ML) approach. *Journal of Building Physics, 47*(4), 439–471. https://doi.org/10.1177/17442591231219 02
37. Samuel, D.L., Dharmasastha, K., Nagendra, S.S. & Maiya, M.P. (2017). Thermal comfort in traditional buildings composed of local and modern construction materials. *International Journal of Sustainable Built Environment, 6*(2), 463–475. https://doi.org/10.1016/j.ijsbe.2017.08.001
38. Santamouris, M., Pavlou, K., Synnefa, A., Niachou, K. & Kolokotsa, D. (2007). Recent progress on passive cooling techniques: Advanced technological developments to improve survivability levels in low-income households. *Energy and Buildings, 39*(7), 859–866. https://doi.org/10.1016/j.enbuild.2007.02.008
39. Shaeri, J., Yaghoubi, M., Aflaki, A. & Habibi, A. (2018). Evaluation of thermal comfort in traditional houses in a tropical climate. *Buildings, 8*(9). https://doi.org/10.3390/buildings8090126
40. Stavrakakis, G.M., Zervas, P.L., Sarimveis, H. & Markatos, N.C. (2010). Development of a computational tool to quantify architectural-design effects on thermal comfort in naturally ventilated rural houses. *Building and Environment, 45*(1), 65–80. https://doi.org/10.1016/j.buildenv.2009.05.006
41. Thermal Conductivity, Specific Heat Capacity and Density. https://help.iesve.com/ve2021/table_6_thermal_conductivity__specific_heat_capacity_and_density.htm Accessed 18 January 2025.
42. Toe, D.H.C. & Kubota, T. (2015). Comparative assessment of vernacular passive cooling techniques for improving indoor thermal comfort of modern terraced houses in hot–humid climate of Malaysia. *Solar energy, 114*, 229–258. https://doi.org/10.1016/j.solener.2015.01.035
43. Wan, K.K., Li, D.H., Pan, W. & Lam, J.C. (2012). Impact of climate change on building energy use in different climate zones and mitigation and adaptation implications. *Applied Energy, 97*, 274–282. https://doi.org/10.1016/j.apenergy.2011.11.048
44. Wang, H. & Chen, Q. (2014). Impact of climate change heating and cooling energy use in buildings in the United States. *Energy and Buildings, 82*, 428–436. https://doi.org/10.1016/j.enbuild.2014.07.034
45. Wang, X., Chen, D. & Ren, Z. (2010). Assessment of climate change impact on residential building heating and cooling energy requirement in Australia. *Building and environment, 45*(7), 1663-1682. https://doi.org/10.1016/j.buildenv.2010.01.022
46. Yongson, O., Badruddin, I.A., Zainal, Z.A. & Narayana, P.A. (2007). Airflow analysis in an air conditioning room. *Building and environment, 42*(3), 1531–1537. https://doi.org/10.1016/j.buildenv.2006.01.002