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Casement Windows With and Without Screens: CFD Study on Lighting, Thermal, and Malaria

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ABSTRACT

Malaria-endemic tropical regions require residential design strategies that can improve indoor environmental quality while maintaining adequate natural ventilation and lighting performance. However, limited studies have comparatively evaluated the environmental performance of casement windows with and without mosquito screens in tropical residential buildings using Computational Fluid Dynamics (CFD) analysis. This study aims to evaluate the effect of casement windows with and without mosquito screens on natural lighting performance, airflow distribution, and indoor thermal conditions in residential buildings in Sikka Regency, Indonesia. The study employed a quantitative case study approach using field measurements and CFD simulations on a PUPR model house. Environmental parameters including natural lighting intensity, airflow velocity, temperature, and humidity were measured and analyzed under two window configurations. The results show that dwellings with mosquito-screened windows experienced higher humidity levels reaching 68.03% and reduced average natural lighting intensity by approximately 9 lux compared to unscreened windows. In contrast, unscreened casement windows produced more effective airflow circulation, more stable cross ventilation, and relatively lower indoor humidity levels. The findings indicate that window configuration significantly affects indoor environmental quality and may influence indoor microclimatic conditions associated with vector-supportive environments in tropical residential buildings..

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I. Introduction

Climate is one of the environmental factors influencing the transmission of vector-borne diseases, including malaria, in tropical countries such as Indonesia. Based on the Köppen climate classification system, Indonesia is dominated by tropical rainforest (Af), monsoon (Am), and tropical savanna (Aw) climates. East Nusa Tenggara Province, particularly Sikka Regency, is categorized as a tropical savanna climate region characterized by relatively high temperatures and seasonal dryness [1]. Despite ongoing malaria control programs, eastern Indonesia remains one of the priority regions for malaria prevention and management. According to regional health reports, Sikka Regency experienced fluctuating malaria incidence rates between 2013 and 2024, with a notable increase occurring in 2022 after several years of decline [2].

Figure 1. API Trend in Sikka Regency 2013-2024

Figure 1 shows that malaria incidence in Sikka Regency declined significantly between 2013 and 2021 before experiencing a temporary increase in 2022. Although the trend decreased again in subsequent years, these fluctuations indicate that environmental and climatic conditions continue to influence factors associated with malaria transmission dynamics. The persistence of malaria cases suggests the need for environmentally responsive mitigation strategies, including improvements in residential environmental performance and passive building design.

Based on the malaria endemicity map of Sikka Regency, the northern region tends to show moderate to high endemicity levels, while the southern region is generally classified as low endemic or malaria-free. Differences in malaria endemicity patterns are associated with geographical, ecological, and demographic characteristics that influence mosquito breeding habitats and human exposure [3]. Previous studies in Indonesia have demonstrated that environmental and housing conditions play significant roles in malaria transmission dynamics [4]. Environmental variables such as vegetation density, stagnant water, waste disposal areas, livestock proximity, and housing openness may create favorable conditions for mosquito activity and persistence [5]. Studies conducted in East Nusa Tenggara also demonstrate that housing conditions and the surrounding environment are important determinants of malaria vulnerability [6, 7].

Housing design has increasingly been recognized as an important passive environmental strategy for reducing human exposure to malaria vectors [8, 9]. Several studies in Africa have demonstrated that window configuration, ventilation strategies, and mosquito-screened openings significantly affect mosquito entry and indoor exposure risk in residential buildings [10-13]. In addition, natural ventilation has been associated with changes in indoor temperature and humidity, which may indirectly affect indoor environmental conditions associated with mosquito activity [14, 15]. Improved ventilation strategies may reduce indoor heat accumulation and humidity while simultaneously enhancing occupant comfort and indoor environmental quality [12, 13]. Besides thermal performance, window configuration also affects daylight penetration and indoor natural lighting conditions, which are important aspects of healthy residential environments.

In tropical regions, indoor thermal conditions are closely associated with airflow patterns, relative humidity, and building openings. Previous studies have shown that higher humidity and poor airflow may support mosquito survival and increase the likelihood of vector persistence indoors [16-19]. Consequently, building design interventions such as mosquito-screened windows, optimized ventilation, and opening configurations have been proposed as environmentally responsive strategies for improving indoor environmental quality in malaria-endemic regions [20-23]. Furthermore, simulation-based studies in Sikka Regency revealed that wind flow direction, opening configuration, and the distance between opposing openings influence airflow distribution patterns that may affect indoor environmental conditions related to mosquito movement [15, 24].

Although previous studies have examined housing design, ventilation performance, and malaria-related environmental conditions, several research gaps remain. First, limited studies have specifically compared casement windows with and without mosquito screens in relation to indoor thermal performance, airflow characteristics, and daylighting performance in tropical endemic housing. Second, previous malaria-housing studies generally focused on epidemiological or behavioral aspects, while studies integrating building physics parameters such as airflow, humidity, temperature, and natural lighting performance remain limited. Third, CFD-based investigations examining screened and unscreened casement window configurations in the context of residential buildings in Sikka Regency are still rarely discussed in the current literature, particularly those integrating field measurements and environmental performance analysis.

Based on these gaps, this study aims to: (1) compare the natural lighting performance of casement windows with and without mosquito screens; (2) evaluate differences in airflow patterns, temperature, and humidity through field measurements and Computational Fluid Dynamics (CFD) simulations; and (3) analyze the potential implications of indoor environmental conditions on vector-supportive microclimates in residential buildings in Sikka Regency. Unlike previous studies that separately discussed housing conditions or malaria-related environmental factors, this study combines field measurements with CFD-based environmental analysis to evaluate the environmental performance of screened and unscreened casement windows within the context of tropical endemic housing in Indonesia.

II. Research Method

This study employed a quantitative approach using field measurements and Computational Fluid Dynamics (CFD) simulations to evaluate the natural lighting performance and indoor thermal conditions of residential buildings, as well as their potential implications for vector-supportive indoor microclimates. The object of the study was a PUPR model house representing a simple residential typology commonly found in malaria-prone areas in Sikka Regency, East Nusa Tenggara. The building had a total floor area of 36 m² with a spacing distance of approximately 1 meter between adjacent buildings, representing the existing settlement conditions in the study area.

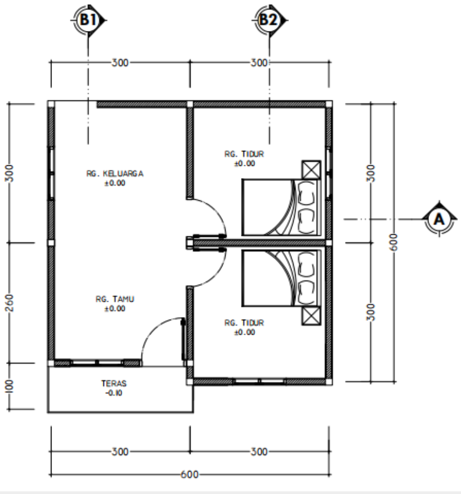

Figure 2. Floor plan

The study focused on the use of casement windows because this opening type is commonly applied in residential buildings in Sikka Regency. The window dimensions were 120 × 115 cm, and two window scenarios were evaluated: (1) casement windows without mosquito screens and (2) casement windows with mosquito screens.

Figure 3. Casement Window Type

Field measurements were conducted to obtain environmental data used as input parameters and boundary conditions for the CFD simulations. The measured parameters included natural lighting intensity using a lux meter, indoor air velocity using an anemometer, and air temperature and relative humidity using a thermohygrometer. Measurements were conducted at several points inside the building, including areas near window openings and central room zones, to capture representative indoor environmental conditions. Data collection was performed during daytime conditions under relatively stable weather conditions. The measurement instruments were checked and adjusted according to standard operational procedures before data collection.

The measured environmental data were subsequently used as boundary conditions for CFD simulations to analyze airflow distribution, temperature, humidity, wind velocity, and indoor environmental performance under both window configurations. The simulation model was developed based on the actual geometry of the building and surrounding spatial conditions. The mosquito screen component was modeled as an airflow resistance layer to represent the reduction of airflow passing through the screened opening.

The CFD simulation utilized the k–epsilon turbulence model due to its stability and efficiency in predicting airflow behavior and indoor turbulence phenomena in naturally ventilated buildings. All solid building surfaces, including walls, floors, windows, and mosquito-screened surfaces, were assigned no-slip boundary conditions to represent airflow deceleration near solid boundaries. The inlet boundary condition was defined as a velocity inlet with airflow velocities ranging from 1.4 to 8.3 m/s and an inlet air temperature of 29 °C, with wind direction originating from the south-southwest (SSW) according to local environmental conditions. Meanwhile, the outlet boundary was modeled as an outflow boundary condition with an ambient temperature of 34 °C to allow airflow recirculation and pressure adjustment within the computational domain.

The meshing process employed approximately 4 to 6 million elements to obtain relatively detailed airflow distribution results while maintaining computational efficiency. A preliminary mesh sensitivity evaluation was conducted to ensure that the selected mesh density produced stable airflow simulation results without significant numerical deviations.

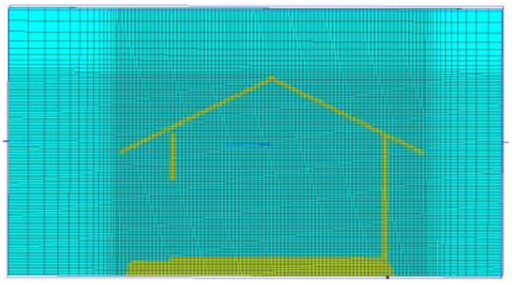

Figure 4. Meshing Section

The simulation process was performed iteratively until stable residual convergence was achieved. CFD simulation outputs were then compared with field observation data to ensure that the airflow and thermal distribution patterns reasonably represented the actual environmental conditions of the building.

The CFD simulation results were analyzed comparatively to identify differences in natural lighting performance, airflow patterns, temperature distribution, and humidity levels between dwellings with and without mosquito screens. Furthermore, these findings were interpreted in relation to indoor environmental conditions that may support mosquito activity and vector persistence within residential spaces.

III. Result and Discussion

A. *Local Climate Characteristics*

Field measurements indicate that the study area is characterized by humid tropical environmental conditions with relatively high thermal exposure. The outdoor air temperature was recorded at approximately 29 °C with a relative humidity level of 90%, indicating highly humid ambient conditions. The dominant wind direction originated from the south-southwest (SSW), reflecting the prevailing airflow pattern surrounding the residential area. In addition, the maximum ambient temperature reached 34 °C during the observation period, indicating a relatively high external heat load on the building envelope.

The north-facing orientation of the building contributes to significant solar exposure throughout the day, which potentially affects indoor thermal conditions and natural lighting distribution. The combination of high ambient temperature, elevated humidity, and solar exposure may increase heat accumulation and indoor moisture levels, particularly in buildings with limited airflow circulation. These climatic conditions highlight the importance of adaptive opening configurations and effective natural ventilation strategies to improve indoor environmental quality in tropical residential buildings.

B. *Natural Lighting Performance*

The simulation results indicate that dwellings with casement windows without mosquito screens achieved an average natural lighting intensity of 96 lux, while dwellings with mosquito-screened casement windows recorded a lower average lighting intensity of 87 lux. These results demonstrate that the addition of mosquito screens reduced indoor daylight penetration by approximately 9 lux.

The reduction in lighting performance is associated with the additional screen layer positioned on the window opening, which partially obstructs both direct and diffuse solar radiation entering the room. Consequently, the screened window configuration produced relatively lower indoor illumination levels, particularly in interior zones located farther from the openings. This condition may become more significant in dense residential areas with limited spacing between buildings, where daylight access is already constrained.

Although both lighting conditions remained below the general daylight recommendation for residential indoor activities, the unscreened casement window configuration showed relatively better daylight performance compared to the screened configuration. These findings indicate that the application of mosquito screens may influence indoor environmental quality not only in terms of airflow, but also in daylight availability within residential spaces.

Previous studies have also reported that limited natural lighting and poor indoor environmental quality may contribute to conditions favorable for microorganism growth and vector persistence [25]. However, the present study does not directly measure mosquito density or malaria incidence. Therefore, the findings should be interpreted as indicating indoor environmental conditions that may support vector-associated microclimatic conditions rather than direct epidemiological impacts.

C. *Temperature, Humidity, and Air Velocity*

1. Thermal Distribution in Dwellings Without Mosquito Screens

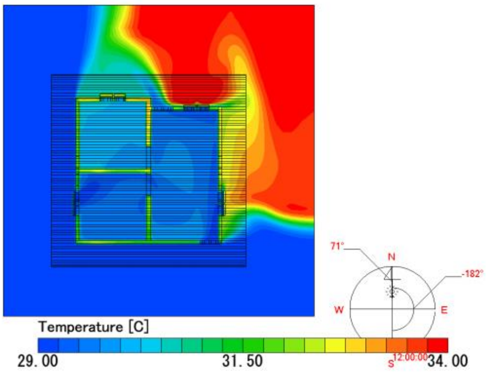

Figure 5. Temperature Simulation Results at Windows Without Blinds

The Computational Fluid Dynamics (CFD) simulation results show that the indoor air temperature distribution in dwellings without mosquito screens ranged between 29–31.5 °C, while exterior temperatures reached approximately 32–34 °C. The relatively homogeneous indoor temperature distribution indicates that natural ventilation contributed to convective heat transfer and reduced excessive heat accumulation inside the room.

Under relative humidity conditions of approximately 54.52%, airflow circulation inside the building remained relatively more stable compared to the screened-window configuration. The lower humidity level indicates that airflow movement assisted the removal of heat and moisture from the indoor environment, thereby contributing to improved indoor environmental conditions.

2. Airflow Distribution in Dwellings Without Mosquito Screens

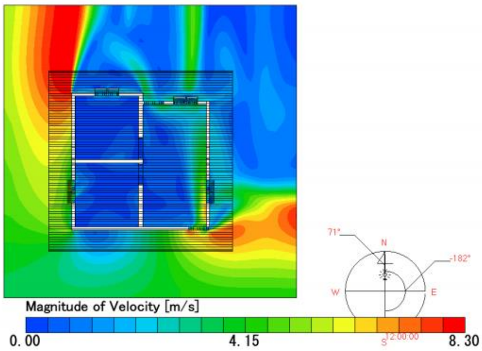

Figure 6. Wind Speed Simulation Results

The airflow simulation results indicate that air movement inside the building was distributed more effectively through the window openings, although several low-velocity zones remained in the central area of the room. Compared to screened windows, the unscreened window configuration allowed more direct airflow penetration and improved cross-ventilation performance.

Previous studies have shown that improved natural ventilation and enhanced airflow circulation can reduce indoor environmental conditions favorable to mosquito persistence and malaria exposure [26, 27]. Higher airflow circulation may also contribute to reduced indoor humidity and thermal accumulation, thereby improving indoor environmental quality in tropical residential buildings.

3. Thermal Distribution in Dwellings with Mosquito Screens

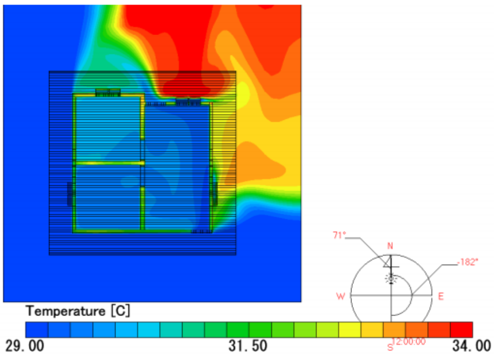

Figure 7. Temperature Simulation Results on Windows

The CFD simulation results for dwellings with mosquito-screened windows show that indoor air temperatures ranged between 29–31.5 °C, while temperatures near exterior building surfaces exposed to solar radiation increased to approximately 34 °C. Compared to the unscreened configuration, the screened windows demonstrated relatively higher humidity conditions, reaching approximately 68.03%.

The higher humidity levels indicate reduced airflow effectiveness due to the additional resistance created by the mosquito-screen layer. This condition contributed to reduced air exchange and increased moisture retention inside the building. In several interior zones, the airflow pattern became less evenly distributed, creating localized areas with relatively stagnant air movement.

4. Airflow Distribution in Dwellings With Mosquito Screens

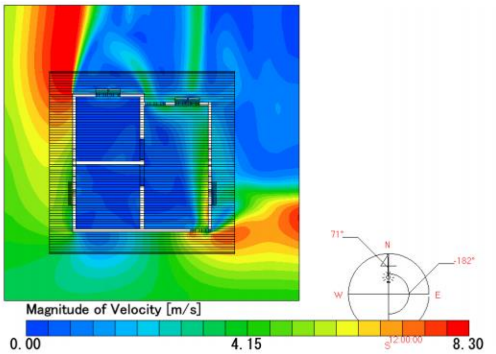

Figure 8. Wind Speed Simulation Results

The airflow velocity distribution shows that indoor air movement generally remained below 4.15 m/s, with several central interior zones experiencing relatively weak airflow circulation. Airflow acceleration occurred mainly near openings directly exposed to the dominant wind direction, while airflow intensity decreased significantly in deeper interior areas.

The presence of stagnant airflow zones indicates that the screened-window configuration reduced the effectiveness of cross ventilation within the building. Under indoor temperature conditions of approximately 29–31.5 °C and relative humidity levels above 60%, the indoor microclimate became relatively more humid and thermally stable.

Previous entomological studies reported that environmental conditions characterized by warm temperatures, elevated humidity, and limited airflow may support mosquito resting activity and indoor persistence [28-30]. Nevertheless, the present study only evaluates building environmental parameters and airflow conditions through field measurements and CFD simulations. Therefore, the findings should be interpreted as potential indoor environmental conditions associated with vector-supportive microclimates rather than direct evidence of malaria transmission risk.

The results also demonstrate that airflow distribution plays an important role in maintaining indoor environmental quality. Continuous airflow circulation may help reduce indoor heat accumulation and humidity levels while minimizing stagnant air zones within residential spaces. These findings are consistent with healthy housing principles emphasizing the importance of effective natural ventilation and airflow circulation in tropical buildings [31].

Overall, the CFD simulation results indicate that the interaction between temperature, humidity, and airflow distribution significantly influences indoor environmental conditions in residential buildings. The screened-window configuration tended to produce higher humidity levels and less effective airflow circulation, whereas the unscreened configuration demonstrated relatively better ventilation and indoor environmental performance.

IV. Conclusion

This study demonstrates that window configuration significantly affects natural ventilation performance, indoor airflow distribution, natural lighting performance, and the formation of indoor thermal conditions in tropical residential buildings. Casement windows without mosquito screens showed relatively better environmental performance by producing more effective airflow circulation, more stable cross ventilation, lower humidity levels, and slightly higher natural lighting intensity compared to screened window configurations. In contrast, the application of mosquito screens increased airflow resistance, reduced daylight penetration, and contributed to higher indoor humidity levels reaching approximately 68.03%.

The CFD simulation results indicate that airflow distribution and humidity conditions play an important role in shaping indoor environmental quality. Screened window configurations tended to produce localized stagnant airflow zones and higher moisture accumulation, whereas unscreened configurations demonstrated more effective ventilation performance and more evenly distributed airflow patterns. These findings suggest that window configuration and ventilation strategy are important passive design considerations for improving indoor environmental quality in tropical residential buildings.

From a practical perspective, this study contributes to the development of environmentally responsive housing design strategies in malaria-endemic tropical regions, particularly in relation to natural ventilation and indoor environmental control. The integration of field measurements and CFD simulations also demonstrates the potential of simulation-based approaches for evaluating residential environmental performance in humid tropical climates.

Nevertheless, this study has several limitations. The research was conducted using a single residential building typology and limited environmental scenarios. In addition, the study focused on building environmental parameters and CFD-based airflow analysis without direct entomological observations or epidemiological measurements. Therefore, the findings should be interpreted as indicating indoor environmental conditions associated with vector-supportive microclimates rather than direct evidence of malaria transmission risk.

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