Mitigating Overheating and Improving Ventilation in Dense Taiwanese Townhouses Using a Termite-Mound-Inspired Hybrid Stack System

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Abstract

Urban Taiwanese townhouses are typically narrow, deep, and tightly spaced, with limited façade openings. These conditions restrict wind access and cross-ventilation, amplify solar-driven heat accumulation, and increase reliance on air conditioning. Although termite-mound-inspired ventilation has been implemented in commercial buildings, its effectiveness for high-density residential townhouses remains underexamined. This study proposes a termite-mound-inspired hybrid stack-ventilation system that integrates a ceiling plenum, a central vertical shaft, and a low-power exhaust fan to sustain upward flow under weak-wind conditions. A conventional townhouse and the biomimetic alternative were developed using Building Information Modeling (BIM) and evaluated with Computational Fluid Dynamics (CFD) under a controlled daytime scenario that includes adjacent buildings and asymmetric solar exposure. The conventional configuration exhibits uneven ventilation with extensive stagnation and strong thermal stratification under peak solar loading. In contrast, the biomimetic design establishes a stable upward ventilation pathway with improved airflow distribution across occupied zones, maintaining inlet and outlet air temperatures within ±0.6 °C of ambient. The results indicate that fan-assisted, pressure-driven stack action can enhance ventilation robustness in window-limited townhouses, providing a transferable biomimetic design approach to reduce cooling dependence in dense urban housing in Taiwan.

Keywords –

Termite mound, biomimetic design, urban townhouse, sustainable architecture, energy efficiency, hybrid ventilation, BIM, CFD.

1 Introduction

Climate change is increasing the frequency and severity of heat waves, driving a growing dependence on air-conditioning (AC) to maintain health and comfort [1]. However, widespread AC use creates a feedback loop: it raises electricity demand and associated emissions, which in turn exacerbate warming. This challenge is especially acute in tropical and subtropical regions such as Taiwan, where summer heat and humidity make residential cooling a necessity [2].

The built environment is a major contributor to global emissions. The construction sector accounts for roughly 30% of annual global carbon emissions, while building operations represent a substantial share of energy-related greenhouse gas emissions [3]. In Taiwan, the increasing penetration of mechanical cooling in housing raises concerns about energy efficiency, peak-load stress, and residential carbon footprints. These pressures motivate architectural solutions that can reduce cooling demand while maintaining indoor environmental quality.

Biomimicry offers a pathway to such solutions by translating nature's strategies for energy efficiency and climate resilience into design. Termite mounds are a prominent example: despite large diurnal temperature swings outdoors, mound structures can maintain relatively stable internal conditions by coupling porous envelopes, thermal mass, and networked air pathways that promote ventilation and heat exchange [4]. As illustrated in **Fig. 1**, the connectivity of mound chambers supports continuous gas exchange and air circulation, enabling passive regulation of temperature and humidity in harsh climates.

Dense Taiwanese townhouses commonly suffer from overheating and poor ventilation because their narrow, deep-plan layouts and close proximity to neighboring buildings restrict side openings and weaken cross-ventilation. Although termite-mound-inspired ventilation has informed several building concepts and precedent projects, its application to Taiwanese urban townhouses has not been clearly documented, and its effectiveness in this residential typology remains insufficiently understood. Existing studies and built examples have focused mainly on commercial or institutional buildings, or on contexts that differ from Taiwan's subtropical, high-density townhouse environment. Therefore, a clear research gap remains regarding whether termite-mound-inspired ventilation principles can be adapted effectively to Taiwanese townhouses with front-and-rear openings and blocked side façades.

This study investigates how termite-mound-inspired ventilation and thermal regulation principles can be adapted to Taiwanese urban townhouses. The scope is a representative four-storey townhouse. The objective is to reduce cooling dependence and improve indoor air quality by enhancing airflow pathways and passive heat moderation within the constraints of high-density urban blocks.

Fig. 1. Termite mound schematic [5]

To evaluate feasibility, we compare a baseline townhouse with a termite-inspired alternative. Distinct from conventional buoyancy driven stacks, the proposed design integrates a low power fan at the top of the central shaft, transforming it into an assisted, pressure-driven stack (an active–passive hybrid) that can sustain airflow when wind is obstructed or buoyancy is weak. Building Information Modeling (BIM) supports consistent geometry definition and data export, while Computational Fluid Dynamics (CFD) is used to enable a controlled, like-for-like comparison between the baseline and biomimetic cases and to resolve airflow paths, temperature gradients, and buoyancy-driven heat removal under dense urban blockage and asymmetric solar loading. These coupled effects are difficult to capture adequately through simplified calculations alone, especially at the early design stage.

Accordingly, this paper makes three contributions: (1) it develops a townhouse-scale hybrid stack-ventilation layout inspired by termite mounds and tailored to front-and-rear openings; (2) it establishes a BIM-to-CFD workflow for a fair baseline-versus-biomimetic comparison under an urban block constraint; and (3) it reports comparative thermal distribution outcomes under a representative daytime loading scenario.

Figure 2 summarizes the research workflow. First, the literature on passive ventilation and termite-inspired strategies was reviewed to define the design rationale and evaluation criteria. Next, two BIM models, a baseline townhouse and a termite-inspired alternative, were developed in Autodesk Revit with matched overall geometry to ensure comparability. Simulation assumptions and boundary conditions were then specified, including façade orientation and inlet/outlet locations. CFD simulations were conducted to evaluate airflow behavior and temperature responses, followed by verification against reference benchmarks and post-processing for visualization and reporting.

2 Literature Review

2.1 Real-life applications of termite-inspired architecture

Termite-mound-inspired ventilation concepts have been incorporated into several high-profile buildings, indicating the potential of biomimicry to reduce reliance on mechanical cooling and to improve indoor environmental quality. **Table 1** compiles representative precedents and the performance impacts most commonly reported in the literature. Because reported savings depend on climate, operation, and evaluation methods, results should be interpreted within their original contexts. Notably, prior work has concentrated predominantly on commercial and institutional building types, with comparatively limited evidence from subtropical climates or from townhouse typologies where cross-ventilation is intrinsically constrained. Consequently, the applicability of termite-inspired approaches to Taiwan's dense urban residential context remains insufficiently documented.

Beyond these representative precedents, prior studies have shown that biomimetic and stack-based ventilation strategies can improve passive cooling and airflow organization through vertical exhaust paths and distributed air routes. However, most existing work has focused on commercial or institutional buildings, or on contexts with less restrictive façade conditions than dense Taiwanese townhouses.

As a result, limited evidence is available for narrow, deep-plan residential buildings with blocked side façades and constrained cross-ventilation in a subtropical urban setting. Therefore, the novelty of this study lies not only in its townhouse application, but also in its hybrid ventilation configuration and controlled BIM-to-CFD comparison of baseline and biomimetic cases under dense urban constraints.

Based on the preceding case studies, three transferable design principles emerge: (i) establish a continuous vertical route for buoyancy-driven exhaust, (ii) distribute supply air via branching paths or plenums to improve spatial uniformity, and (iii) apply minimal mechanical assistance (e.g., low-power fans) to stabilize airflow when external driving forces are weak.

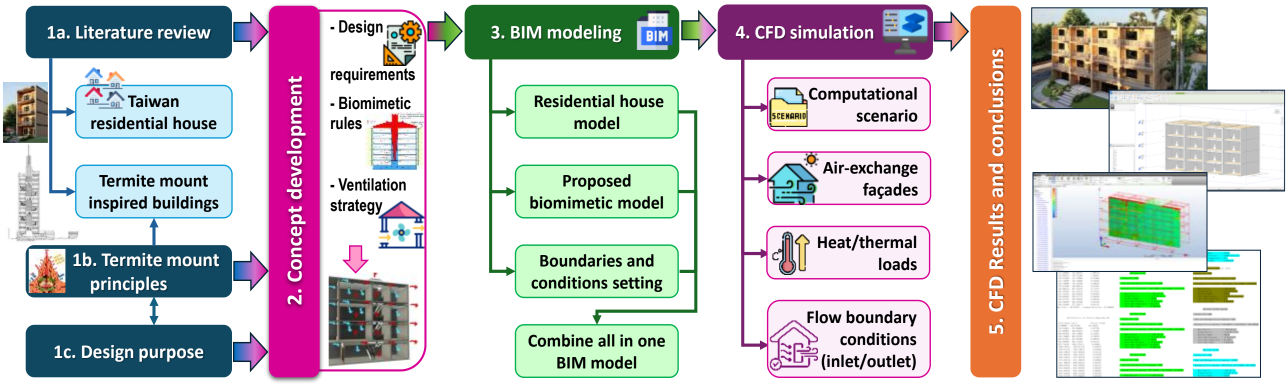

Fig. 2. Research workflow

Table 1. Notable cases of termite-inspired architecture

Project	Location	Design Features	Energy Efficiency Impact
Eastgate Centre	Harare, Zimbabwe	Passive cooling and natural ventilation via air channels	Reported to use 90% less energy for heating and cooling than comparable conventional buildings [6]
Council House 2	Melbourne, Australia	Natural ventilation and biomimetic façade elements	85% reduction in electricity and 87% reduction in gas consumption compared to the previous Council House of similar size [7]
Commerzbank Tower	Frankfurt, Germany	Central atrium and sky gardens for ventilation and daylighting	Extensive natural ventilation/daylighting; reported to have achieved ~20% lower energy consumption than predicted [8]
Queen's Building	Leicester, UK	Stack ventilation and thermal mass strategies	Measured operational energy (1994–1995) compared favorably with UK 'low target' benchmarks for university academic buildings [9].

Guided by these principles, this study adapts mound-inspired airflow pathways to the spatial and façade constraints of Taiwanese townhouses. The proposed concept combines predominantly passive ventilation with fan-assisted stack driving and distributed warm-air collection to sustain air exchange and moderate indoor thermal stratification with minimal energy input.

2.2 Typical Taiwanese Townhouse Layout

To track housing conditions amid rapid social and environmental change, Taiwan's Construction and Planning Agency (Ministry of the Interior) conducts a national housing condition survey approximately every decade. The most recent publicly available survey, the Report on the Housing Status Survey 2015, provides key statistics for prevalent housing typologies [10].

The survey indicates that townhouses constitute the most common housing type nationwide, totalling about 3.586 million units (49.20% of housing stock) [10]. These buildings are typically reinforced masonry or reinforced concrete structures, reflecting cost efficiency and durability. The four-storey townhouse is particularly prevalent in dense urban areas, where narrow plots and high land values encourage vertical stacking of functions.

Tseng, et al. [11] described Taiwanese townhouses as narrow, deep-plan buildings, commonly three to four stories, optimized for space efficiency under budget constraints. Typical layouts progress from an entrance and living area to dining and kitchen zones, with bedrooms on upper floors. Staircases and bathrooms are often centrally located. On average, habitable rooms comprise about 78% of total floor area, stairs 13.1%, and bathrooms 8.7% [11]. Reported window-to-wall ratios are around 30% [12], and double-glazed windows are common in recent construction [13].

Table 2. Typical townhouse parameters in Taiwan

Content	Value
Floor height	Living/dining: 3.4–3.6 m; Other floors: 3.0–3.2 m
House width	4.1–6.38 m
House length/depth	7.67–12.68 m
Building coverage ratio	50%
Space allocations	Habitable room areas: 78%, Stairs: 13.1%, Bathrooms: 8.7%.
Window-to-wall ratio	30%
Window types	Double-glazed windows (13 mm air gap between two 4 mm panes)

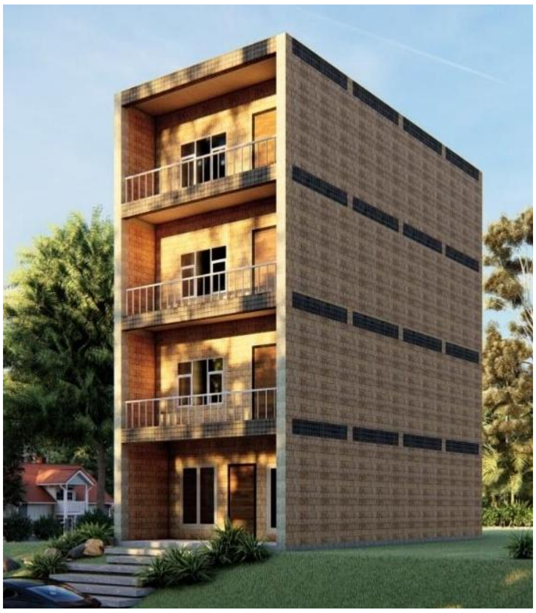

Fig. 3. Typical residential house in Taiwan

Table 2 consolidates parameter ranges for Taiwanese townhouses reported in the national housing survey and prior studies, including storey height, plan dimensions, building coverage ratio, space allocation, and façade opening characteristics. Drawing on these ranges and published descriptions of typical Taiwanese residential layouts, a representative baseline townhouse was developed in BIM (**Fig. 3**). The model comprises four storeys with a 6.5 m × 12.0 m floor plate, a 3.2 m storey height, and a centrally located staircase core. Façade openings are assigned to the front and rear elevations, reflecting the high-density urban condition in which adjacent buildings generally preclude windows along the side walls. This baseline configuration serves as a consistent reference for evaluating the proposed biomimetic alternative.

3 Proposed Termite-mound-inspired Design for Taiwanese Townhouses

The proposed design follows functional biomimicry by translating termite-mound climate-control mechanisms into architectural elements suitable for urban housing. Similar to a mound's central chimney, a vertical shaft is introduced to support upward transport and exhaust of warm air. To address the unreliable driving forces of purely passive stacks in wind-obstructed street canyons, a low-power exhaust fan is placed at the top of the shaft to establish a consistent pressure differential. Incoming air is guided through near-slab zones to leverage thermal mass for temperature moderation, and horizontal ducts and distributed vents are arranged across floors to promote more uniform circulation and collection of buoyant warm air.

Based on the baseline townhouse parameters (**Table 2**), the prototype has a footprint of 6.5 m x 12.0 m (78 m²) and four stories, yielding a gross floor area of approximately 312 m². The termite-inspired townhouse retains the baseline floor plan to enable a controlled comparison, but introduces two key modifications: (i) a ceiling plenum that distributes incoming air laterally before it descends into occupied zones, and (ii) a central vertical shaft that promotes buoyancy-driven exhaust to the roof, where a low-power fan can assist extraction to stabilize upward flow. **Figure 4** illustrates the proposed termite-mound-inspired design, and **Fig. 5** depicts the termite-inspired ventilation system.

As shown in **Fig. 5**, outdoor air is supplied through façade openings and guided into a ceiling plenum that acts as a branching distribution network. Air is then delivered to interior spaces and extracted through the central shaft, supporting a predominantly upward flow path. A roof-level exhaust fan is introduced as a hybrid element to maintain a target extraction rate during low-wind or adverse pressure conditions, thereby reducing short-circuiting and improving floor-to-floor temperature uniformity. For the CFD prototype in this study, the ceiling plenum depth was set to 0.30 m, and the central shaft had a 0.8 m × 0.8 m clear section extending the full building height. Supply and transfer vents were distributed at each floor along the plenum and adjacent to the stair core to promote uniform delivery and collection of buoyant warm air.

The roof fan was represented as a low-power exhaust boundary delivering 250 L/s (0.25 m³/s) and was assumed to operate continuously during the simulated daytime period. The 250 L/s roof exhaust fan is expected to consume only tens of watts under typical operating conditions, which is substantially lower than the electrical input of room-scale air-conditioning units that commonly operate in the several-hundred-watt to kilowatt range. Accordingly, the fan is intended as a low-energy airflow booster that complements and may reduce, rather than replace, AC operation.

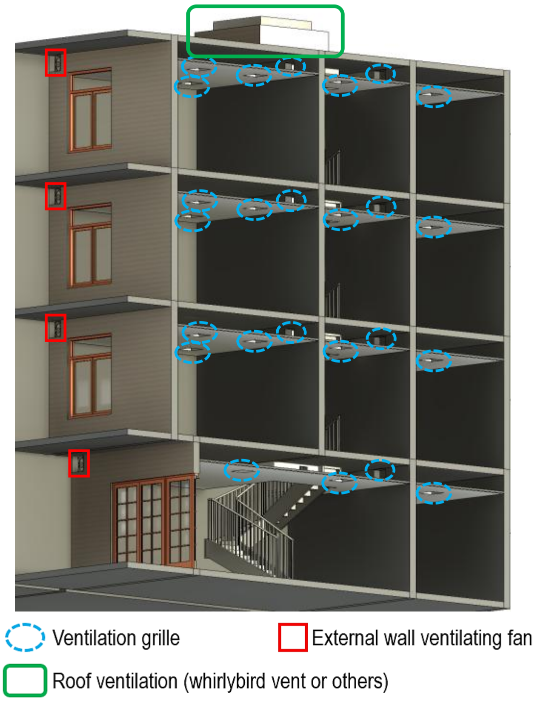

Fig. 4. Proposed termite-inspired design

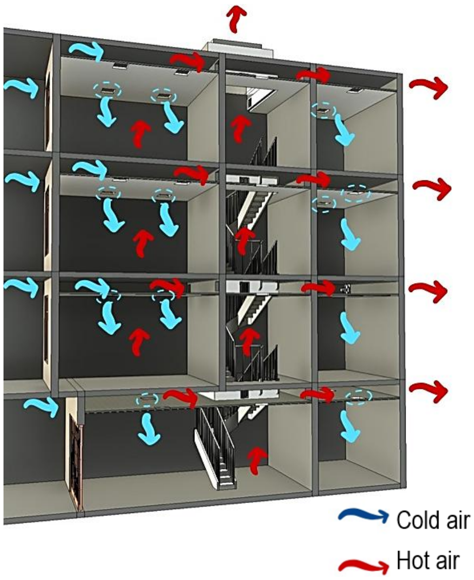

Fig. 5. Termite-inspired ventilation system

4 BIM Modeling, CFD Simulation, and Discussion

4.1 BIM Modeling and CFD Setup

Computational fluid dynamics offers high-resolution insight into coupled airflow and temperature fields and is therefore widely used to evaluate passive and hybrid ventilation strategies in sustainable building design. In this study, CFD was employed to compare a baseline townhouse and a termite-mound-inspired alternative under matched environmental and operational assumptions. Two BIM-derived geometries were prepared and exported to Autodesk CFD for simulation: (i) a conventional townhouse with front and rear openings and a central staircase, as described in Section 2.2; and (ii) a biomimetic variant that retains the baseline floor plan while incorporating termite-mound-inspired ventilation features, as described in Section 3. Both models shared identical external dimensions and internal zoning, enabling a controlled, like-for-like comparison.

Figure 6 shows the assembled BIM configuration in this research, representing the dense urban condition typical of Taiwanese townhouses, where narrow and elongated dwellings are immediately flanked by neighbors. The conventional reference unit (B) was placed adjacent to the termite-inspired unit (C), with additional neighboring townhouses (A and D) added on the outer sides to reproduce blocked side façades and the consequent suppression of cross-ventilation. This arrangement constrains airflow exchange to the primary façades and avoids unrealistically exposed side boundaries. Units A and D therefore serve as contextual geometry only; all CFD comparisons and reported results are extracted from Units B and C.

Two BIM-derived townhouse models were exported to Autodesk CFD and simulated under matched geometric, thermal, and ventilation conditions. The north and south façades were defined as the principal air-exchange boundaries. A volumetric flow rate of 250 L/s at 0 Pa gauge pressure was prescribed at the inlet to standardize the ventilation input across cases. Internal sensible gains and façade heat-flux assignments were used to represent representative daytime thermal loading, and airflow turbulence was modeled using the standard k–ε formulation. These settings were adopted to enable a controlled comparison of the baseline and biomimetic cases under the same dense urban boundary conditions.

To ensure comparability, the south and north façades were defined as the principal air-exchange interfaces, providing opposing exposure and a consistent driving condition for performance evaluation. Boundary conditions were specified to represent controlled air entry and exit while maintaining physically consistent thermodynamic properties. Air properties (including reference pressure and temperature-dependent assumptions) followed the standard values provided by Autodesk CFD. A volumetric flow rate of 250 L/s at 0 Pa gauge pressure was prescribed at the inlet to represent cool air intake under atmospheric conditions and to standardize the ventilation input across cases.

Fig. 6. Four-unit townhouse block in BIM-to-CFD

For the conventional townhouse, the prescribed intake was implemented as a velocity inlet at the façade opening (i.e., an equivalent inlet velocity corresponding to 250 L/s over the opening area), representing façade-driven inflow. For the termite-inspired townhouse, the inlet was modeled as fan-assisted to enhance circulation and support the intended biomimetic airflow routing, while maintaining the same nominal intake condition for comparison. Outlet boundaries were configured to allow warm air to leave the domain; in the termite-inspired case, the vent and heat-exchange features were explicitly utilized to promote upward exhaust and cooling consistent with the design intent.

Thermal loads were defined as approximate representative daytime conditions based on a Taiwanese townhouse database, capturing both internal and external heat gains. Internal sensible heat generation accounted for metabolic loads from occupants, while solar effects were represented through surface heat-flux assignments: sun-exposed walls were assigned higher heat flux values to reflect increased thermal loading, whereas shaded walls received lower values. This specification enables resolution of temperature stratification and buoyancy interactions that are critical to ventilation effectiveness in warm-climate operation.

Airflow turbulence was modeled using the standard k–ε formulation to capture mixed regimes of relatively smooth bulk flow and localized recirculation, particularly around staircases, vents, and biomimetic passages. For outlet backflow/ambient specification, the temperature of any reverse-flow air entering the domain was set to 24–26°C, representing outdoor conditions during the simulated period and supporting stable coupling between the thermal and flow solutions.

4.2 Results and Discussion

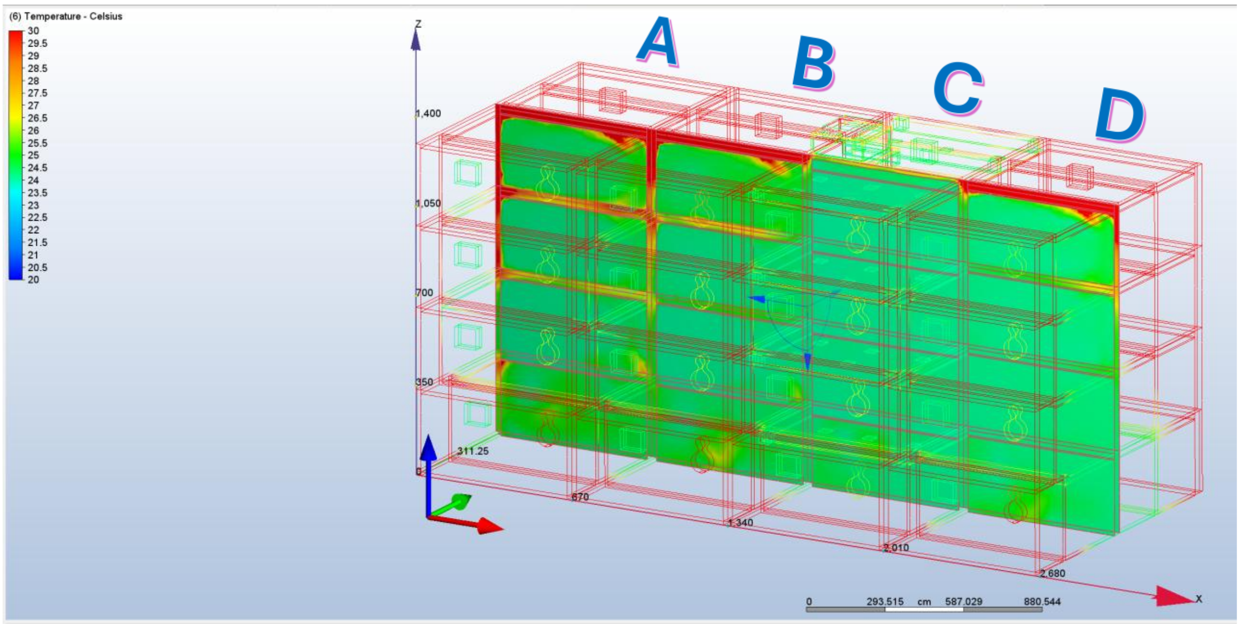

Fig. 7. CFD temperature contours on a vertical section

Table 3. Opening bulk-temperature indicators for Units B and C

Unit	Interface / opening set	Count (n)	Bulk temperature summary (°C)
C (termite-inspired)	South termite inlets	11	25.0 (all)
C (termite-inspired)	North termite inlets	12	25.1–26.9 (avg ≈ 25.6)
C (termite-inspired)	North–south inlet difference	—	Δavg ≈ +0.59 (north slightly warmer)
B (conventional)	Selected baseline openings with elevated bulk T	4	25.7 - 37 (avg ≈ 27.2)

The simulation time of 11:51 AM was selected for the CFD comparison setup as a representative near-noon daytime condition, when solar heat gain is already substantial and overheating risk is elevated, while still allowing a controlled single-scenario comparison between the baseline and biomimetic cases. **Figure 7** presents a representative temperature contour on a vertical section through the two target units (B and C). Under identical imposed loads and ventilation-rate settings, both units maintain most of the indoor field within the 25–30°C band, while the spatial distribution differs. The termite-mound-inspired unit (C) shows a more uniform temperature field across floors, with warm regions largely confined near envelope interfaces, consistent with sustained vertical transport and continuous heat removal through the integrated shaft–chimney pathway. In contrast, the conventional unit (B) exhibits stronger temperature gradients and more localized warming, indicating weaker vertical coupling between floors and less effective purge of buoyant warm air.

To provide a boundary-level diagnostic of ventilation stability, opening bulk temperatures were extracted from the CFD opening report for key air-exchange interfaces (**Table 3**). Opening bulk temperature represents the mass-flow-weighted temperature of air crossing the boundary face rather than the exterior surface temperature. For Unit C, the south-side termite inlets remain at the ambient intake temperature (25°C), while the north-side termite inlets are only slightly warmer (25.1–26.9°C), yielding an average north - south difference of approximately 0.59°C. This small façade imbalance suggests that asymmetric solar exposure does not translate into significant inlet overheating in the biomimetic design, supporting its intent to stabilize intake conditions while exhausting warm air upward.

By comparison, the openings associated with the baseline townhouse configuration (Unit B) report substantially elevated bulk temperatures (25–37°C), indicating thermally unstable exchange surfaces and/or hot recirculation near openings within the modeled configuration. While these bulk values are local to the opening control surfaces (and may reflect flow reversal and localized heating), the contrast with Unit C highlights the superior thermal buffering of the termite-inspired ventilation interfaces.

To quantify how consistently the termite-inspired ventilation maintains near-ambient intake conditions, deviation metrics were computed from the CFD-reported bulk temperatures at the termite inlet openings. The set of inlet temperatures $\{T_i\}$extracted from the south and north termite inlets was compared against the prescribed ambient intake temperature $T_{\text{ref}} = 25°\text{C}$. The deviation at each inlet was defined as $e_i = T_i - T_{\text{ref}}$, and summary measures were then calculated as the mean absolute deviation (MAE), the root-mean-square deviation (RMSE), and the mean absolute percentage deviation (MAPE) (**Table 4**). In this context, these statistics serve as stability indicators describing how tightly inlet temperatures cluster around the ambient reference under asymmetric solar loading.

Overall, the exported CFD results support that the termite-mound-inspired strategy (Unit C) achieves more robust thermal regulation than the conventional baseline (Unit B) by stabilizing inlet conditions and promoting coherent upward heat removal under dense urban adjacency constraints.

Table 4. Inlet-temperature stability metrics for Unit C

Metric	Value	Interpretation
$\text{MAE} = \frac{1}{N}\sum \mid e_i \mid$	0.295°C	Very small mean deviation from ambient
$\text{RMSE} = \sqrt{\frac{1}{N}\sum e_i^2}$	0.42°C	No evidence of large fluctuations/ outliers
$\text{MAPE} = \frac{100}{N}\sum \mid \frac{e_i}{T_{\text{ref}}} \mid$	1.18%	Excellent relative stability around ambient

5 Conclusion

This study translates termite-mound climate-control principles into a buildable hybrid stack-ventilation layout for dense Taiwanese townhouses, where side façades are typically blocked and cross-ventilation is unreliable. The proposed system integrates façade inlets feeding a ceiling plenum for distributed supply, a central vertical shaft that collects buoyant warm air from multiple storeys, and a roof-level low-power exhaust fan that stabilizes upward flow when wind-driven or buoyancy-driven forces are weak. In doing so, it offers a practical pathway to improve ventilation performance without requiring major façade modifications.

Using a BIM-to-CFD workflow, a conventional four-storey townhouse and the biomimetic alternative were evaluated under the same dense-block context and asymmetric solar exposure. The results indicate that the termite-inspired townhouse forms a clearer upward ventilation path, reduces stagnant regions, and yields a more uniform temperature field across storeys. At the inlets, the biomimetic case maintained near-ambient intake conditions, with stability metrics of MAE 0.295°C, RMSE 0.42°C, and MAPE 1.18%, whereas the baseline reported elevated opening bulk temperatures (25.7–37°C) consistent with thermally unstable exchange and local recirculation. These outcomes substantiate the research contribution of a townhouse-scale termite-inspired hybrid stack concept and an evaluation approach that quantifies inlet-temperature robustness, not only qualitative contour improvements.

From a practice perspective, the study suggests design moves that can be incorporated in new-build or retrofit projects: (i) use a shallow plenum or ducted ceiling layer to extend fresh-air reach beyond the façade, (ii) connect upper-zone exhaust points to a shared vertical shaft to purge accumulated heat, and (iii) operate a small roof fan as an on-demand "booster" to maintain extraction during calm periods. This hybridization is intended to complement, not replace, air-conditioning in hot-humid climates by improving background air exchange, limiting inlet overheating, and potentially reducing the hours and intensity of mechanical cooling required for comfort.

The study also has limitations. It is based on a single controlled daytime scenario with simplified heat-flux assignments and fixed ventilation-rate boundary conditions, and the results have not yet been validated through experiments or field monitoring. Accordingly, the findings should be interpreted as a comparative proof-of-concept under matched conditions rather than a full representation of real operational performance under changing weather patterns, seasonal variations, and occupant behavior. Near-term work should therefore extend the analysis to transient, multi-day, and seasonal conditions, and incorporate occupant-dependent operating scenarios. Future work should also extend the evaluation beyond airflow and temperature fields to include thermal comfort indices and indoor air quality metrics, thereby providing a more comprehensive assessment of occupant conditions and building performance.

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