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THERMAL PERFORMANCE: INFLUENCE OF MATERIAL AND INCLINATION ANGLE ON VAULTED ROOFS IN TROPICAL CLIMATE

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Abstract: *Rapid urbanization demands significant growth in basic infrastructure, particularly in affordable housing. Concurrently, the escalating development necessitates an increased demand for energy. Among the strategies to mitigate high energy consumption is the optimization of building envelopes, such as roofs which experience the highest solar gain in tropical regions. This research aims to identify the effect of inclination angle and material of roof on thermal performance in tropical climate. Five configurations of roof inclination angles with various materials, facing both North-South and East-West orientations, were analyzed using Ladybug and Honeybee Tools. The results revealed that roof inclination angle, material significantly affect the average conduction. In a sequential order, the roofing materials with the lowest average conductivity values are concrete tiles, clay tiles, PVC roofs, and metal roofs. A greater inclination angle correlates with a lower average conductivity value, indicative of enhanced thermal performance, and vice versa. Roofs with inclination angles > 0°, featuring the same material, oriented North-South exhibit lower average conductivity compared to those facing East-West.*
Keyword: *Thermal Performance, Roof Inclination Angle, Roof Materials*

Abstrak: Urbanisasi yang pesat menuntut pertumbuhan infrastruktur dasar yang signifikan, khususnya perumahan yang terjangkau. Pada saat yang sama, peningkatan pembangunan memerlukan peningkatan kebutuhan energi. Salah satu strategi untuk memitigasi konsumsi energi yang tinggi adalah optimalisasi selubung bangunan, seperti atap yang memperoleh perolehan sinar matahari tertinggi di wilayah tropis. Penelitian ini bertujuan untuk mengetahui pengaruh sudut kemiringan dan material atap terhadap kinerja termal pada iklim tropis. Lima konfigurasi sudut kemiringan atap dengan material berbeda, menghadap orientasi Utara-Selatan dan Timur-Barat, dianalisis menggunakan Ladybug dan Honeybee Tools. Hasil penelitian menunjukkan bahwa sudut kemiringan atap, material berpengaruh nyata terhadap konduksi rata-rata. Secara berurutan, bahan atap dengan nilai konduktivitas rata-rata paling rendah adalah genteng beton, genteng tanah liat, atap PVC, dan atap metal. Sudut kemiringan yang lebih besar berkorelasi dengan nilai konduktivitas rata-rata yang lebih rendah, yang menunjukkan peningkatan kinerja termal, dan sebaliknya. Atap dengan sudut kemiringan > 0°, dengan bahan yang sama, berorientasi Utara-Selatan menunjukkan konduktivitas rata-rata lebih rendah dibandingkan atap yang menghadap Timur-Barat
Kata Kunci: Kinerja Termal, Sudut Kemiringan Atap, Material Atap

INTRODUCTION

In 2020, Indonesia saw a significant urban population of 56.7%, projected to rise to 66.6% by 2035 (BPS, 2020). This rapid urbanization calls for extensive development in basic infrastructure, especially affordable housing. The demand for housing, particularly among low-income groups, is substantial, with 7.64 million units needed by 2020 (Prasetya et al., 2023). While previous development plans aimed to reduce housing backlog and improve homeownership, the current focus has shifted towards providing decent and affordable housing.

With increased construction comes a higher demand for energy. Buildings globally accounted for 36% of final energy consumption and 37% of energy-related CO2 emissions in 2020 (United Nations Environment Programme, 2021). Residential buildings contribute significantly to energy consumption and emissions. In Indonesia, household energy use surged by 15% annually during the pandemic compared to pre-pandemic levels (Surahman et al., 2022), underscoring the need for energy-efficient residential buildings.

The primary culprit for high energy consumption in buildings is heating, ventilation, and air conditioning (HVAC) systems, which consume over half of the energy (Elaouzy & El Fadar, 2022). Passive design strategies offer a cost-effective approach to reducing energy consumption, with optimizing the building envelope being a key tactic (Elaouzy & El Fadar, 2022).In tropical climates like Indonesia, roofs receive the highest solar radiation compared to other building elements (Fang et al., 2022). This solar exposure leads to increased environmental temperatures and heat flow downwards during the day (Mitorogo et al., 2013), exacerbating the need for effective passive design strategies to mitigate heat gain and reduce reliance on cooling systems.

LITERATURE REVIEW

Thermal Performance

Heat transfer in building roofs is generally quantified by a specific value known as the Roof Thermal Transfer Value (RTTV). The RTTV is used to predict the thermal performance of roofs under different climatic conditions (He et al., 2021). In determining the RTTV, each country develops its own calculation models and standards considering its specific context. Indonesia has established regulations on building envelope energy conservation in the form of Indonesian National Standards (SNI).

As stated in the SNI 6389-2011 standard, to obtain comprehensive thermal transfer values, several parameters must be calculated, namely: thermal absorptance (α), thermal transmittance (U), equivalent temperature difference (TDEK), solar radiation factor (SF), shading coefficient (SC). These parameters apply to both roof and wall components to calculate heat transfer through conduction in opaque surfaces, conduction in glass, and radiation in glass.

In this case, the roof being studied is an opaque roof without any transparent elements, hence heat transfer likely occurs through conduction in the roof surface with opaque materials. Therefore, the thermal performance referred to in this study is assessed through the average conduction value occurring on the vaulted roof.

Roof Material and Inclination Angle

The influence of roofing materials and insulation on building performance is highly significant. Roof insulation plays a key role in maintaining indoor comfort during extreme temperatures and can enhance energy efficiency, reduce energy costs, and extend the service life of buildings (Zussman, 2021). In climates with four seasons, the type of roofing material and its energy performance can affect building energy consumption, with more than 60% of heat transfer occurring through the roof (Badiee, 2015).

Based on the nature and type of roofing materials, there are several options for roof pitch angles that can be considered. Additionally, the degree of roof pitch is highly dependent on local climatic conditions. In tropical regions with dry climates, roofs typically have a pitch between 0 to 10 degrees (Rochimah, 2014). Conversely, in humid tropical areas, the roof pitch angle can vary due to high rainfall. The relationship between roof pitch angles tends to be associated with the type of material used (Mangunwijaya, 1998).

METHODOLOGY

This research employed a simulation methodology incorporating Grasshopper software in conjunction with the Ladybug and Honeybee Tools plugin. Initially, the construction of building models commenced, encompassing diverse roof material variations and inclination angles within the Grasshopper platform. Subsequently, thermal performance simulations were conducted utilizing Ladybug and Honeybee Tools to ascertain thermal conduction values across roofs. The simulation process within Grasshopper was structured into four distinct stages: (1) Establishing building models; (2) modeling roof configurations; (3) executing simulations; and (4) visualizing resultant data.

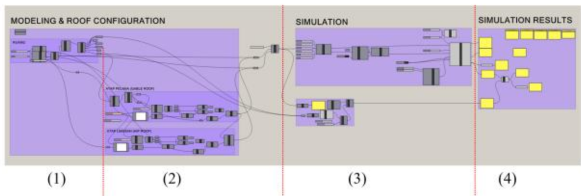

Figure 1. Definition and phases of simulation in Grasshopper.

Simulation Building Model

The study utilized a hypothetical building model based on regulations set forth by the Ministry of Public Works and Housing (PUPR) No. 242/KPTS/M/2020. According to these regulations, subsidized housing buildings typically range from 21 m² to 36 m² in size, subject to adjusted land area requirements as specified in PERMEN PUPR NO 23, 2020. Specifically, type 36 houses, which are common in this context, typically have dimensions of either 6 x 6 meters or 9 x 4 meters (DPUPKP, 2022). In adherence to these standards, the building model in this study was designed to represent the largest permissible house size, maintaining dimensions of 9 meters x 4 meters. This design choice was made to ensure consistency in orientation, which is one of the variables under investigation.

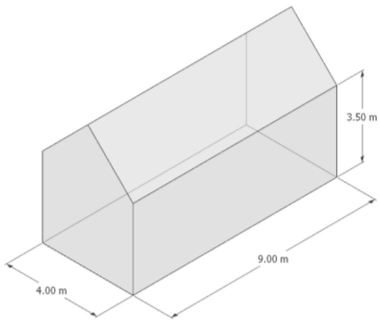

Figure 2. Hypothetical building model.

Building orientation is simulated in four orientations: North-South and East-West. The variation in orientation is simulated to observe the tendency of the best roof type and slope in each orientation.

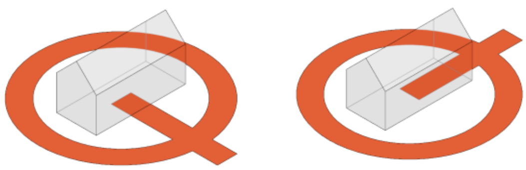

Figure 3. Building orientation configuration.

Roof Shape, Inclination Angle, and Material Variations

The roof shape configurations applied in this study consist of vaulted roof shape which is based on the common roof type found in Indonesia. The configurations of roof inclination angles for each roof shape used in this study include angles of 0°, 15°, 30°, 45°, and 60°. These inclination angles are commonly found in house roofs in Indonesia. The type of roof construction used in this research is a vaulted ceiling construction roof made from gypsum, with single layer of air space with a 300mm thickness and various outer roof materials.

Table 1. Roof Shape and Inclination Angle Variations

Roof Inclination Angle (°)				
∡0°	∡15°	∡30°	∡45°	∡60°

Roof material configuration involving clay roof tiles, metal roofs, PVC roofs, and concrete roof tiles, followed by the thermal properties of each material. The choice of roof material type is obtained from general empirical use. The thermal properties of the material in question include the level of surface roughness, thickness, conductivity, density and specific heat. Following are the material details and their property values.

Table 2. Roof material configuration and properties

Material Property	Roof Material Configuration			
	Clay Roof Tile	Metal Roof	PVC Roof	Concrete Roof Tile
Roughness	Medium--Rough	Smooth	Smooth	Medium-Rough
Thickness (m)	0.03	0.0002	0.01	0.03
Conductivity (W/m-K)	0.840	0.290	0.850	1.100
Density (Kg/m^3)	1900	1250	2000	2100
Spesific Heat (J/kg-K)	800	1000	900	837

The research location simulated is in the province of DKI Jakarta, the capital city of Indonesia. In HVAC simulations, 6 timesteps per hour were set to enhance surface and zone air temperature calculation accuracy by reducing time intervals between calculations. Simulation Control components such as *ZoneSizingCalculation* and *SystemSizingCalculation* were utilized for HVAC zone and system sizing calculations. *runSimulationforRunPeriods* was employed for year-round energy usage simulation. Other parameters included maximum (100 days) and minimum (6 days) heating days, and terrain settings as "*Country*" to describe open environments with surrounding objects under 10m height, typical of residential settings. Ground temperature was set at 22°C for 12 months, adjusted based on secondary data for the specified location. The simulation period is conducted from 06:00 AM to 06:00 PM for 31 days per month and 12 months per year.

Table 3. Simulation parameter

Energy Plus Weather file (EPW)	IDN_JW_Jakarta-Soekarno.Hatta.Intl.AP.967490_TMYx	
Timesteps	6 timesteps per hour	
Simulation Control	Zone Sizing Calculation	
	System Sizing Calculation	
	Max. Warm up Days	100
	Min. Warm up Days	6
Terrain	Country	
Monthly Ground Temperature	22	
Simulation Period	**Simulation Hour**	06.00-18.00
	Simulation Day	Day 1 – 31
	Simulation Month	January - December

RESULT AND DISCUSSION

In a North-South orientation within the same inclination angle, metal roofs exhibit the highest average thermal conduction values, followed by PVC roofs, clay tile roofs, and, lastly, concrete tile roofs, which demonstrate the lowest average thermal conduction values. Furthermore, within the same material category, roofs with a ∡0° inclination angle yield the highest average thermal conduction values, while those with a ∡60° inclination angle exhibit the lowest average thermal conduction values.

Table 4. Average Conduction (W/m^2) on North-South Orientation

∡ (°)	Average Conduction (W/m^2) North-South Orientation			
	Metal Roof	Clay Roof Tile	Concrete Roof Tile	PVC Roof
0	17.835997	16.728035	15.635221	17.076255
15	17.303719	16.195378	15.129508	16.567042
30	16.348309	15.253852	14.216249	15.635942
45	14.457676	13.430507	12.46551	13.803363
60	12.171827	11.242806	10.381811	11.593863

At a ∡45° inclination, metal tile roofs exhibit lower average conduction values compared to concrete tile roofs with inclinations between ∡0° to ∡15°. At a ∡60° inclination, metal roofs show slightly lower average conduction values compared to concrete tile roofs with a 45-degree inclination. The optimal configuration is represented by concrete tile roofs with a ∡60° inclination, which demonstrate the lowest average conduction value at 10.381811 Watt/m^2. Conversely, the least favorable configuration is represented by metal roofs with a 0-degree inclination, exhibiting an average conduction value of 17.835997 Watt/m^2.

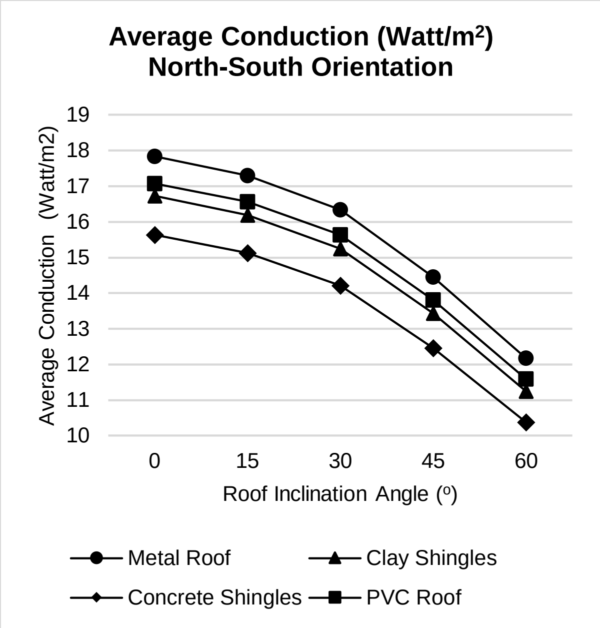

Figure 4. Average Conduction (Watt/m²) North-South Orientation.

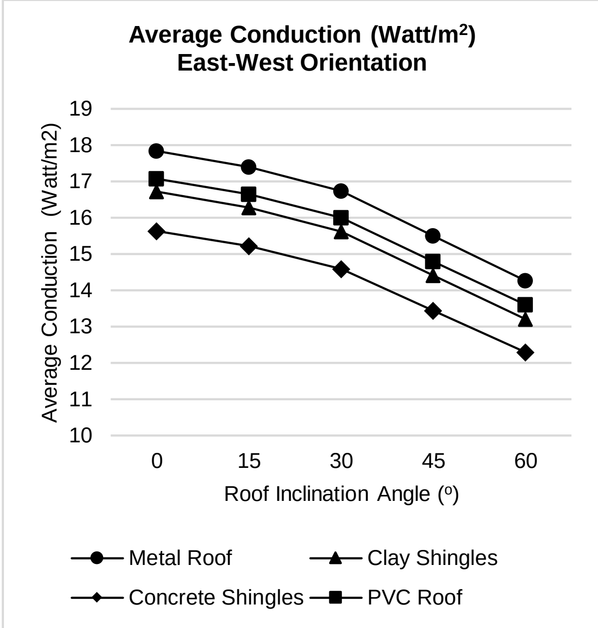

Figure 4. Average Conduction (Watt/m²) East-West Orientation.

In an East-West orientation, there is a similar trend in conduction values as observed in the North-South orientation, with the same inclination angle. The highest average conduction values are typically found on metal roofs, followed by PVC roofs, then clay tile roofs, with concrete tile roofs exhibiting the lowest average conduction values. Additionally, within the same material category, roofs with a ∡0º inclination angle yield the highest average conduction values, while roofs with a ∡60º inclination angle yield the lowest average conduction values.

Table 5. Average Conduction (W/m²) on East-West Orientation

∡ (º)	Average Conduction (W/m²) East-West Orientation			
	Metal Roof	Clay Roof Tile	Concrete Roof Tile	PVC Roof
0	17.835997	16.728035	15.635221	17.076255
15	17.394738	16.285989	15.220991	16.653135
30	16.729427	15.621461	14.582572	15.99759
45	15.498949	14.420223	13.44003	14.798766
60	14.262692	13.207908	12.289949	13.602127

At a ∡0º inclination in the East-West orientation, the average conduction values for all materials are the same as those observed in the North-South orientation. At a ∡45º inclination, metal tile roofs exhibit lower average conduction values compared to concrete tile roofs with inclinations between ∡0º to ∡15º. At a ∡60º inclination, metal roofs show slightly lower average conduction values compared to concrete tile roofs with a ∡45º inclination. The optimal configuration is represented by concrete tile roofs with a ∡60º inclination, which demonstrate the lowest average conduction value at 10.381811 Watt/m². Meanwhile, the least favorable configuration is represented by metal roofs with a ∡0º inclination, exhibiting an average conduction value of 17.835997 Watt/m².

At a ∡0º inclination in the East-West orientation, the average conduction values for all materials are the same as those observed in the North-South orientation. However, at a ∡15º angle, roofs facing North-South with the same materials exhibit lower average conduction values compared to those facing East-West, with an average difference of 0.089801 Watt/m². Similarly, at a 30-degree inclination, roofs facing North-South also demonstrate lower average conduction values compared to those facing East-West, with an average difference of 0.3691745 Watt/m². Likewise, at ∡45º and ∡60º, roofs in the North-South orientation display lower average conduction values compared to those facing East-West, with average differences of 1.000228 Watt/m² and 1.99309225 Watt/m², respectively. As the inclination angle increases, the difference in average conduction values between the North-South and East-West orientations also increases.

The thermal conductivity of each material, in sequence from highest to lowest, is concrete tile, PVC, clay tile, and metal roof. However, the average conduction results, from lowest to highest, are concrete tile, clay tile, PVC, and metal roof. Hence, it can be concluded that there is an influence from the thickness and specific heat of the material that affects the average conduction results. The inclination angle of the roof determines its orientation. The larger the angle, the more the roof faces away from the perpendicular direction facing upwards. Therefore, the greater the inclination angle of the roof, the greater the influence of the building orientation on the received solar radiation, and consequently, it affects the average conduction values of the roof. A smaller inclination angle results in a greater tendency towards orientation, whereas a larger angle increases the tendency for the roof orientation to face a particular cardinal direction.

Therefore, the optimal thermal configuration for roofs in Indonesia is one with a large inclination angle facing North-South, thus allowing the roof surface to avoid direct exposure to the sun's movement from East to West.

CONCLUSION

In consecutive order, the roofing materials with the lowest average conductivity values are concrete tiles, clay tiles, PVC roofs, and metal roofs. The average thermal conductivity values of different materials cannot be directly inferred from the thermal conductivity values alone, as the thickness of the material and its specific heat also influence the final average conductivity of a surface.

In all orientations, roofs with a ∡0º inclination exhibit the highest average conductivity, whereas roofs with a ∡60º inclination have the lowest conductivity. At a ∡0º inclination in the North-South orientation, the average conductivity of all materials is identical to that of the East-West orientation. However, at ∡>0°, with the same material, roofs oriented North-South have lower average conductivity compared to those facing East-West. The greater the slope angle, the greater the difference in average conductivity values between roofs facing North-South and those facing East-West.

Therefore, it is concluded that the greater the slope angle, the lower the average conductivity value, indicating better thermal performance. The optimal thermal configuration for roofs in a tropical climate is one with a steep slope facing North-South, thereby avoiding direct sunlight exposure moving East-West.

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