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The impact of materials and design on achieving thermal comfort in Acehnese traditional architecture: An approach to achieve sustainability

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ABSTRACT

This study investigates the impact of material selection and architectural design strategies in Acehnese traditional houses on indoor thermal comfort, aiming to contribute to sustainable building practices in hot-humid climates. While thermal comfort has been widely studied, there is limited research on how traditional architectural elements and indigenous materials affect thermal performance. To bridge this gap, this study evaluated thermal comfort using predicted mean vote-predicted percentage of dissatisfied (PMV-PPD) and standard effective temperature (SET) indices, supported by computational fluid dynamics (CFD) simulations conducted using ANSYS. Field measurements were carried out on two traditional house models with differing layouts and roof materials. Additionally, simulation analyses were performed on four models with various wall and roof material combinations. The main numerical results, from both field measurements and simulations show that traditional houses constructed with wooden walls and rumbia (palm leaf) roofing provide superior thermal comfort compared to models using other materials. The key contributing factors include the insulating properties of rumbia, natural ventilation, spatial configuration, and extended roof overhangs that provide shading. These conclusions emphasize the effectiveness of passive design strategies embedded in Acehnese traditional architecture, suggesting their potential application in contemporary sustainable design. The study underscores the value of local knowledge in creating thermally comfortable environments with minimal energy use. However, the scope of the study is limited to a specific regional architectural style and climate, which may affect the generalizability of the results. Despite this, it provides a foundation for future research on the ole of traditional architecture in sustainable building design and supports the efforts to preserve cultural heritage while addressing modern environmental challenges.

Keywords: Acehnese traditional architecture, ansys, design, materials, thermal comfort.

INTRODUCTION

Ensuring thermal comfort is a critical factor in the architectural design process, as it directly influences the physiological well-being of building occupants. Thermal comfort refers to the human perception of the thermal environment, which is significantly affected by architectural and environmental conditions (Frick and Koesmartadi, 2008). The increasing concerns over global warming and energy consumption in buildings have intensified the research into strategies for maintaining indoor thermal comfort while promoting energy efficiency in building design (Zheng et al., 2022). Over time, the construction methods aimed at achieving indoor thermal comfort have evolved, spanning from traditional dwellings to modern architectural forms (Afshari, 2011). Traditional houses, despite being constructed in challenging climatic zones, have historically succeeded in maintaining occupants' comfort (Chkeir et al., 2024). Indigenous climatic strategies developed through empirical practices in local and vernacular architecture provide valuable insights that are often neglected in contemporary building design (Shaeri et al., 2018).

One such example is the Rumoh Aceh, a traditional stilt house indigenous to Aceh, Indonesia. Aside from its cultural value, this house type also serves as a local attraction, located in a region characterized by a warm and humid tropical climate (Djamaludin et al., 2024). According to meteorological records, in 2024, Aceh experienced peak temperatures of up to 34 °C and relative humidity reaching 98% (Meteoblue, 2025; Rizwan et al., 2023). These conditions exceed the thermal comfort thresholds defined in SNI 03-6572-2001, which specifies that indoor temperatures above 27.2 °C and humidity levels above 60% are considered thermally uncomfortable. Despite this, previous studies have shown that Rumoh Aceh is capable of maintaining indoor thermal comfort, owing to its vernacular design principles that support human activity within the space (Salsabilah et al., 2022).

The stilted form of Rumoh Aceh is a significant architectural feature that contributes to passive cooling and thermal regulation (Widosari, 2010). Several architectural elements embedded in its design enhance its thermal performance, including pitched and gable roofs, porous wall structures, as well as elevated flooring. These features promote natural ventilation and allow cool air to circulate within the interior, thereby contributing to a thermally comfortable environment (Izziah et al., 2020).

In addition to architectural design, the choice of construction materials in Rumoh Aceh plays a crucial role in achieving thermal comfort. The traditional structure predominantly utilizes wood for walls and rumbia (sago palm) leaves for roofing. Roofing materials, in particular, have a significant impact on indoor thermal performance (Kindangen et al., 2024). Wood, as a wall material, provides lower thermal mass compared to concrete or brick, which minimizes heat absorption during the day and prevents heat release at night, thereby enhancing indoor comfort (Attaufiq et al., 2024).

However, economic and material availability factors have driven changes in traditional construction practices across Indonesia. The rising cost of timber has led many communities to replace wood with concrete in traditional house construction (Tsai and Wonodihardjo, 2018). This transition is also evident in Aceh, where many Rumoh Aceh structures have been modified. Younger generations tend to prefer minimalist designs using modern materials, and the relatively lower cost of these materials is a key consideration for rural populations opting for concrete houses (Dewi et al., 2024). Additionally, the scarcity of natural materials such as timber and rumbia leaves, combined with the specialized skills required for constructing and maintaining thatched roofs, has contributed to a decline in traditional construction methods (Novita et al., 2020). Furthermore, rumbia roofing is highly flammable, presenting a fire hazard (Steger, 2023). These challenges have led to the widespread use of zinc roofing, which is now the dominant material in Indonesia, covering over 95% of buildings (Kindangen et al., 2024). Despite its practicality, zinc is a good thermal conductor (Firman, 2023), and its use may compromise thermal comfort by facilitating heat transfer into the interior.

Thermal comfort was evaluated using the predicted mean vote–predicted percentage of dissatisfied (PMV–PPD) indices and the standard effective temperature (SET) index. These indices provide more precise and quantifiable evaluations of thermal comfort than subjective assessments. The PMV index estimates the average thermal sensation of occupants based on the ASHRAE thermal comfort scale, while the PPD index quantifies the expected percentage of dissatisfied individuals (ASHRAE, 2021). The PMV–PPD analysis was conducted using the CBE Thermal Comfort Tool. In addition, airflow patterns and indoor air temperatures were analyzed using simulations performed in ANSYS R19.2. These simulations provided insight into the thermal behavior of both house types, highlighting the influence of material composition and architectural design on overall thermal performance.

Numerous studies have investigated thermal comfort within the context of Acehnese traditional architecture. The research conducted by Muslimsyah et al. (2021) indicated that traditional houses constructed using natural materials offer a warm yet comfortable indoor environment, suggesting that such buildings remain capable of delivering adequate thermal performance. However, when assessed quantitatively using the predicted mean vote (PMV) index, several case studies revealed that these dwellings often fell outside the thermally comfortable range. In a study by Sawab et al. (2021), it was noted that the thermal comfort conditions in Acehnese traditional houses have declined over time, with original structures providing longer durations of comfort compared to their modified counterparts. Further investigation by Meutia et al. (2021) on a modified traditional house in Gampong Jawa identified a shift in residents' thermal comfort preferences. Specifically, comfort was perceived at elevated indoor temperatures ranging from 30.5 °C to 33 °C, with relative humidity levels exceeding 70% and air velocity surpassing 0.47 m/s. This study also reported indoor temperature deviations of up to 7 °C above the standard thermal comfort range.

The architectural configuration of Rumoh Aceh, including elements such as pitched roofs, gable vents, porous wall structures, and raised flooring, plays a critical role in promoting passive ventilation. These features create a "breathing roof" system that facilitates air movement and supports thermal regulation within the living space (Izziah et al., 2020). In the context of humid tropical climates, the open subfloor space of stilt houses serves dual purposes – functioning as both a social gathering area and a thermal buffer zone. This space enables cross-ventilation and supports the stack effect, thereby enhancing indoor thermal conditions through continuous airflow. Additionally, the use of low thermal transmittance (U-value) materials for walls and roofing in traditional designs slows heat propagation. Combined with average wind speeds of approximately 1.5 m/s, this configuration contributes to a thermal time lag that allows significant portions of heat to be dissipated through evaporation, before it enters the interior spaces (Sawab and Ivan, 2018).

Further supporting this, Majid et al. (2017) emphasized that Rumoh Aceh responds effectively to the region's hot and humid climate by implementing design principles such as elevating the structure above ground level, orienting buildings along the east-west axis, adopting elongated floor plans, incorporating high ceilings, extending roof overhangs, and selecting the materials with low thermal conductivity. These architectural strategies are integral to maintaining thermal comfort while remaining contextually appropriate.

Despite these strengths, the transformation of traditional architectural elements – particularly in materials and spatial design – has had a measurable impact on indoor thermal comfort. The widespread substitution of traditional components with modern materials such as concrete and zinc has introduced thermal inefficiencies and diminished the climatic responsiveness of the original design. Additionally, many earlier assessments of thermal comfort in Rumoh Aceh relied on single indices or limited parameters, which may not fully capture the multidimensional nature of thermal experiences in vernacular buildings.

To bridge this gap, the present study aimed to comprehensively evaluate the influence of material selection and architectural modification on the thermal comfort performance of Rumoh Aceh. Two housing types were compared: one that retains the traditional rumbia (sago palm) leaf roof and another that has been altered using zinc roofing. Both dwellings also exhibit changes in layout and spatial configuration. Thermal comfort is assessed through a combination of the PMV–PPD indices and the SET model, along with airflow analysis conducted via computational simulation. By employing a multifaceted analytical framework, this research sought to enhance understanding of how traditional Acehnese architecture responds to environmental conditions as well as to provide informed and more sustainable preservation practices in the context of architectural heritage and climatic adaptation.

MATERIALS AND METHODS

The research method used in this study was quantitative. Data collection was conducted through observation of the existing conditions of the research object, including measurements of its dimensions and thermal environment. The dimensional data were then modeled using SketchUp 2023 to produce a three-dimensional representation of the research object. Thermal condition data were analyzed using the PMV (predicted mean vote), PPD (predicted percentage of dissatisfied), and SET (standard effective temperature) indices. The CFD (computational fluid dynamics) simulation, conducted using ANSYS R19.2, was employed to visualize the airflow within the room. Both the measurement and simulation data were analyzed to assess the level of thermal comfort, allowing for evaluation of the impact of material use and architectural design on the thermal performance of the research object.

Study area and case study

Study area and case study, the research objects are located in Gampong Pineung, Syiah Kuala District, Banda Aceh City, and Gampong Blang Krueng, Baitussalam District, Aceh Besar Regency, Indonesia (Figure 1). The Rumoh Aceh in Banda Aceh City (House 1) is characterized by an open-plan interior without insulation or partition walls between rooms; spatial distinctions are indicated solely by differences in floor height (Figures 2a and 3). The primary construction material is wood, while the roof is covered with traditional roofing material, specifically *rumbia* (sago palm) leaves. In contrast, the Rumoh Aceh located in Aceh Besar Regency (House 2) features interior spaces separated by walls and doors. The main structural materials for the walls and columns are wood, and the roof is modified with bitumen tile, which is internally coated with aluminium foil (Figure 2b). A summary of the characteristics of both research objects is presented in Table 1.

The selection of the two objects that use materials and designs that are different from each other can support the research objectives to be able to determine the effect of the use of materials and designs on thermal comfort in Aceh Traditional Architecture (Rumoh Aceh).

Field measurement

Field measurement, data collection was conducted through field measurements to obtain building dimension data and indoor thermal

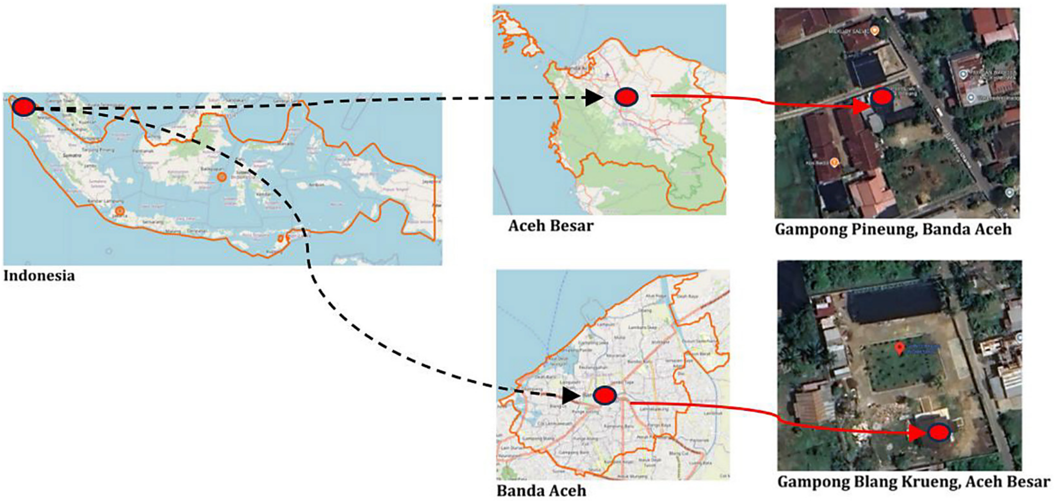


Figure 1. The case study of two Acehnese traditional house located in Gampong Pineung, Banda Aceh (H1) and Gampong Blang Krueng, Aceh Besar (H2)

Figure 2. The houses surveyed in the research (a) House 1 located in Banda Aceh and (b) House 2 located in Aceh Besar

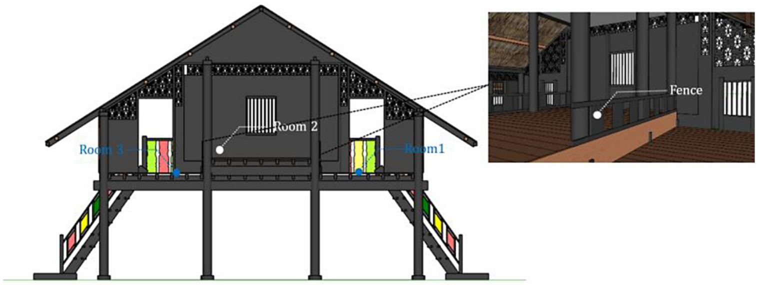


Figure 3. The split level distinguishing the space in House 1

Table 1. Characteristic of the house

Object of study	Orientation	Separator between spaces	Materials	Opening type
House 1	East-West	No separators	Roof: *rumbia* leaves Walls: wood Floor: wood Frame: wood	Side opening window
House 2	East-West	Yes, insulated	Roof: bitumen tile coated withaluminum foil insulation Walls: wood Floor: wood Frame: wood	Glassed-jalousie window

condition data, using the research instruments listed in Table 2. The dimensional data were processed using SketchUp 2023 and Ansys R19.2 to create a three-dimensional model, which was then utilized in CFD simulations to analyze indoor airflow patterns. Thermal condition measurements were carried out on September 18th and 19th, 2024, with data recorded every 10 minutes from 08:00 on September 18th until 23:00 on September 19th, at Indonesia-local time (UTC+7). The parameters measured included wet bulb globe temperature (WBGT), air temperature (Ta), relative humidity (RH), and air velocity (Va). The specifications of the research instruments are illustrated in Table 2.

The location of the measuring instrument is shown in Figure 4. Figure 4 illustrates the measurement points used in the study. The points located within House 1 and House 2 represent indoor measurement locations. In contrast, a single measurement point was employed to represent the outdoor environment for both houses. This point was strategically positioned at a location

Table 2. Research instruments and the specifications

Instruments	Name	Parameters	Accuracy	Operation
	87782 AZ Handheld type WBGT	Ta, Rh	± 0.6 °C ±3%RH, ±5%RH	Manual record, Interval 10 Minutes
	Misol WH-5302 Automatic weather station	Ta, Rh, Va	+/-1 °C +/- 5% +/- 1m/s	Automatic record, Interval 10 Minutes
	Benetech GM8903 Hot wire anemometer	Va	±3%±0.1m/s	Manual record, Interval 10 Minutes

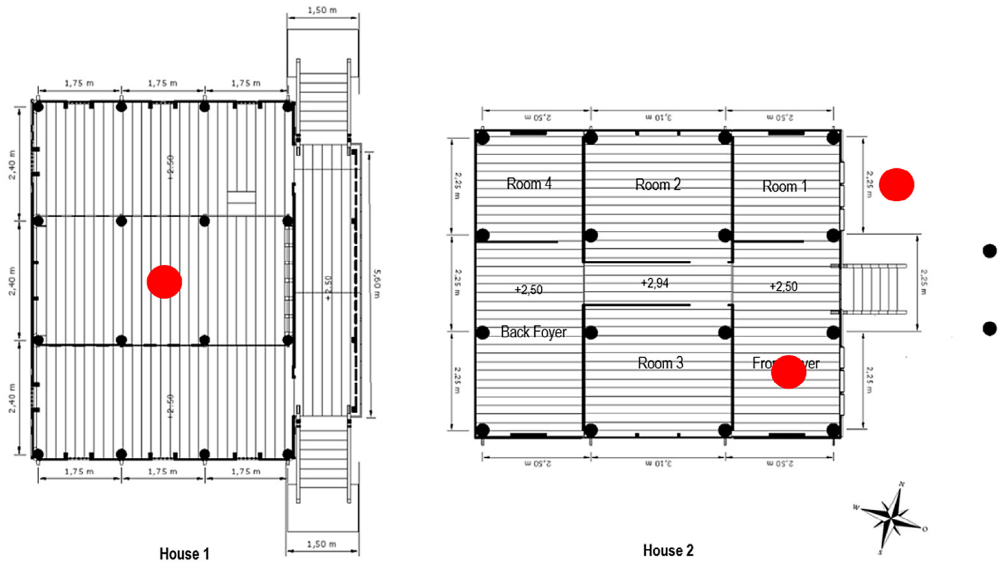


Figure 4. Location of the measuring tool

equidistant from the two houses and deemed representative of the surrounding outdoor conditions. Given the relatively short distance between House 1 and House 2, this single outdoor measurement was considered adequate to capture the external environmental data without compromising accuracy or representativeness.

Thermal comfort evaluation

Thermal comfort evaluation, thermal comfort is a general term commonly used to describe a person's desired or positive thermal state (Hall, 2010). A thermal comfort index is a single value that represents the level of thermal comfort or discomfort experienced (Parsons, 2020). Building envelopes and clothing together create a microclimate that influences subjective sensations by involving various forms of heat and moisture transfer. The fundamental approach in thermal comfort research is the objective quantification of subjective sensations, using a set of quantification rules to relate these sensations to the physical state of heat balance (Luo et al., 2020).

One such method is to use the technique proposed by Fanger. Fanger's model is based on neutral thermal conditions and the development of PMV and PPD indices for adaptive approaches based on buildings operating with natural ventilation (Bienvenido-Huertas and Rubio-Bellido, 2021). PMV is an index that predicts the mean value of the thermal sensation votes (self reported perceptions) of a large group of persons on a sensation scale expressed from –3 to +3 corresponding to the categories "cold," "cool," "slightly cool," "neutral," "slightly warm," "warm," and "hot" (Table 3).

The calculation process of PMV is outlined in Equation 1 (Dong et al., 2019).

$$PMV = f\,(M, I_{cl}, RH, t_r, t_{air}, v) \qquad (1)$$

where: M is metabolic rate, met, 1.0 met = 58.2W/m^2; I_{cl} is heat transfer resistance of clothing, clo, 1.0 clo = 0.155 m^2·°C/W; RH is relative humidity,%; t_r is mean radiation tempperature, °C; v is air flow rate, m/s; t_{air} is indoor temperature, °C. The estimated clothing insulation value (I_{cl}) and estimated metabolism value are shown in Tables 4 and 5, respectively.

In this study, the clothing insulation value is based on the usual clothing worn by the Acehnese i.e long pants and long-sleeved clothing, which is 0.61 clo in total. The metabolic rate

Table 3. Fanger's thermal sensation scale

Sensation	PMV
Hot	+3
Warm	+2
Slightly warm	+1
Neutral	0
Slightly cool	-1
Cool	-2
Cold	-3

Table 4. Fanger's estimations of clothing insulation values (I_{cl}) (Hall, 2010)

Clothing ensemble	Clo	m^2KW^{-1}
Naked	0.0	0.0
Shorts	0.1	0.016
Briefs (underpants), shorts, open neck skirt with short sleeves, light socks and sandals	0.3	0.047
Briefs, long lightweight trousers, open neck shirt with short sleeves, light socks and shoes	0.5	0.078
Underwear, cotton working shirt with long sleeves, working trousers, woollen socks and shoes	0.8	0.124
Underwear, shirt with long sleeves, trousers, sweater with long sleeves, heavy socks and shoes	1.0	0.155
Cotton underwear with long legs and sleeves, shirt, suit comprising trousers, jacket and waistcoat (US vest), woollen socks and heavy shoes	1.5	0.233

Table 5. Fanger's estimations of metabolic rates (M) (Hall, 2010)

Activity	Met	Wm^{-2}
Lying down	0.8	47
Seated quietly	1.0	58
Sedentary activity (office, home, laboratory, school)	1.2	70
Standing, relaxed	1.2	70
Light activity, standing (shopping, laboratory, light industry)	1.6	93
Medium activity, standing (shop assistant, domestic work, machine work)	2.0	116

is about 1.0 Met, corresponding to a person sitting still. For a seated person, the formula is as follows (Dong et al., 2019):

$$T_r = \{0.18 \times [t_{pr}(up) + t_{pr}(down)] + 0.22 \times [t_{pr}(right) + t_{pr}(left)] + 0.30 \times [t_{pr}(front) + t_{pr}(back)]\}/[2(0.18 + 0.22 + 0.20)] \quad (2)$$

On the other hand, *PPD* is an index that establishes a quantitative prediction of the percentage of thermally dissatisfied people determined from PMV (ASHRAE, 2023). The formula of *PPD* is shown as follows (Dong et al., 2019):

$$PPD = 100\ 95e^{-(0.03353PMV4 + 0.2179PMV2)} \quad (3)$$

The percentage of subjective *PPD* corresponding to each PMV (Dong et al., 2019) is shown in Table 6.

The SET is defined as the temperature of an isothermal environment (where ta = tr, with still air and 50% relative humidity) in which a person wearing a standard level of clothing insulation would experience the same heat loss, mean skin temperature, and skin wettedness as in the actual environment and clothing conditions under consideration. As noted in the work of Kasteren et al., (2019), thermal comfort and other perceived sensations are influenced by the level of physical activity.

To ensure that a given SET value provides neutral comfort (e.g., 24 °C SET), the standard clothing level used in defining a standard environment is adjusted based on activity levels. For an activity level of 1.1 Mets (1 Met = 58.15 W/m²), the standard clothing insulation is 0.6 clo, the mean body temperature (a weighted average of skin and core temperatures) is tb = 36.35 °C, and the skin wettedness is w = 0.07. For a higher activity level of 2.9 Mets, the standard clothing insulation is reduced to 0.4 clo, with tb = 36.71 °C and w = 0.21 (Hall, 2010). SET values and the corresponding predicted physiological and thermal sensation responses are provided in Table 7 (Hall, 2010).

Airflow evaluation

Airflow evaluation, natural ventilation which functions as a natural air exchange mechanism,

Table 6. Subjective PPD percentages corresponding to each PMV

PMV	Percent dissatisfied
[-3, -2.5]	95–100%
[-2.5, -1.5]	50–95%
[-1.5, -0.5]	10–50%
[-0.5, +0.5]	0–10%
[+0.5, +1.5]	10–50%
[+1.5, +2.5]	50–95%
[+2.5, +3]	95–100%

Table 7. Standard effective temperatures (SET) and corresponding thermal sensation and physiological response

SET (°C)	Sensation	Physiological state
> 37.5	Very hot, very uncomfortable	Failure of regulation
34.5–37.5	Hot, very unacceptable	Profuse sweating
30.0–34.5	Warm, uncomfortbale, unacceptable	Sweating
25.6–30.0	Slightly warm, slightly unacceptable	Slight sweating, accepted vasodilation
22.2–30.0	Comfortable and acceptable	Neutrality
17.5–22.2	Slightly cool, slightly unacceptable	Vasoconstriction
12.5–17.5	Cool and unacceptable	Slow body cooling
10.0–14.5	Cold, very unacceptable	Shivering

is one of the factors that can influence thermal comfort (Aiyubi et al., 2024). Natural ventilation systems can provide adequate thermal comfort in warm climates (Sari et al., 2023; Muslimsyah et al., 2025). However, natural ventilation is only effective under certain conditions, such as in buildings with an open-plan design and in environments with minimal air and noise pollution (Haiqal et al., 2025). The position, size, and shape of openings are crucial in determining the airflow characteristics within a building, as they directly impact ventilation performance (Haiqal et al., 2025).

CFD has been widely used to study heat transfer, fluid flow, and the transport of chemical species. Recent developments in computational tools have enabled more accurate analysis of indoor building environments using CFD. The validation studies to evaluate the accuracy of CFD tools in predicting indoor airflow distribution, comparing the results with experimental data and finding a good match. Therefore, this research employed the CFD method to analyze air movement within the study object (Kummitha et al., 2021). The CFD simulations in this study were performed using ANSYS R19.2 software. Four different material conditions were examined on the research object to evaluate the thermal and airflow characteristics under varying construction scenarios. The first condition (M1) represents the existing state of House 1, which features wooden walls and a thatched roof. The second condition (M2) corresponds to the existing state of House 2, consisting of wooden walls and a zinc roof. The third condition (M3) is a modified scenario incorporating concrete walls and a zinc roof, while the fourth condition (M4) involves concrete walls combined with a tile roof.

The CFD simulation process followed a structured workflow comprising several stages. Initially, a simulation plan was developed, outlining the objectives and parameters for each test condition. This was followed by the determination of the physical dimensions of the research object. Subsequently, the geometry of each housing condition was designed using CAD tools, and a computational mesh was generated to discretize the simulation domain. The next step involved setting up the simulation environment in ANSYS, which included defining boundary conditions, material properties, and solver configurations. Finally, the CFD simulations were conducted, and the resulting data were extracted for analysis.

CFD has been used to determine heat transfer, fluid flow, and chemical species transport. Recent developments and improvements in the latest computational tools (CFD) enable the use of these tools to analyze the indoor environment of buildings. CFD tools can predict indoor airflow distribution as well as compare it with experimental results and identify a good match of results (Kummitha et al., 2021). Therefore, this research used the CFD method to analyze the air movement that occurs in the research object. The application used to perform CFD simulation in this research is Ansys R19.2. The simulation process was carried out on four material conditions on the research object, the first condition was the condition found in the existing House 1 (H1) (wooden walls, thatched roof), the second condition was the condition found in the existing House 2 (H2) (wooden walls, zinc roof), the third and fourth conditions were material modification conditions, namely the research object with concrete walls and zinc roof (M1) and concrete walls and tile roof (M2). Before the simulation was carried out, the first step was to collect the data to be used in the simulation, which included initial condition data and boundary condition data. This simulation used time variations starting from 08.00 to 16.00 (UTC+7, Western Indonesian Time), which can be seen in Table 8. This study evaluated the thermal comfort performance of Rumoh Aceh by combining field measurements with computational simulations using CFD software. Prior to the simulation, relevant input data, including initial and boundary conditions, were collected through direct measurement. The simulation was conducted over a time range from 08:00 to 16:00 local time (UTC+7), as shown in Table 9. These data serve as the basis for subsequent simulations aimed at analyzing the impact of material selection and architectural design on the thermal behavior of Rumoh Aceh.

Figure 5 shows the geometry design of the research object with an overall length of 820 cm, an overall width of 943 cm, a roof height of 628 cm, and a house pole height of 238 cm.

Meshing is done after inputting the geometry in DesigncModeler. Figure 6 displays the meshing results on the geometry of the research object.

This meshing stage used a tetrahedron mesh type. Tetrahedron mesh was chosen because of its advantages in creating complex and intricate geometries. In addition, tetrahedron mesh is much better at analyzing fluid flow compared to other mesh types. The shape of the tetrahedron mesh can be seen in Figure 7.

The next process after the meshing stage was to set up the simulation in the Ansys application. Figure 8 shows the menu settings that used in the simulation process.

On the basis of the picture above, the initial stage started from general. In the general stage, the solver method used will be determined. The second stage is the selection of models used in the simulation, in this simulation the energy is turned on, for the viscous part of the model selected STT k-ω and for the Radiation part selected Rosseland. Then, the material selection stage to be used in the simulation was entered. Next the boundary conditions were determined. Boundary condition settings include input data on velocity, temperature, thermal conditions, selection of conditions and wall momentum. Setting reference values includes determining the method used and the number of initializations simulated.

CFD simulation of Rumoh Aceh was conducted using Ansys Fluent. The boundary conditional tent is shown in Figure 9.

The CFD simulation of the research object was conducted using a set of defined parameters to ensure accuracy and reliability. A tetrahedral mesh with an element size of 200 mm was employed to discretize the computational domain, providing an adequate balance between computational efficiency and solution accuracy. The simulation utilized a pressure-based solver with double precision and steady-state time formulation, chosen for its robustness in modeling single-phase flows and its computational efficiency under steady flow conditions.

The physical models incorporated in the simulation included the energy equation (enabled), the SST k–ω viscous model, and the production limiter option to enhance numerical stability and accuracy in near-wall treatment. Radiative heat transfer was activated using the Rosseland

Table 8. Initial conditions applied into the Ansys for the simulations

Initial conditions	Planning
Flow type	Pressure based
Time	Steady state
Velocity formulation	Absolute
Viscous models	STT k-ω
Radiation	Rosseland
Solar loading (solar calculator: Global position	Banda Aceh
Langitude (deg)	95.32375
Latitude (deg)	5.54829
Time Zone (+-GMT)	7
Mesh orientation (North)	Z=1
Mesh orientation (East)	X=-1
Material (fluid)	Air
Material (solid)	Concrete, Zinc, Roof tile, Wood, Rumbia leaves

Table 9. Boundary conditions applied to the simulation run by Ansys

Boundary conditions		Physiological state
Inlet		Velocity-inlet
Outlet		Pressure-outlet
Wall		Solid, proof against flow of fluid
Wall momentum	Wall motion	Stationary wall
	Shear condition	No slip
	Wall roughless	Standard
Inlet temperature per hour local time (UTC+7)	08.00	24 °C
	09.00	25.9 °C
	10.00	28.4 °C
	11.00	28.8 °C
	12.00	29 °C
	13.00	29.3 °C
	14.00	28.1 °C
	15.00	28.7 °C
	16.00	28.3 °C
Free stream temperature per hour local time (UTC+7)	08.00	26.2 °C
	09.00	28.1 °C
	10.00	30.6 °C
	11.00	31 °C
	12.00	30.2 °C
	13.00	30.5 °C
	14.00	29.3 °C
	15.00	29.9 °C
	16.00	29.5 °C
Velocity per hour local time (UTC+7)	08.00	1.67 m/s
	09.00	1.7 m/s
	10.00	2.22 m/s
	11.00	2.4 m/s
	12.00	2.52 m/s
	13.00	2.9 m/s
	14.00	3.05 m/s
	15.00	3.1 m/s
	16.00	3 m/s
Thermal condition		Convection
Radiation		Participates in solar ray tracing (opaque)
Solution methods		Simple
Initialization methods		Standard

radiation model. For solar radiation effects, the solar calculator was enabled by specifying the geographical coordinates of Banda Aceh, with a longitude of 95.32375°, latitude of 5.54829°, and a time zone of GMT+7.

The material properties used in the simulation consisted of both fluid and solid materials. Water was defined as the fluid medium, while the solid components included concrete, wood, zinc, roof tiles, and thatched leaves. The thermal properties of these materials, specifically density, specific heat capacity (Cp), and thermal conductivity, are detailed in Table 10.

The boundary conditions for the CFD simulation were defined to reflect realistic environmental inputs and material interactions. The inlet was modeled using a velocity-inlet boundary condition under steady-state assumptions. The inlet temperature and air velocity values were set based on previously recorded field data, which correspond to specific time parameters during temperature and wind speed measurements. At the outlet, a pressure-outlet boundary condition

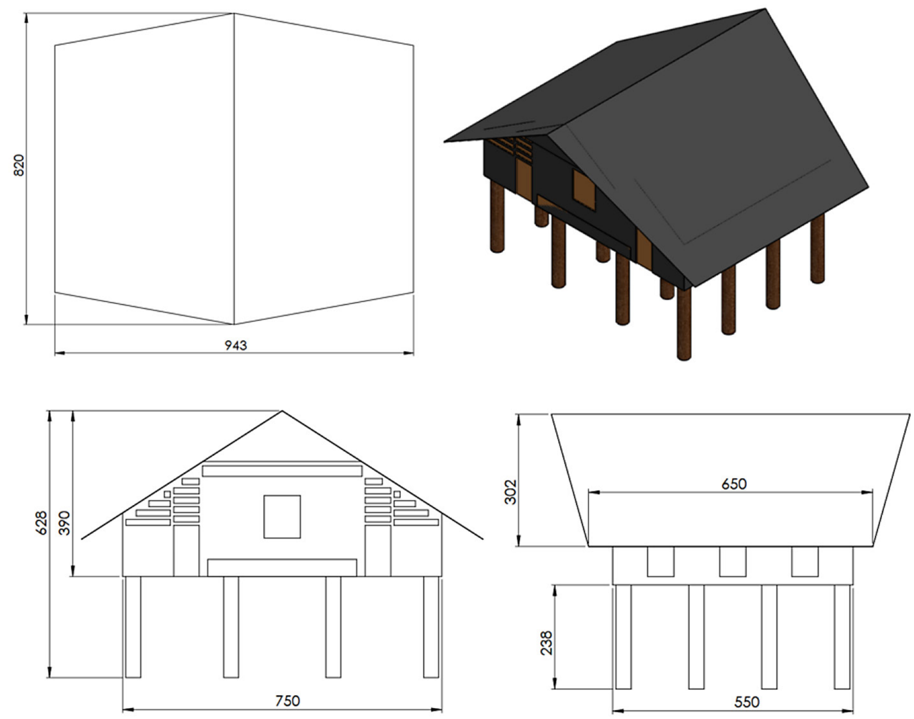


Figure 5. The dimension of the Acehnese traditional house model

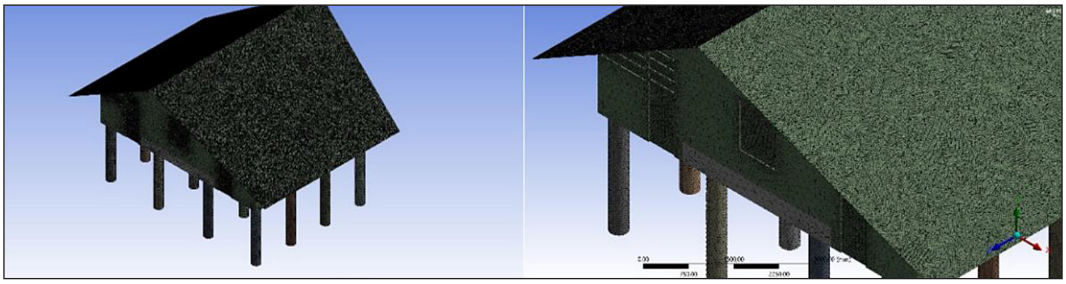


Figure 6. Meshing results in the research object

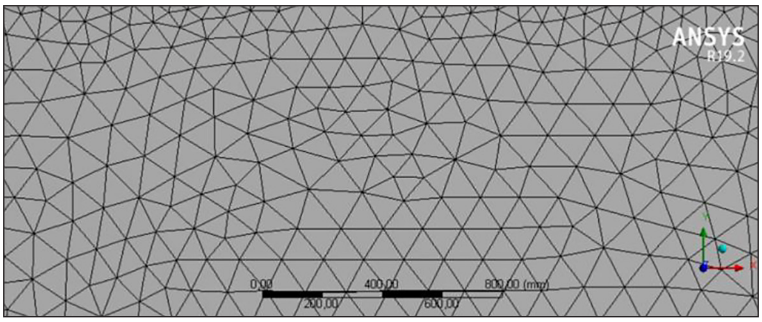


Figure 7. Tetrahedron mesh

with default settings was applied to allow for natural outflow of air from the simulation domain.

The wall boundaries were defined using appropriate material specifications. The walls and floors were assigned concrete and wood materials, while the roof surfaces were assigned zinc, roof tiles, or rumbia (thatched palm) leaves, depending on the housing condition modeled. All wall surfaces were defined as no-slip boundaries using the standard wall function. For thermal conditions, convective heat transfer was applied, with the free-stream temperature values obtained

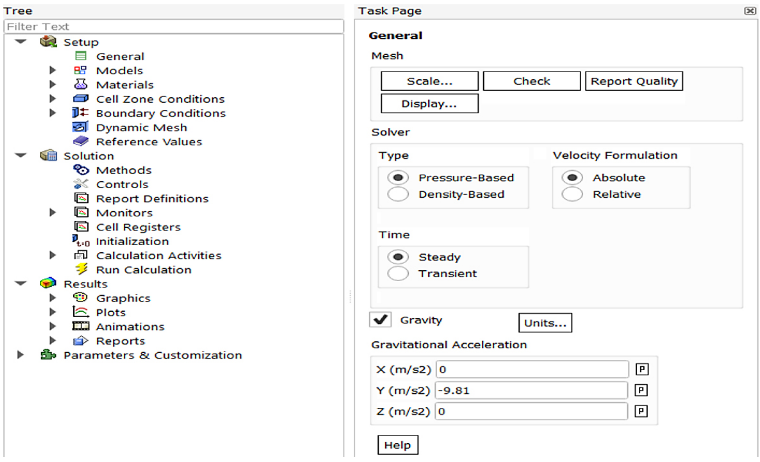


Figure 8. Setup menu display

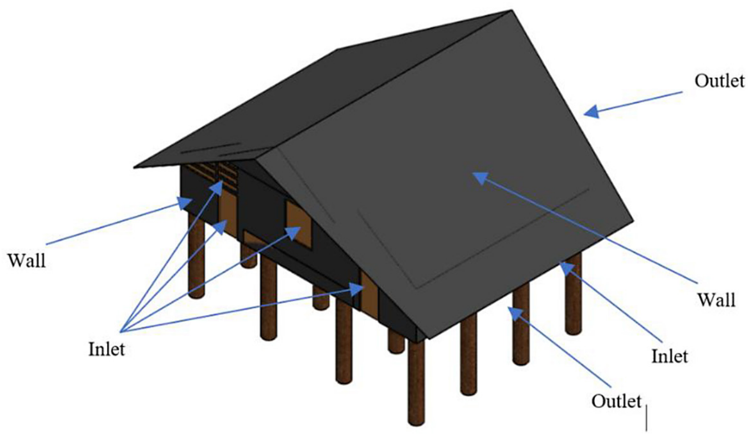


Figure 9. Boundary condition in research objects

Table 10. Material thermal conductivity

Material	Density (kg/m³)	Specific heat (Cp) (J/kg.K)	Thermal conductivity (W/m.K)
Concrete	2400	4.459	0.8 – 2.5
Zinc	7140	6.942	116
Roof tile	1620	878	0.463
Wood	700	2310	0.173
Rumbia leaves roof	600	2400	0.169

from the measured environmental data. In the radiation settings, the wall surfaces were specified as opaque and set to participate in solar ray tracing to accurately model solar heat gain.

The simulation was initialized using the standard initialization method, and the solution was carried out using the SIMPLE algorithm with default solver settings. The computational mesh consisted of tetrahedral elements with a uniform size of 200 mm, resulting in a total of 785,024 nodes and 3,941,385 elements.

Material selection is a critical factor influencing indoor thermal comfort. The thermal environment within a building is largely governed by the thermal properties of the construction materials, which in turn are affected by external conditions, such as ambient temperature and humidity (Hyde, 2000). Materials characterized by low thermal conductivity, thermal diffusivity, and solar absorptivity tend to exhibit reduced temperature fluctuations on the interior wall surfaces, as compared to those with higher thermal conductivity values (Ozel, 2011). In traditional buildings, such as the original Acehnese houses, the wall and roof materials typically possess low thermal transmittance (U-value), which delays the rate of heat transfer from the exterior to the interior. This delay, known as the time lag, is further influenced by natural ventilation. For instance, under average wind conditions of approximately 1.5 m/s, a substantial portion of the incoming heat is dissipated through evaporative cooling before it penetrates the building envelope (Sawab and Ivan, 2018). In the present study, the thermal conductivity characteristics of the building materials were evaluated to understand their contribution to the thermal comfort experienced within the indoor environment.

RESULTS

The results of the analysis of the relationship between design and materials to thermal comfort conditions on the research object will be adjusted to the design components of the Aceh House that can respond well to the climate according to Majid et al., (2017) which was described in section 2.4. and combined with some passive design strategies that are often applied in tropical climates according to Nguyen (2011), namely shape and orientation, shadings, natural ventilation, and materials in buildings.

The height of the house in both research objects still applies the height applied to Aceh Traditional Houses in general. The height of the two research objects is +/- 2.5 meters from the ground (Figure 10). On the basis of the research conducted by Jin and Zhang, (2021) on stilt houses located in subtropical climates it was shown that people living in stilt houses have a wider range of thermal comfort than urban dwellers. In the research conducted by Bassaleng et al., (2024) stilt houses have proven that the form is adaptive to the thermal comfort of the areas that have a humid tropical climate. The height of the Aceh house allows cool air to enter through the bottom of the house, namely the wooden floor that has been arranged with a certain distance (Izziah et al., 2020). The application of the stage form in the Aceh Traditional House is also applied to catch the wind at a higher location to cool down the air temperature in the room (Sari, 2017). According to Nguyen (2011), The wind speed that occurs at a height of 2 meters is greater than the wind speed that occurs at a height of 1 meter.

Orientation

Orientation, both research objects have an east-west orientation, this orientation is the orientation applied to Traditional Aceh Houses. Orientation facing east-west allows the arrival of west winds that can provide thermal comfort in space. Building orientation has a significant influence to bring thermal comfort in the room because it can prevent solar radiation from entering directly into the house (Karyono, 2010). The orientation toward the sun also would affect the wind speed that can enter the room which can reduce the humidity (Rilatupa, 2019). East-west orientation is the optimum orientation for tropical climates, where the position of openings in the building affects the amount of solar heat

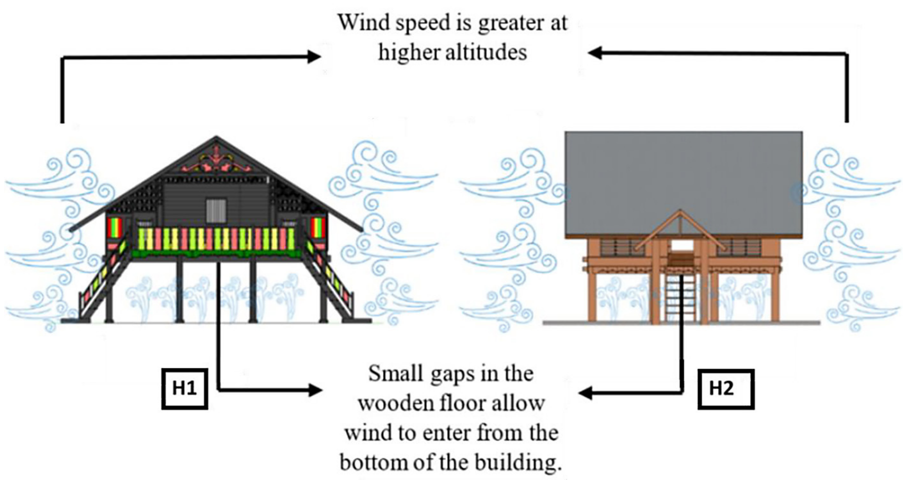


Figure 10. Effect of house height on thermal comfort for flowing the air

radiation into the building (Prasetyo et al., 2022). Generally, Rumoh Aceh faces towards the west because they are influenced by religious beliefs, but the direction harvests the west wind which helps to reduce the relative humidity, as shown in Figure 11 (Meutia, 2017).

The open-concept floor plan is one of the design components that is considered to affect the thermal comfort that occurs in the Rumoh Aceh. Through an open-concept floor plan, airflow can run smoothly in the building. Rumoh Aceh Pineung applies an open concept to the room, the Rumoh Aceh has undergone modifications with absolutely no division in the room, this allows the air flow that occurs in the room to be smoother and can move freely because of the condition of the room and openings that allow cross ventilation.

There is additional space in the division of space in House 2. In the Aceh Traditional House the room (bilik) is only found on the middle porch. House 2 has rooms on the front and back porches because the house functions as a resting place for workers who need a lot of space. The condition of this space can be one of the factors that affect the entry of wind into the room. Wind into the room can work optimally to provide thermal comfort if the condition or design of the room allows the process of cross ventilation. However, in House 2, the wind entering the room through the opening (inlet) can not work optimally because there are no other openings (outlet) that allow cross ventilation (Figure 12). The airflow moving in House 2 cannot move maximally when compared to House 1. This is also indicated by the measurement results that can be seen in explanation 3.1.3 where the average wind speed measurement results in House 1 are greater than the wind speed in House 2.

Traditional Acehnese houses have a wide roof overhang that can serve as a terrace for the house. According to Porritt et al. (2012), The overheating situation in buildings can be reduced by a combination of window size, orientation and sun protection using shading. On the basis of thr on research conducted by Hashemi and Khatami (2017), the use of shading is the most effective strategy to reduce indoor overheating by up to 52%. Both research objects apply wide roof overhangs. However, the location of the roof overhangs is different. In House 1, the roof overhangs are located to the north and south of the house, while in House 2, the roof overhangs are located to the east and west. When viewed based on house orientation, the house that benefits more from the application of this overhang is House 2, because the location of the overhang is in the direction of the sun's movement so that it can prevent sunlight from entering the room directly.

In tropical regions where energy resources are limited, the strategic use of building materials as passive design techniques offers an effective approach to enhancing indoor thermal comfort (Latha, 2015). Both House 1 and House 2 primarily utilize wood as the main construction material. According to Hendriani et al. (2017), wooden structures exhibit an adaptive thermal behavior in response to ambient conditions, as wood inherently stores and moderates radiative heat, enabling temperature regulation within a space. This makes wooden walls particularly well-suited for residential buildings in tropical coastal areas, compared to those in mountainous regions, where surface temperature differences are more pronounced. Moreover, as highlighted by the Healthy Building Workshop (2000) in Latha (2015), wood and wood-based products applied to the building envelope contribute to indoor thermal regulation by moderating humidity fluctuations.

The high specific heat capacity (ranging from 1.6 to 3 kJ/kg·K) and relatively low density of wood, compared to conventional materials such as concrete, glass, and brick, make it a favorable

Figure 11. West wind entering a house that is oriented east-west

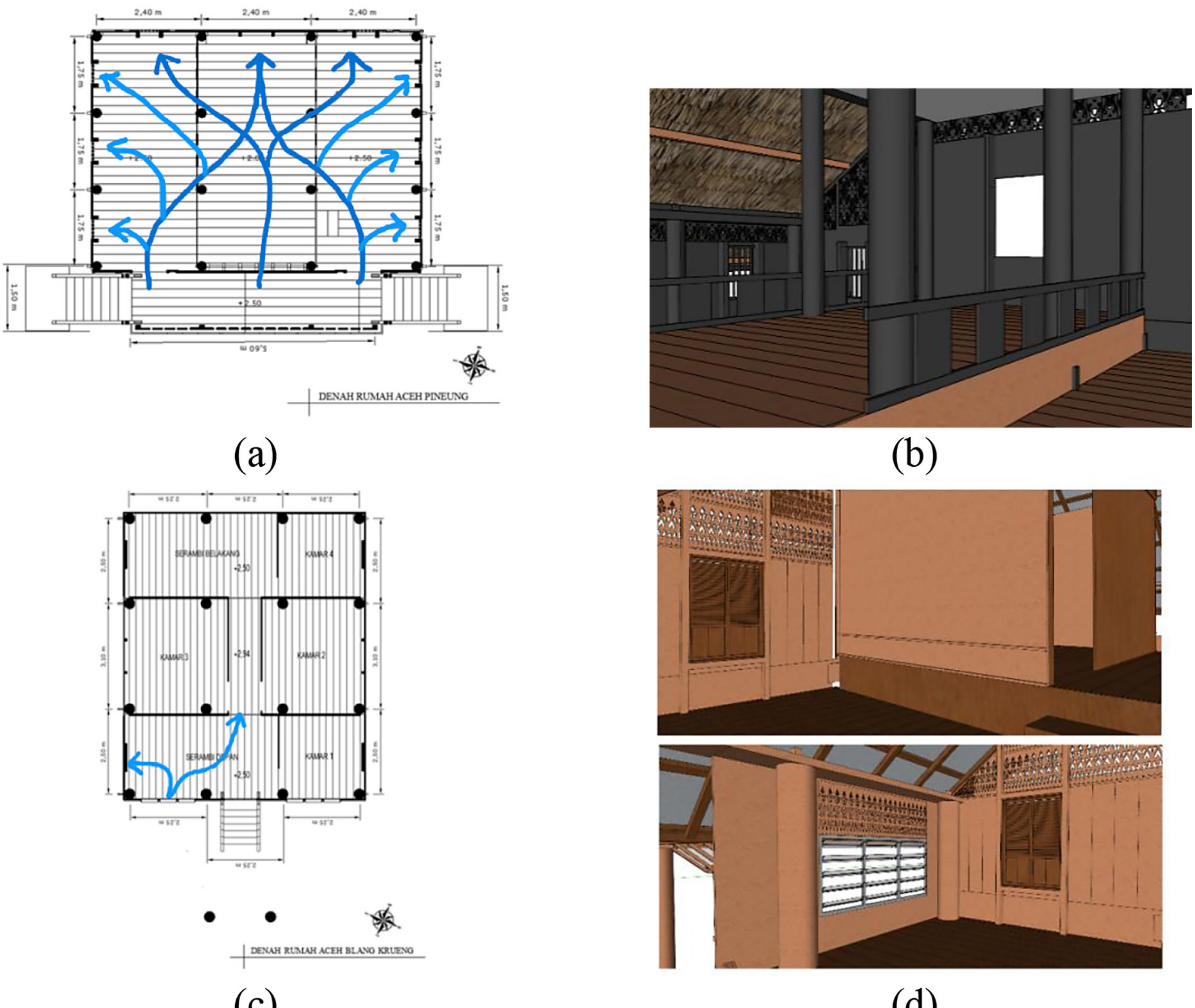


Figure 12. (a) airflow movement in House 1, (b) space conditions in House 1, (c) airflow movement in the space of House 2, (d) space conditions in House 2.

choice for thermal insulation applications (Kordjamshidi, 2013). Its low thermal conductivity further supports its role as an effective insulator (Latha, 2015). Despite both case studies using wood for their primary structure, the roofing materials differ: House 1 employs a thatch (rumbia leaf) roof, while House 2 is fitted with a zinc roof complemented by an inner aluminum foil insulation layer. Traditionally, Rumoh Aceh utilizes lightweight, natural materials, such as rumbia leaves for roofing due to their insulating properties (Maulinda, 2023). The roofs designed with high solar reflectance and emissivity significantly enhance building cooling performance in hot climates (Latha, 2015). Cool roofs, characterized by high solar reflectance index (SRI) values and high thermal emittance, can limit roof surface temperatures to approximately 316–319 K (43–46 °C) under peak solar exposure (Tijen and Cohen, 2008).

Incorporating both natural and synthetic insulation materials – such as coconut or palm leaves, reflective membranes, or vegetation around and atop roofs – can further improve a the thermal performance of a building and reduce energy consumption (Ouldboukhitine et al., 2011). Simulation models have demonstrated that combining green roofs with solar shading can effectively maintain indoor temperatures near 298.9 K (25.7 °C). According to Halim et al. (2022), the effectiveness of a roofing material in preventing overheating is closely associated with its low thermal transmittance (U-value). The U-values of the roofing materials used in the two studied houses are presented in Table 11, providing a comparative overview of their thermal performance characteristics.

From the results of the u-value of the roofing materials, it is found that the u-value of the rumbia leaves roofing material is lower when compared to the zinc roof added with insulation material. Therefore, the roofing material in House 1 can prevent heat from entering through the roof better than the roof in House 2.

Rumoh Aceh

Rumoh Aceh maximizes natural ventilation in the space through the building envelope. According to Izziah et al. (2020), fresh air and wind can enter freely into the room in the Rumoh Aceh through the window without being blocked by the insulation wall. Air conditioning and lighting in Rumoh Aceh can enter maximally into the room through the openings found in Rumoh Aceh. In this study, the openings found in House 1 are the types of openings that are often found in Rumoh Aceh. However, in House 2, the openings used are nako type openings with aluminum material. According to Daryanto and Utama (2012), nako glass window openings have advantages when compared to other types because the air flow can be adjusted according to the conditions desired by the homeowner. Thus, it can be concluded from some of these opinions that both research objects receive enough air flow into the room through openings.

Field measurement result of air temperature

Field measurement result of air temperature (T), 87782 AZ Handheld Type WBGT and Misol WH-5302 Automatic Weather Station are the instruments used to measure air temperature in the research object. 87782 AZ Handheld Type WBGT is a manually operated tool to measure the amount of air temperature in H1, while Misol WH-5302 Automatic Weather Station is a tool that can operate automatically by recording air temperature data in H2. The air temperature measurement data can be seen in Table 11.

The results of air temperature measurements in H1 and H2 as a whole show results that are not much different. On September 18th, 2024, the largest air temperature was found in H2, which was 30.9 °C at 12.00 local time (UTC+7), the lowest air temperature was found in H2 at 25.6°C at 16.00. On September 19th, 2024, the largest air temperature was also found in H2, which was 32.3 °C at 16.00 local time (UTC+7) and the lowest air temperature was found in H1 at 27.8 °C at 16.00 local time (UTC+7). Overall, the average air temperature that occurs in H1 is greater when compared to the average air temperature in H2.

Field measurement result of relative humidity

Field measurement result of relative humidity (RH), 87782 AZ Handheld Type WBGT and Misol WH-5302 Automatic Weather Station is the instrument used to measure relative humidity in the research object. 87782 AZ Handheld Type WBGT and Misol WH-5302 Automatic Weather Station is a manually operated tool to measure the amount of air humidity in H1, while Misol WH-5302 Automatic Weather Station is a tool that can operate automatically by recording air humidity data in H2. The data on air humidity measurement results can be seen in Table 11.

The results of air humidity measurements in H1 and H2 as a whole show results that are not much different. On September 18th, 2024, the largest air humidity is found in H1, which is 71.5% at 08.00, the lowest air humidity is found in H1 at 55.2% at 16.00 local time (UTC+7). On September 19th, 2024, the largest air humidity was found in H1, which is 69.5% at 08.00 a.m. and the lowest air humidity is found in H2 at 42.4% at 16.00 local time (UTC+7). Overall, the average air humidity that occurs in H2 is lower when compared to the average air humidity in H1.

Field measurement result ofair velocity

Field measurement result of air velocity (Va), Benetech GM8903 Hot Wire Anemometer the instrument used to measure air velocity in both research object. Benetech GM8903 Hot Wire Anemometer is a manually operated tool to measure the amount of wind speed that exists in both research objects. Wind speed measurement data can be seen in Table 11.

Table 11. U-value of roofing materials

Object of study	Material	U-value (W/m^{2}K)
House 1	Roof: rumbia leaves	4.459
House 2	Roof: zinc coated aluminum foil insulation	6.942

The results of wind speed measurements on September 18th, 2024 show that the largest wind speed data is found in H1, which is 0.593 m/s at 12.00, the lowest wind speed is found in H2 at 0.11 m/s at 16.00 local time (UTC+7). On September 19th, 2024, the largest wind speed was found in House 1, which is 0. 647 m/s at 12.00 p.m. and the lowest wind speed was found in H2 at 0.3 m/s at 12.00 local time (UTC+7). Overall, the average wind speed that occurs in H1 is greater when compared to the average wind speed in H2 (Table 12).

DISCUSSION

The thermal comfort data collected on 18th and 19th September 2024 for Houses H1 and H2 (Table 13 and Figure 13) provides insights into the impact of construction materials and environmental exposure on indoor thermal environments in Acehnese traditional houses. The PMV and PPD were calculated based on ISO 7730 standards, offering a quantitative assessment of occupant comfort.

On both days, the PMV values remained in the slightly warm to warm categories, with peak discomfort at 16:00 local time (UTC+7), coinciding with maximum solar intensity. Notably, H2 consistently registered higher PMV and PPD values, suggesting its construction, possibly featuring zinc roofing and concrete walls, absorbs and retains more heat. This is consistent with research by Yang et al. (2023), which demonstrated that thermal comfort is compromised in buildings with high thermal mass and low ventilation in warm-humid climates.

The SET values also confirmed this trend, where temperatures in H2 exceeded those of H1, especially during midday hours. The effectiveness of thermal comfort in H1, likely using more breathable and insulating traditional materials such as rumbia roofs and wooden walls, supports findings by Murtyas et al. (2024) and Nguyen et al. (2014) that traditional tropical architecture often outperforms modern materials in passive cooling performance.

The PMV range from 0.83 to 1.85 indicates a significant thermal load even in the highland environment of Gayo, which traditionally enjoys cooler conditions than lowland regions. This aligns with Feriadi and Wong, 2004, who observed that buildings in tropical highlands must still address solar gain through material choice and ventilation strategies.

Airflow performance via CFD analysis

Airflow performance via CFD analysis, The CFD simulation results (Figures 14 and 15) offer a valuable visualization of air movement patterns within the houses. The airflow distribution

Table 12. Air temperature, relative humidity and air velocity measurement data

18th September 2024				
Object of study	Time local time (UTC+7)	Ta (°C)	Rh (%)	Va (m/s)
H1	08.00	27.1	69.4	0
	12.00	30.3	58.6	0.593
	16.00	31.0	55.2	0.244
	20.00	26.0	78.4	0
H2	08.00	27.1	71.5	0
	12.00	30.9	57.4	0.4
	16.00	30.5	58.2	0.11
	20.00	25.6	79.8	0
19th September 2024				
Object of study	Time local time (UTC+7)	Ta (°C)	Rh (%)	Va (m/s)
H1	08.00	27.8	69.5	0
	12.00	31.9	49.5	0.647
	16.00	31.8	42.4	0.269
H2	20.00	26.0	78.4	0
	08.00	28.27	68.1	0
	12.00	32.6	47.8	0.3
	16.00	31.8	44.1	0.56
	20.00	29.5	58.1	0

Table 13. PMV, PPD and SET results of H1 and H2

18th September 2024					
Object of study	Time local time (UTC+7)	PMV	PMV Desc.	PPD	SET
H1	08.00	0.83	Slightly Warm	19%	28.0 °C
	12.00	1.04	Slightly Warm	21%	28.1 °C
	16.00	1.70	Warm	62%	30.5 °C
	20.00	0.50	Slightly Warm	10%	27.1 °C
H2	08.00	0.85	Slightly Warm	20%	28.1 °C
	12.00	1.28	Slightly Warm	39%	29.3 °C
	16.00	1.85	Warm	70%	31.2 °C
	20.00	0.37	Neutral	8%	26.6 °C
19th September 2024					
Object of study	Time local time (UTC+7)	PMV	PMV Desc.	PPD	SET
H1	08.00	1.08	Slightly Warm	30%	28.9 °C
	12.00	1.48	Slightly Warm	50%	29.6 °C
	16.00	1.5	Warm	45%	30.7 °C
	20.00	1.28	Slightly Warm	39%	29.6 °C
H2	08.00	1.22	Slightly Warm	36%	29.3 °C
	12.00	1.7	Slightly Warm	62%	30.3 °C
	16.00	1.81	Warm	67%	31.7 °C
	20.00	1.48	Warm	50%	30.1 °C

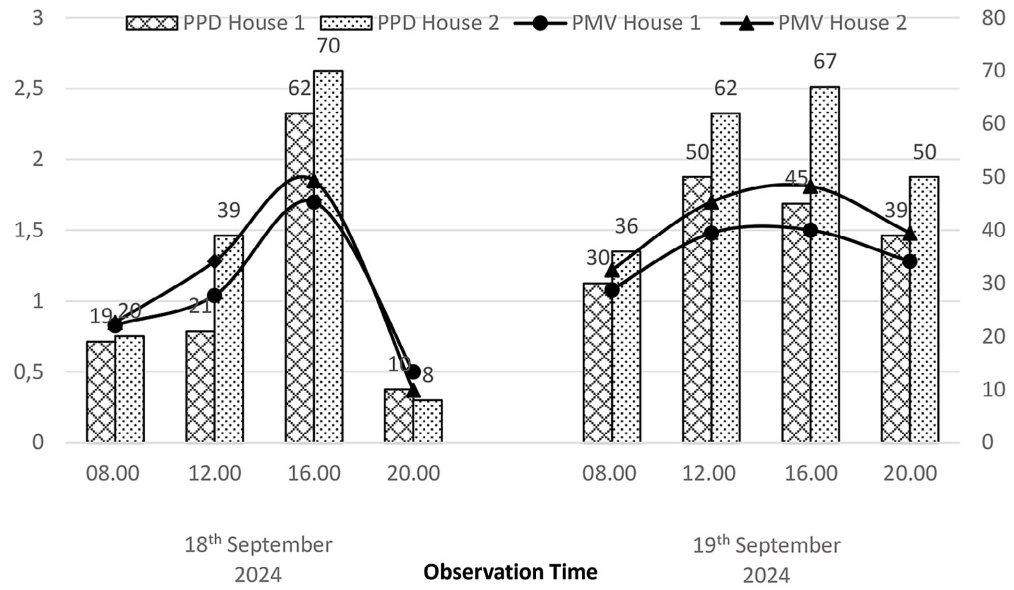
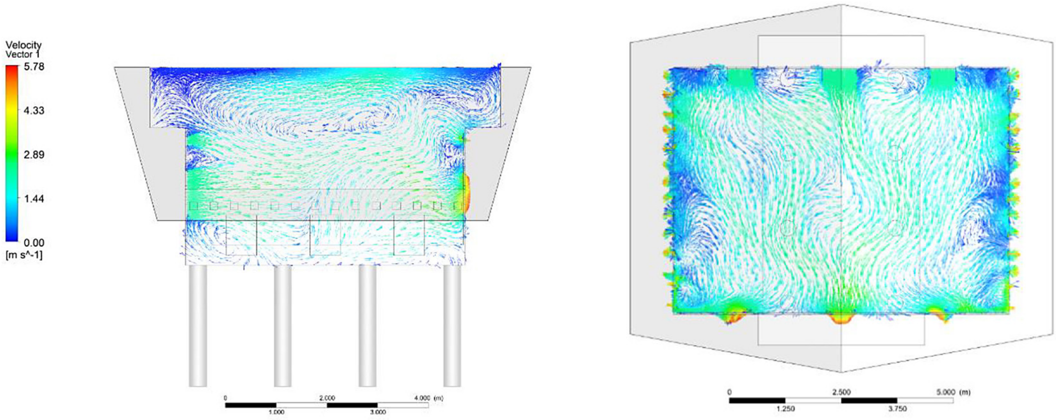


Figure 13. PMV and PPD of House 1 and House 2

remained consistent across all material configurations (Table 14), with velocities rising from 1.22 m/s at 08:00 to a peak of 2.54 m/s at 15:00, local time (UTC+7). This uniformity suggests that architectural form and window placement play a dominant role in shaping airflow, a finding corroborated by Mao et al. (2024) who emphasized that spatial openness and alignment with prevailing wind directions were more influential than the wall or roof material in natural ventilation performance.

Nonetheless, the air velocity alone does not guarantee comfort if the internal temperature remains high, a crucial insight when viewed in conjunction with PMV and temperature data. The absence of significant material effect on airflow also implies that passive strategies like cross ventilation, elevated floorings, and stack effect may require enhancement to improve indoor conditions, especially in houses retrofitted with modern materials.



(a) (b)

Figure 14. The airflow running throughout the Acehnese traditional house simulated in Ansys: (a) vertical, (b) horizontal section at 12:00 local time (UTC+7)

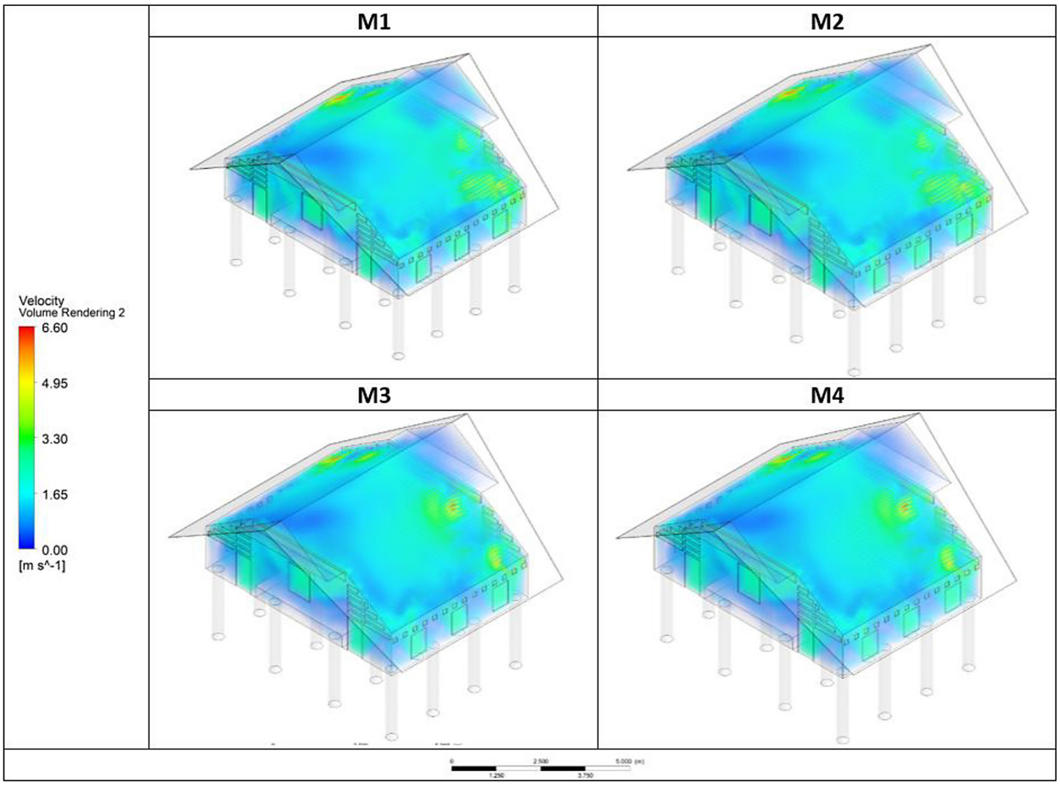


Figure 15. Air velocity simulation results of the four variations of Acehnese traditional house at 12:00 local time (UTC+7)

Material impact on indoor temperature

Material impact on indoor temperature, as present in Table 15 and Figure 16, compares simulated indoor temperatures for four variations of Acehnese house materials. The results clearly indicate that M1 (wooden wall, rumbia roof) is the most thermally efficient configuration, maintaining the lowest temperature across all hours. At 12:00 local time (UTC+7), M1 recorded 28.7 °C, while M3 (concrete wall, zinc roof) reached 30.0 °C, reflecting a difference of 1.3 °C, which significantly influences thermal perception and comfort.

Table 14. Air velocity simulation results

Average of indoor air speed (m/s)				
Time local time (UTC+7)	Wooden wall, rumbia roof (M1)	Wooden wall, zinc roof (M2)	Concrete wall, zinc roof (M2)	Concrete wall, tile roof (M2)
08.00	1.22	1.22	1.22	1.22
09.00	1.27	1.27	1.27	1.27
10.00	1.62	1.62	1.62	1.62
11.00	1.85	1.85	1.85	1.85
12.00	1.86	1.86	1.86	1.86
13.00	2.28	2.28	2.28	2.28
14.00	2.45	2.45	2.45	2.45
15.00	2.54	2.54	2.54	2.54
16.00	2.5	2.5	2.5	2.5

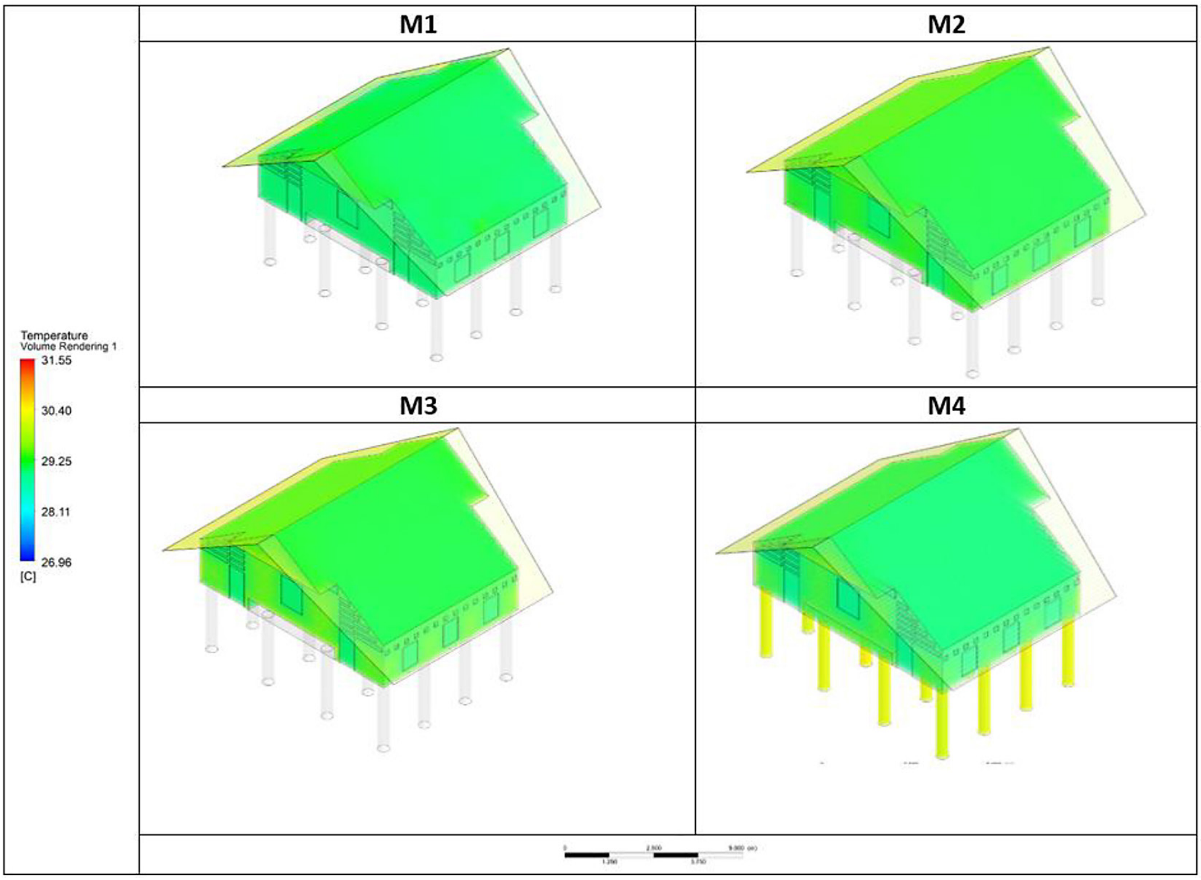


Figure 16. The simulation results of temperature volume rendering

This disparity can be explained by the thermal properties of the materials are first, Rumbia palm roofing has a high insulation capacity due to its fibrous composition, as discussed in Sari et al. (2024). Second, concrete and zinc, on the other hand, possess higher thermal conductivity, leading to rapid heat gain and slower release, which is detrimental in warm, humid conditions (Yuliani et al., 2021). These results are aligned with studies from Mainali et al. (2025), who advocate for the re-adoption of indigenous materials in modern tropical architecture for their passive thermal benefits.

CONCLUSIONS

This research has demonstrated that traditional Acehnese architectural strategies, particularly

Table 15. Average of indoor air temperature within the four simulated houses

Time local time (UTC+7)	Average of indoor air temperature (°C)			
	Wooden wall, rumbia roof (M1)	Wooden wall, zinc roof (M2)	Concrete wall, zinc roof (M3)	Concrete wall, tile roof (M4)
08:00	23	24.2	25.01	24
09:00	25.8	26.1	26.32	26
10:00	28.3	28.7	29.12	28.5
11:00	28.5	29.1	29.4	29
12:00	28.7	29.3	30	29.1
13:00	29.2	29.6	30.5	29.45
14:00	28	28.4	29.6	28.3
15:00	28.4	28.73	29.4	28.6
16:00	27.9	28.3	29.2	28.1

those embodied in Rumoh Aceh, remain effective in enhancing thermal comfort through passive design principles. By comparing two house models (H1 and H2) with variations in material and spatial configuration, the study found that:

1. Material selection significantly influences indoor thermal performance. House 1 (H1), which uses rumbia leaf roofing and wooden walls, exhibited better thermal insulation properties than House 2 (H2), which uses zinc roofing with aluminum foil and similar wooden walls. The lower U-value of the rumbia roof (4.459 W/m²K) compared to the zinc-aluminum combination (6.942 W/m²K) resulted in cooler indoor temperatures and more stable thermal comfort levels.
2. Thermal comfort indices (PMV, PPD, and SET) consistently showed that H1 maintained a more comfortable indoor environment than H2. While both houses experienced slightly warm to warm conditions during peak hours, H2 recorded higher discomfort levels, confirming the negative impact of modern roofing materials in tropical highland climates.
3. Architectural elements, such as elevated floors, open-concept plans, east-west orientation, and roof overhangs contributed positively to air circulation and thermal moderation. H1, with fewer spatial partitions and openings that facilitate cross ventilation, allowed for more effective natural airflow, supported by higher recorded wind speeds and favorable CFD simulation results.
4. CFD simulations revealed that the airflow rates within the same house layout but different building materials perform the similar air flow and speed across the house. However, material selection remains critical in managing internal heat gain, as reflected in the temperature differences. The combination of traditional materials and forms (wooden walls, rumbia roofs, stilt construction) provided superior performance in terms of both airflow and thermal resistance. These findings advocate for a hybrid approach in architectural design, merging cultural heritage with modern needs, especially in tropical and highland settings.

Overall, the study supports the reintroduction and preservation of indigenous Acehnese design principles as viable solutions for sustainable architecture and thermal comfort, offering a low-energy, culturally sensitive response to climatic challenges.

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