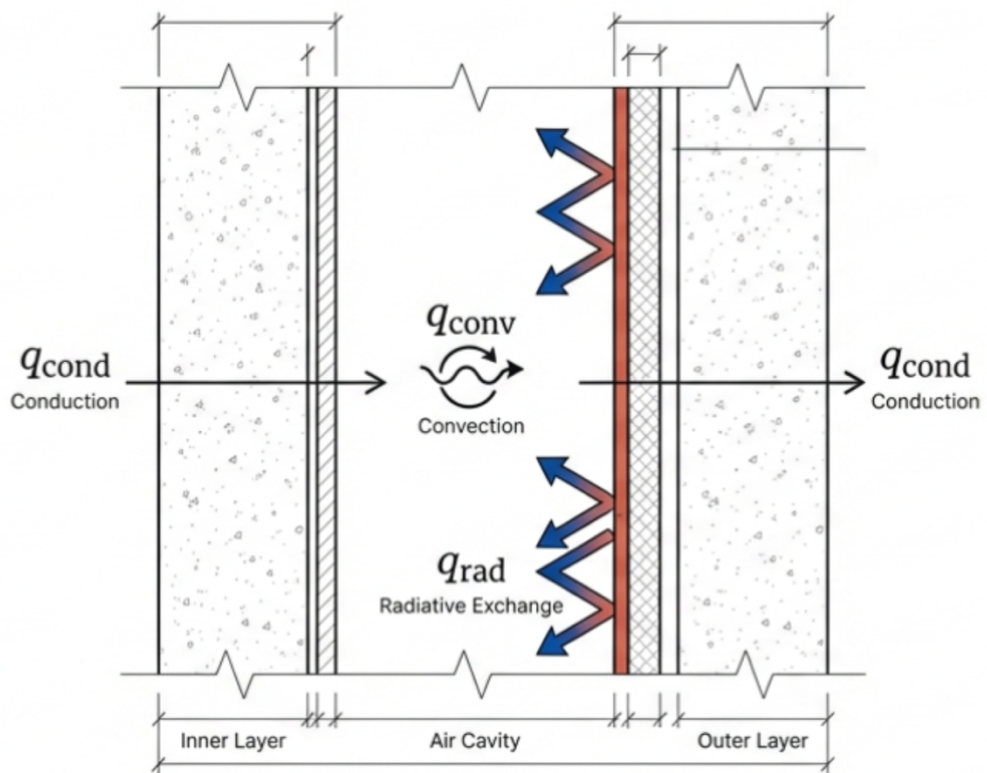




Evaluating the Energy Efficiency of Hollow Precast Walls with Integrated Active Ventilation using the EDGE Certification Framework and Application

Kongphat Phaiboonnukulkij¹

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Abstract

This study evaluates the thermal and energy performance of an Active Double-Layered Precast Wall (ADLP) system for buildings in hot-humid climates using the EDGE (Excellence in Design for Greater Efficiencies) certification framework. While airflow-assisted wall systems can reduce heat transfer and cooling demand, their dynamic thermal behavior cannot be directly represented within the standard EDGE methodology. This study proposes a practical approach for translating airflow-dependent thermal performance into equivalent U-values compatible with EDGE energy assessment. The ADLP system incorporates a hollow cavity with controlled upward airflow to enhance convective heat removal and reduce heat gain through the building envelope. Analytical heat-transfer modeling and transient thermal analysis were used to evaluate wall performance under three airflow conditions: 0 m/s, 0.1 m/s, and 1.0 m/s. The resulting equivalent U-values were then applied within the EDGE App to assess whole-building energy performance for a two-storey residential building in Bangkok, Thailand. Results indicate that the effective wall U-value decreased from 0.590 W/m²·K under the unventilated condition to 0.256 W/m²·K and 0.177 W/m²·K at airflow velocities of 0.1 m/s and 1.0 m/s, respectively. Corresponding annual energy savings increased from 7.23% to 9.35% and 9.85%. The findings suggest that cavity ventilation can improve envelope thermal performance and reduce cooling-energy demand. The study presents a methodology for integrating active wall systems into certification-oriented energy assessments and supports the application of airflow-assisted envelopes in tropical climates.

Keywords: EDGE certification, EDGE application, energy savings quantification, thermal performance, active ventilation

¹ Faculty of Architecture, Chulalongkorn University

Corresponding Author E-mail: kongphatphaiboonnukulkij@gmail.com

1. Introduction

Buildings account for a substantial share of global energy use, with cooling demand in hot-humid climates continuing to rise due to urbanization, climate change, and increased occupant comfort expectations. The building envelope acting as the primary thermal interface between outdoor conditions and indoor spaces plays a decisive role in moderating heat transfer, reducing cooling loads, and improving overall building energy performance. As the construction sector shifts toward low-energy and high-performance design, innovative envelope technologies are becoming increasingly important not only for operational efficiency but also for achieving environmental certifications and compliance with international sustainability standards.

1.1 Building Envelope and the Active Double-Layered Precast Wall System

This hybrid passive-active approach enhances envelope performance by improving thermal resistance, reducing peak cooling demand, and supporting improved indoor comfort. Similar performance improvements have been reported in ventilated hollow wall systems where forced airflow through cavities increases convective heat removal and lowers effective heat flux through the envelope (Yu et al., 2018; Rezvanpour et al., 2023). The modular nature of the precast panel makes it viable for both new construction and retrofitting applications, consistent with findings from studies on ventilated masonry and precast systems that emphasize constructability and adaptability (Laken & Fowler, 2008). It also provides future adaptability, enabling integration with advanced ventilation strategies such as underground cooling channels, solar-assisted ventilation, smart façades, or high-efficiency blower technologies. Comparable research indicates that combining ventilated cavities with auxiliary systems such as renewable-powered ventilation or adaptive façade controls can further enhance envelope effectiveness (Domínguez-Torres et al., 2022).

Limitations remain particularly the reliance on simulation data and simplified airflow assumptions which highlight the need for full-scale experimental validation and further optimization through enhanced airflow control, renewable-powered operation, or combined systems such as phase-change materials or evaporative cooling layers. Previous experimental investigations of ventilated wall and façade systems similarly emphasize the

importance of validating numerical models with physical testing and addressing airflow non-uniformity and transient effects (Yu et al., 2018; Domínguez-Torres et al., 2022).

1.2 Green Building Certification and the EDGE Framework

Within the global transition toward low-carbon buildings, green building certification systems have become central mechanisms for verifying environmental performance and promoting energy-efficient design. Among these systems, EDGE (Excellence in Design for Greater Efficiencies) has gained prominence for its streamlined methodology, international applicability, and emphasis on quantifiable savings. EDGE requires projects to demonstrate at least 20% reductions in energy, water, and embodied energy in materials compared with a localized baseline building. These savings must be validated using the EDGE App, a simplified modeling tool that prioritizes accessibility, standardized assumptions, and speed of assessment.

However, the EDGE framework is inherently oriented toward passive, steady-state envelope improvements, such as insulation thickness, material density, glazing performance, and Window-to-Wall Ratio (WWR). As a result, highly dynamic envelope technologies particularly hybrid or active systems like the ADLP wall face challenges in being accurately represented within EDGE's prescriptive input structure. The dynamic heat removal effect created by ventilated cavities and induced airflow is not directly modeled within the tool, leading to potential underestimation or omission of the system's true energy impact. The thermal performance of exterior walls directly influences whole-building energy consumption by regulating conductive heat transfer between outdoor and indoor environments. In cooling-dominated climates, reductions in wall heat gain decrease cooling loads imposed on mechanical air-conditioning systems, resulting in lower annual energy use. Consequently, improvements in wall thermal resistance can contribute to measurable changes in overall building energy performance when evaluated using building-energy assessment tools.

This creates a critical research gap: the lack of standardized methodologies to correlate advanced thermal modeling of active envelope systems with the static quantification methods used by EDGE. Bridging this gap is essential for validating innovative

technologies, ensuring fair representation of performance, and supporting broader adoption of high-efficiency envelope systems within certified green buildings.

The integration of advanced building envelopes into mainstream green building frameworks is currently hindered by a fundamental methodological disconnect. While dynamic systems such as Double Skin Façades (DSF) and Glass Solar Chimney Walls (GSCW) demonstrate significant thermal benefits in tropical regions, they operate on transient environmental principles—including fluctuating solar radiation and diurnal temperature swings—that are difficult to capture in standardized assessments (Ratanachotinun & Pairojn, 2014; Lim & Ismail, 2023). These technologies are usually validated through high-fidelity tools like Computational Fluid Dynamics (CFD) or EnergyPlus, which provide a granular view of time-dependent airflow and heat transfer. However, global certification systems like EDGE (Excellence in Design for Greater Efficiencies) prioritize scalability and ease of use, often relying on quasi-steady-state calculations (IFC, 2021). In these models, the building skin is typically treated as a static barrier defined by fixed parameters like Shading Coefficients and U-values. While this simplification allows for broad market adoption, it creates a "performance gap" where the actual energy-saving potential of an active system is not fully recognized (Donn, 2025). For instance, although detailed simulations indicate that DSF systems can cut cooling loads by over 40% in tropical climates, these dynamic gains are frequently underestimated by simplified tools that cannot account for variable cavity airflow (Lim & Ismail, 2023). Current implementations of the EDGE framework underscore an "efficiency-first" philosophy that favors standardized, static measures (Condezo-Solano et al., 2024). This focus can inadvertently sideline complex, adaptive technologies that do not fit into traditional input fields. To address this, there is a pressing need for a bridge between sophisticated thermal modeling and simplified certification metrics. This research explores a practical approach to translating dynamic performance—specifically the reduction in effective U-values caused by induced airflow—into a format compatible with EDGE requirements. By quantifying these "active" benefits through a transparent methodology, this study aims to create a viable pathway for incorporating innovative systems, such as the Active Double-Layered Precast Wall (ADLP), into established green building evaluation structures.

2. Literature Review

The building envelope governs the primary pathways for solar, conductive, and convective heat transfer into conditioned interior spaces. For buildings in cooling-dominated climates, envelope optimization is therefore one of the most effective strategies for reducing operational energy demand. Conventional envelope design relies predominantly on passive measures like thermal insulation, glazing specifications, and solar-control features, to limit heat gain. Dynamic or active envelope strategies, however, introduce deliberate time-dependent mechanisms such as cavity ventilation, phase-change materials (PCM), or variable-resistance assemblies. These systems modulate the envelope's effective thermal properties in real time, responding to external boundary conditions and diurnal temperature profiles to suppress heat gains more efficiently than static assemblies. The following review studies consistently demonstrate that dynamic insulation and ventilated façade (VF) systems can meaningfully reduce heat transfer and cooling loads, especially in regions characterized by high solar exposure and notable day–night temperature differentials. Fawaier and Bokor (2022) as well as Gregório-Atem et al. (2020) highlight that dynamic façade systems improve envelope heat-rejection capacity and tend to yield more pronounced energy savings in hot–humid climates where minimizing solar-driven gains and peak cooling loads are essential for comfort and system efficiency. However, a recurring theme in the review literature is that performance outcomes are highly context dependent. Variables such as climate, façade orientation, solar intensity, cavity geometry, and control strategy significantly influence the magnitude of savings. Comprehensive analyses, including Cuce and Cuce (2025), caution that claims of universal savings must be validated at the whole-façade scale because component-level findings often overestimate or misrepresent operational performance.

Ventilated façades and cavity-ventilated wall systems operate by introducing an air channel between an exterior cladding layer and the structural inner wall. Airflow whether naturally induced by buoyancy and wind pressures or mechanically driven by fans extracts heat absorbed by the exterior layer before it can penetrate the insulated interior. This mechanism reduces outer-leaf temperature, weakens conductive and radiative heat transfer, and ultimately lowers the cooling load. Experimental and numerical studies consistently report substantial thermal benefits, with cooling-load reductions frequently

cited in the range of 20–55% under cooling-dominant conditions compared to unventilated building envelope. Key design parameters identified across the literature include cavity depth, vent opening geometry, vent-area ratio, and airflow velocity, all of which significantly shape system performance (Pujadas-Gispert et al., 2020).

A specific branch of this research concerns hollow-core and hollow-precast building elements adapted for controlled cavity ventilation. These systems leverage internal voids inherent to precast or hollow-block construction as heat-extraction channels. Experimental testing and numerical modeling show that low-velocity forced ventilation within hollow cavities can dramatically reduce conductive heat transfer, lower internal surface temperatures, and improve overall envelope resistance (Pujadas-Gispert et al., 2020). Several studies report dynamic U-value reductions similar to those observed in active double-layer precast systems for example, decreases from approximately 0.6 W/m²K to 0.2–0.3 W/m²K under active ventilation alongside substantial reductions in peak heat flux (Figure 1).

Rezvanpour et al. (2023) provide a comprehensive evaluation of ventilated block-wall configurations, demonstrating how cavity airflow rate, vent placement, and operational schedule influence annual thermal performance across different climates. Their findings indicate that properly engineered airflow within hollow blocks can re-distribute internal thermal loads and reduce cooling energy demand. Similarly, Huang et al. (2018) conducted a parametric study on ventilated hollow-block walls and confirmed that cavity dimensions and inlet-air temperature strongly affect thermal response. Their model results show inner-surface heat-flux reductions of approximately 45–56% under optimized airflow conditions, reinforcing the potential of hollow-cavity ventilation as an envelope cooling strategy.

Within green-building assessment frameworks, the EDGE standard provides a global certification pathway focused on quantifying energy, water, and materials savings relative to a local baseline. The EDGE App is designed for speed, transparency, and auditability, relying on prescriptive envelopes primarily U-values, glazing properties, and window-to-wall ratio (WWR) to estimate whether the project meets the minimum 20% energy-savings requirement. While effective for conventional envelopes, this simplified, steady-state-oriented modeling approach is not inherently configured to capture the time-dependent thermal behavior of active or ventilated wall systems. EDGE does allow “custom” measures

or non-standard envelope inputs, but these require supporting evidence and auditor validation (EDGE, 2025), making the integration of dynamic façade technologies less straightforward.

In the context of dynamic and airflow-assisted building envelopes, the concept of the Glass Solar Chimney Wall (GSCW) provides relevant empirical support for the effectiveness of ventilation-driven thermal regulation in tropical climates. The GSCW operates as a double-layered façade system that utilizes solar-induced buoyancy to drive airflow within an air cavity, thereby reducing heat transfer into the interior space. Similar to ventilated precast wall systems, the GSCW introduces a dynamic insulation mechanism where moving air acts as a thermal buffer rather than relying solely on static material resistance. A study conducted in Bangkok by Ratanachotinun and Pairojn (2014) demonstrated that such systems can consistently lower indoor temperatures by approximately 1.30–2.46°C across seasonal conditions, with corresponding energy savings ranging from 5% to 14% depending on climatic variations. These findings confirm that cavity ventilation can reduce cooling demand in hot-humid environments.

However, while the GSCW primarily applies to transparent façade systems and relies on solar-driven natural ventilation, the present study extends this principle to opaque wall assemblies through the Active Double-Layered Precast Wall System (ADLP). Unlike glass-based systems, the ADLP integrates airflow within a solid precast structure, enabling controlled convective heat removal while maintaining structural and thermal mass advantages. The comparison highlights a broader applicability of airflow-assisted envelopes, demonstrating that the benefits of dynamic insulation are not limited to façade glazing systems but can be effectively adapted to conventional wall construction. This positions the ADLP as a complementary and potentially more versatile solution for reducing heat gain and improving energy efficiency in residential buildings under tropical conditions.

To further strengthen the understanding of dynamic insulation strategies in tropical Asia-Pacific contexts, additional studies on Double Skin Façades (DSF) and Glass Solar Chimney Walls (GSCW) provide important empirical and simulation-based evidence. These systems, which rely on ventilated cavities to reduce heat transfer, demonstrate consistent effectiveness in mitigating solar heat gain and improving indoor thermal conditions in hot-humid climates.

Comparative studies across tropical cities such as Kuala Lumpur, Phnom Penh, Jakarta, and Nha Trang indicate that DSF systems can significantly reduce cooling energy demand, with reported annual energy savings exceeding 40% in some cases, alongside indoor temperature reductions of approximately 4°C (Lim & Ismail, 2023; Rahmani et al., 2012). These findings highlight the strong potential of cavity-based ventilation systems in reducing reliance on mechanical cooling. The performance of such systems is highly dependent on design parameters, particularly cavity depth. For instance, a cavity depth of approximately 1000 mm has been identified as optimal for enhancing the stack-driven “chimney effect,” enabling efficient removal of accumulated heat in tropical environments (Rahmani et al., 2012).

Material selection also plays a critical role in enhancing the effectiveness of dynamic façades. The integration of low-emissivity (low-e) glazing has been shown to improve ventilation efficiency by up to 13% compared to conventional clear glass, indicating that both airflow dynamics and material properties must be considered in tandem for optimal performance (Lim & Ismail, 2023). In addition, smaller-scale applications such as window-integrated solar chimneys have demonstrated measurable reductions in indoor temperature compared to conventional single-glazing systems, suggesting that dynamic insulation strategies can be adapted to residential-scale implementations (Chantawong et al., 2006; Ratanachotinun & Pairojn, 2014).

These studies collectively reinforce the principle that airflow within façade cavities acts as a dynamic thermal buffer, reducing conductive and radiative heat transfer into the building. While most existing research focuses on transparent or semi-transparent façade systems, the present study extends this concept to opaque wall assemblies through the Active Double-Layered Precast Wall System (ADLP). By integrating controlled airflow within a solid precast structure, the ADLP system applies similar thermodynamic principles—such as convective heat removal and temperature gradient reduction—while maintaining structural integrity and compatibility with conventional construction practices. This positions the ADLP as a novel adaptation of dynamic insulation strategies, bridging the gap between façade-based ventilation systems and conventional building envelopes in tropical climates.

3. Methodology

The methodology for evaluating the hollow precast wall with active ventilation integrates theoretical modeling, transient heat-transfer analysis, and a numerical experimental framework that serves as a substitute for physical testing. The hollow precast system incorporates an air-blower mechanism positioned at the base of the internal cavity, supplying cool air upward through the hollow core. As this air travels through the cavity, it absorbs accumulated heat and is discharged at the top, creating a forced-convection pathway that reduces heat retention and modifies the wall's effective thermal resistance. This mechanism is consistent with established principles of ventilated air layers and dynamic insulation, where airflow through an envelope alters conductive and convective heat-transfer paths. This dynamic response is particularly advantageous in hot-humid climates where suppressing envelope heat gain is essential for reducing cooling energy demand. Prior studies on ventilated hollow block walls and ventilated façades in warm climates have demonstrated measurable reductions in inner-surface temperature and cooling loads as airflow rates increase (Yu et al., 2018; Domínguez-Torres et al., 2022). The study uses a quantitative modeling strategy that combines physics-based predictive calculations with numerically derived performance metrics. Material characterization including thermal conductivity, density, specific heat, and thermal diffusivity of lightweight concrete and air, forms the foundation for applying Fourier's Law and the transient heat diffusion equation, as commonly adopted in transient envelope analysis (Incropera et al., 2007). The research adopts an integrated methodology consisting of:

1. Analytical and transient heat-transfer modeling, establishing baseline conduction behavior, quantifying temperature gradients, and capturing the interaction between conduction in the solid layers and convection within the cavity.
2. Dimensionless and heat-transfer correlation evaluation, used to classify the thermal regime, express performance through key non-dimensional parameters, and quantify the effect of varying airflow intensity.
3. Numerically assisted estimation of equivalent thermal resistance, used to translate airflow-dependent heat-transfer behavior into steady-state U-values compatible with building-energy tools.

3.1 Case Study Building

A two-storey residential building located in Bangkok, Thailand, was selected as the case-study building for evaluating the thermal and energy performance of the Active Double-Layered Precast Wall (ADLP) system. The building represents a typical low-rise residential design in a hot-humid tropical climate and provides a practical context for assessing the impact of envelope improvements on whole-building energy performance. The geometric configuration of the building is illustrated in Figure 1.

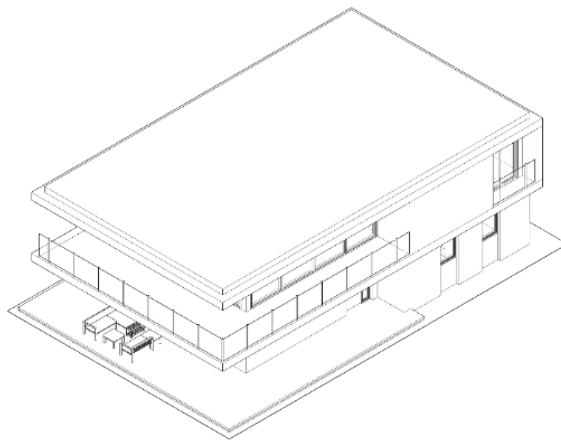


Figure 1. Three-dimensional view of the two-storey residential case-study building used for EDGE energy simulations, illustrating the overall building geometry and envelope configuration evaluated in this research.

Source: Author

The building geometry is presented sequentially from the ground floor to the second floor to illustrate the complete distribution of ADLP wall segments incorporated into the energy model.



Figure 2. Ground-floor plan of the case-study building showing the distribution of exterior wall segments where the Active Double-Layered Precast Wall (ADLP) system was applied for thermal-performance evaluation.

Source: Author

The thermal performance of the Active Double-Layered Precast Wall (ADLP) system was evaluated at the building scale using a two-storey residential case-study building. Figures 2 and 3 illustrate the ground-floor and second-floor layouts, respectively, highlighting the wall segments where the ADLP system was applied. These floor plans were used to identify envelope areas incorporated into the EDGE energy model and to determine the distribution of opaque wall surfaces affected by the proposed wall system.

Figure 2 presents the ground-floor configuration of the case-study building. The highlighted wall segments indicate locations where the ADLP system was incorporated into the building envelope. These areas form part of the exterior wall assembly represented within the EDGE model and contribute to the calculation of heat transfer through the building envelope.

Figure 3 illustrates the second-floor configuration and the corresponding distribution of ADLP wall segments. Together with the ground-floor layout, the figure defines the total wall area included in the envelope-performance assessment and provides the geometric basis for evaluating the influence of airflow-enhanced wall performance on whole-building energy consumption.

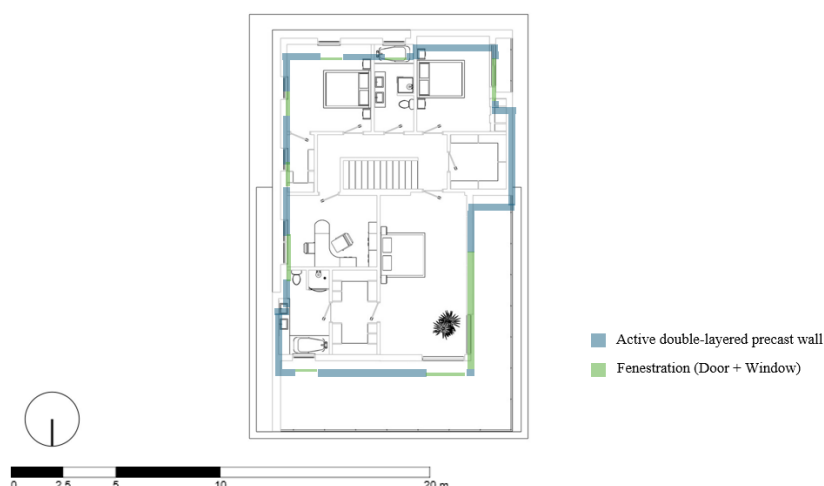


Figure 3. Second-floor plan of the case-study building showing the distribution of exterior wall segments where the Active Double-Layered Precast Wall (ADLP) system was applied for whole-building energy analysis.

Source: Author

Analytical evaluation begins with the governing heat-transfer equations for transient conduction through a solid medium. Fourier’s Law and the unsteady heat diffusion equation are used to calculate temperature profiles and heat flux through the precast concrete layers under varying boundary conditions. Realistic boundaries and initial conditions are incorporated to ensure the theoretical predictions align with observed thermal behavior and established empirical ranges. The forced-convection mechanism in the cavity is treated as an air-temperature-dependent heat sink whose effectiveness varies with airflow velocity, consistent with correlations for internal forced convection and ventilated air cavities (Incropera et al., 2007). The output of this modeling step includes temperature distributions across the wall, estimated reductions in heat flux due to ventilation, and preliminary values of dynamic R-value and U-value reductions (Incropera et al., 2007).

To apply the analytical findings within a building-energy context, the airflow-dependent thermal performance is translated into equivalent steady-state U-values. Similar approaches where dynamic or ventilated assemblies are represented by equivalent U-values are widely used in building energy studies to maintain compatibility with simplified energy-

assessment frameworks (Dominguez-Torres et al., 2022). Therefore, the methodology extracts representative U-values under:

- basecase (no ventilation),
- low forced ventilation, and
- moderate forced ventilation conditions.

The equivalent U-value is obtained by converting analytically and numerically derived heat-flux results into thermal resistance values and inverting them to produce U-values. The selected U-value represents the operating condition most realistic for actual building use and defensible under certification review. The final step evaluates the feasibility of the active hollow precast wall within the EDGE green-building certification framework, which requires prescriptive envelope inputs primarily wall U-value and window-to-wall ratio to estimate cooling-energy savings relative to baseline building.

The integration procedure includes:

1. Inserting the derived effective U-value of the ventilated wall into the EDGE envelope specification.
2. Maintaining consistent assumptions regarding orientation, wall construction description, internal loads, and climate zone.
3. Executing EDGE's simplified energy-savings model to determine the reduction in cooling-energy consumption attributable to the improved envelope.
4. Assessing feasibility, specifically whether the active envelope enables the project to more readily achieve or surpass the required 20% energy-savings threshold for certification.

By linking the analytical modeling outputs with a standardized green-building evaluation mechanism, the methodology establishes both the technical behavior of the active envelope and its real-world applicability within a certification-oriented context.

3.2 Translation of Wall Performance into Whole-Building Assessment

The thermal analysis conducted in this study was performed at the wall-assembly level. To evaluate the impact of the wall system on whole-building energy performance, the airflow-dependent thermal behavior was converted into equivalent steady-state U-values. These equivalent U-values were then entered into the EDGE App as the exterior-wall thermal transmittance parameter (EEM08 – Insulation of Exterior Walls). All other building characteristics, including floor area, orientation,

glazing ratio, cooling-system efficiency, and occupancy assumptions, were maintained constant. As a result, differences in annual building energy consumption predicted by EDGE can be attributed primarily to changes in wall thermal performance resulting from cavity ventilation.

4. The Active Double-Layered Precast Wall Panel

A hollow precast wall is a prefabricated building component commonly used for structural walls and building-envelope assemblies in industrialized construction systems. In this study, the ADLP Wall is configured as a modular element with overall dimensions of 280 × 20 × 100 cm (Figure 4). The wall assembly consists of a lightweight concrete outer layer and an internal air cavity, forming a double-layered configuration that supports airflow-assisted thermal performance. The physical and thermal properties of the constituent materials are summarized in Table 1. The lightweight concrete properties—including density, specific heat capacity, and thermal conductivity—are defined in accordance with the requirements and performance ranges specified in ASTM C330/C330M for structural lightweight aggregates and EN 206 for concrete composition and classification. The air cavity properties are defined using standard thermophysical values for dry air at ambient conditions.

Table 1. Physical parameters of the material used for active double-layered precast wall.

Layer	Height (cm)	Length (cm)	Layer Thickness (cm)	Density (kg/m^3)	Specific heat (J/kg*K)	Thermal Conductivity (W/mK)
Lightweight concrete	280.00	100.00	4.00	600	1000	0.19
Air Cavity	280.00	100.00	16.00	1.293	1005	0.02596

Source: Author

The dimensional configuration of the Active Double-Layered Precast Wall (ADLP) system was established as a research-based design configuration for thermal-performance evaluation. The selected dimensions were intended to represent a practical wall assembly suitable for residential construction while providing sufficient cavity space to facilitate

airflow-induced convective heat removal. The dimensions were therefore adopted as modeling assumptions for the purpose of comparative thermal and energy-performance analysis rather than representing a specific commercial product.

A total wall thickness of 200 mm was selected to accommodate two precast concrete layers with two sides 2 cm thick on each side and an internal ventilation cavity with thickness of 16 mm while remaining consistent with wall dimensions commonly used in low-rise building construction. The selected thickness provides sufficient space for airflow development within the cavity while maintaining practical constructability and structural feasibility.

The wall dimensions were selected as representative design parameters for simulation and do not correspond to a specific commercial product. Their purpose was to provide a consistent basis for evaluating the influence of cavity ventilation on thermal performance.

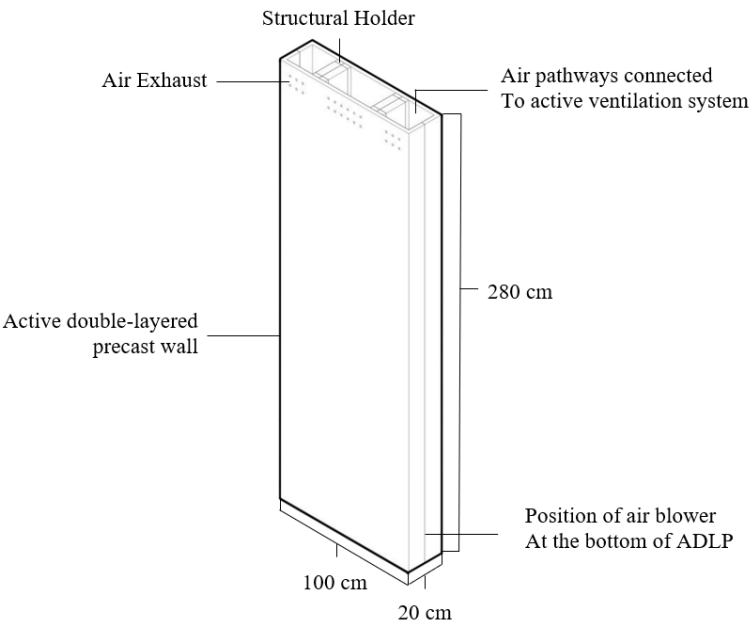


Figure 4. Configuration of the Active Double-Layered Precast Wall (ADLP) system, illustrating the individual precast layers, ventilation cavity dimensions, airflow pathway, and total wall thickness used in the thermal-performance analysis.

Source: Author

4.1 Building Envelope and the Active Double-Layered Precast Wall System

Based on the wall configuration described in Section 4, the thermal performance of the ADLP system was evaluated using a combined conduction–convection heat-transfer approach. The analysis focused on quantifying the influence of cavity airflow on the effective thermal resistance and equivalent U-value of the wall assembly under different ventilation conditions.

4.2 The principle of the Active Double-Layered Precast Wall System on EDGE App

The EDGE assessment framework was used to evaluate the influence of airflow-enhanced wall performance on whole-building energy consumption. Building geometry, window-to-wall ratio (WWR), solar reflectance index (SRI), and cooling-system efficiency were entered according to the case-study design and maintained constant throughout all simulation scenarios. These parameters were not treated as variables in the present study.

To isolate the influence of cavity ventilation, all non-wall parameters were maintained constant across the investigated airflow scenarios. Consequently, the observed differences in annual energy performance between the 0 m/s, 0.1 m/s, and 1.0 m/s cases result from changes in the equivalent wall U-value derived from the thermal analysis. The primary variable investigated was the thermal transmittance (U-value) of the exterior wall assembly. Equivalent U-values obtained from the thermal analysis were entered into EDGE under EEM08 (Insulation of Exterior Walls) to represent the effect of cavity ventilation on wall performance. By maintaining all other model inputs constant, differences in predicted annual energy consumption can be associated with changes in airflow-enhanced wall thermal performance.

The baseline wall U-value of 1.86 W/m²·K was compared with airflow-enhanced U-values derived for the ADLP system. These values were incorporated directly into the EDGE model to assess their influence on annual building energy savings relative to the EDGE reference building.

4.3 Numerical model for theoretical thermal calculation

The thermal performance of the ADLP system was evaluated using a numerical heat-transfer model that accounts for conductive heat transfer through the wall layers and convective heat removal within the ventilated cavity. The objective of the analysis was to

determine the equivalent thermal resistance and corresponding U-value of the wall assembly under different airflow conditions. These equivalent U-values were subsequently used as inputs for the EDGE energy simulations.

The numerical analysis was conducted under a series of simplifying assumptions to enable the estimation of equivalent wall thermal performance. Airflow within the cavity was assumed to be uniform and steady along the full cavity height. Material thermal properties were treated as constant, and one-dimensional heat transfer through the wall assembly was assumed. Airflow velocities of 0 m/s, 0.1 m/s, and 1.0 m/s were prescribed as boundary conditions representing different ventilation scenarios. The resulting equivalent thermal resistance was subsequently converted into an effective wall U-value for use in the EDGE simulations. The selected airflow velocities were intended to represent low- and moderate-ventilation conditions within the cavity and to evaluate the sensitivity of wall thermal performance to airflow enhancement

For steady-state in one-dimensional conduction

$$q = -k \frac{\Delta T}{\Delta x}$$

Where q is heat flux [W/m^2], $\partial T/\partial x$ is temperature gradient [K/m], k is thermal conductivity [$\text{W}/\text{m}\cdot\text{K}$]. Divide the wall into segments: Light weight concrete (layer 1 with thickness of 0.02 m), air cavity (layer 2 with thickness of 0.16 m), and Light weight concrete (layer 3 with thickness of 0.02 m).

$$R_{\text{th, layer}} = \frac{\Delta x}{k}$$

Where R is thermal resistance [K/W], k is thermal conductivity [$\text{W}/\text{m}\cdot\text{K}$], Δx is thickness of the layer, [m]. With total thermal resistance which is $R_{\text{concrete}} + R_{\text{air}} + R_{\text{concrete}}$ to further find heat flux with variable of temperature different of 2 sides of the wall. If temperature on two opposite sides are 313.15 K (outside building) and 293.15 K (inside building).

$$q = \frac{\Delta T}{R_{\text{total}}}$$

Where q is heat flux [W/m^2], ΔT is temperature difference [K], R_{total} is total thermal resistance [K/W]. To find the temperatures at the four key points (outside concrete layer 1, inside concrete layer 1, inside concrete layer 2, and outside concrete layer 2) using theoretical calculations, it requires to apply steady-state heat transfer concepts and consider thermal resistances across the wall layers. Which the boundary conditions of Outside surface temperature are 313.15 K , inside surface temperature is 293.15 K , and Convective heat transfer coefficients is h_{out} (outside) and h_{in} (inside) [$\text{W}/\text{m}^2 \cdot \text{K}$]. to find 2 types of thermal resistance which are convective and conductive resistance to find 4 points of temperature.

a) Convective Resistance

$$R_{\text{conv, out}} = \frac{1}{h_{\text{outside}}}, \quad R_{\text{conv, in}} = \frac{1}{h_{\text{inside}}}$$

b) Conductive Resistance

$$R_{\text{cond, concrete}} = \frac{L_{\text{concrete}}}{k_{\text{concrete}}}, \quad R_{\text{cond, air}} = \frac{L_{\text{air}}}{k_{\text{air}}}$$

c) Total Thermal Resistance

$$R_{\text{total}} = R_{\text{conv, out}} + R_{\text{cond, concrete}} + R_{\text{cond, air}} + R_{\text{cond, concrete}} + R_{\text{conv, in}}$$

Where L_{concrete} is length of the concrete layer [m], L_{air} is length of the air cavity layer [m], k_{concrete} is thermal conductivity of the concrete layer [$\text{W}/\text{m} \cdot \text{K}$], k_{air} is thermal conductivity of the air cavity layer [$\text{W}/\text{m} \cdot \text{K}$]. As Convective heat transfer coefficients assigned as the following; h_{out} is $10 \text{ W}/\text{m}^2 \cdot \text{K}$ and h_{in} is $25 \text{ W}/\text{m}^2 \cdot \text{K}$ according to average point of the natural ventilation and low point on forced ventilation. Convective Resistance for the outside layer $R_{\text{conv, out}} = 0.1 \text{ m}^2 \cdot \text{K}/\text{W}$, for the inside layer $R_{\text{conv, in}} = 0.04 \text{ m}^2 \cdot \text{K}/\text{W}$. Conductive resistance for each concrete layer $R_{\text{cond, concrete}} \approx 0.77 \text{ m}^2 \cdot \text{K}/\text{W}$, and for the air cavity $R_{\text{cond, air}} \approx 0.77 \text{ m}^2 \cdot \text{K}/\text{W}$. Therefore, $R_{\text{total}} = 1.696 \text{ m}^2 \cdot \text{K}/\text{W}$. With provided information the heat flux through the wall is constant in steady-state conditions use the following equation:

$$q = \frac{T_{\text{outside}} - T_{\text{inside}}}{R_{\text{total}}}$$

Where q is heat flux [W/m^2], T_{outside} is temperature outside the building envelope [K], T_{inside} is temperature inside the building envelope [K], R_{total} is total thermal resistance [K/W]. With provided information with defined value $q \approx 11.80 \text{ W/m}^2$. Using the heat flux, calculate the temperature drops across each resistance for temperature at each point:

1) Temperature Drop Across Outside Convective Resistance:

$$T_1 = T_{\text{outside}} - q \cdot R_{\text{conv,out}}$$

2) Temperature Drop Across Concrete Layer 1:

$$T_2 = T_1 - q \cdot R_{\text{cond,concrete}}$$

3) Temperature Drop Across Air Cavity:

$$T_3 = T_2 - q \cdot R_{\text{cond,air}}$$

4) Temperature Drop Across Concrete Layer 2:

$$T_4 = T_3 - q \cdot R_{\text{cond,concrete}}$$

5) Temperature Drop Across Inside Convective Resistance:

$$T_{\text{inside}} = T_4 - q \cdot R_{\text{conv,in}}$$

Where T_{th} is the point of temperature at each location within building envelope [K], q is heat flux [W/m^2]. With provided information the point of temperature shown as $T_1 = 311.97 \text{ K}$, $T_2 = 302.88 \text{ K}$, $T_3 = 293.80 \text{ K}$, and $T_4 = 284.24 \text{ K}$. To further comprehend Unsteady Heat Conduction with the interval of time. At the starting time = 0 s the temperature of concrete surface is 312.843K; after time = 1800 s, the temperature of concrete surface is 318.706K; after time = 3600 s, the temperature of concrete surface is 324.817K. With three-time interval to consider creating rate of temperature change with time with following equation;

$$\frac{\partial T}{\partial t} \approx \frac{T_2 - T_1}{t_2 - t_1}$$

Where $\partial T/\partial t$ is Rate of temperature change with time [K/s], T_1, T_2 is temperature at times t_1, t_2 [K]. t_1, t_2 is times in seconds [s]. Where time interval 1 is $t_1 = 0$ s, $t_2 = 1800$ s, which $\partial T/\partial t \approx 0.00326$ K/s; and time interval 2 is $t_1 = 1800$ s, $t_2 = 3600$ s, $\partial T/\partial t \approx 0.00340$ K/s. To find the average rate of temperature change over the entire 3600 seconds using time at 0 and 3600 seconds with its temperature as $\partial T/\partial t \approx 0.00333$ K/s. To find Second Derivative of Temperature with Respect to Position using spatial temperature data at different depths within the concrete, use the finite difference approximation with the following equation:

$$\frac{\partial^2 T}{\partial x^2} \approx \frac{T_{i-1} - 2T_i + T_{i+1}}{\Delta x^2}$$

Where $\partial^2 T/\partial x^2$ is second derivative of temperature with respect to position [K/ m²], T_{i-1} is Temperature at the previous spatial point [K], T_i is Temperature at the current point [K], T_{i+1} is Temperature at the next spatial point [K], Δx is Distance between points [m]. With temperature values at three or more points along the x-axis. As $T_{i+1} = 312.843$ K, $T_i = 318.706$ K, $T_{i-1} = 324.817$ K with distance of the building envelope is 0.2 m. Finalize the $\partial^2 T/\partial x^2 \approx 6.2$ K/ m². Set overall thermal conductivity as 0.0323 W/m·K from $k_{\text{total}} = L_{\text{total}}/R_{\text{total}}$, and find thermal diffusivity using the following equation;

$$\alpha = \frac{k}{\rho C_p}$$

Where α is thermal diffusivity [m²/s], ρ is density [kg/m³], C_p is specific heat capacity [J/kg·K]. Set overall thermal conductivity as 0.0323 W/m·K. To find overall density, specific heat, use the following equation (in one dimensional model):

$$\rho_{\text{total}} = \frac{\sum (\rho_i \cdot L_i)}{\sum L_i}$$

$$C_{p_{\text{total}}} = \frac{\sum (C_{p_i} \cdot \rho_i \cdot L_i)}{\sum \rho_{\text{total}} \cdot L_i}$$

Where the building envelope consists of: Lightweight concrete (2 layers, 0.02 m each), Air cavity (0.16 m), L_i is the thickness layer of material. The result ρ_{total} is approximately 280.98 kg/m³ and $C_{p_{\text{total}}}$ is approximately 2095.7 J/kg·K. With provided

information, thermal diffusivity of the building envelope equal $5.48 \times 10^{-8} \text{ m}^2/\text{s}$. With all the provided information, Equation for Unsteady Heat Conduction can be use.

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2}$$

Where $\partial T/\partial t$ is Rate of temperature change with time [K/s], α is thermal diffusivity [m^2/s], $\partial^2 T/\partial x^2$ is second derivative of temperature with respect to position [K/ m^2].

$$\rho C_p \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial x^2}$$

Where ρ is density [kg/m^3], C_p is specific heat capacity [$\text{J}/\text{kg}\cdot\text{K}$], $\partial T/\partial t$ is Rate of temperature change with time [K/s], k is thermal conductivity [$\text{W}/\text{m}\cdot\text{K}$], $\partial^2 T/\partial x^2$ is second derivative of temperature with respect to position [K/ m^2]. Set overall thermal conductivity as $0.0323 \text{ W}/\text{m}\cdot\text{K}$ from $k_{\text{total}} = L_{\text{total}}/R_{\text{total}}$ and $\partial^2 T/\partial x^2 \approx 6.2 \text{ K}/\text{m}^2$. thermal diffusivity of the building envelope equal $5.48 \times 10^{-8} \text{ m}^2/\text{s}$. The result of the rate of temperature change with respect to time is approximate $3.40 \times 10^{-7} \text{ K/s}$. With the information provided, the context is enough to be able to find dimensionless number which are The Fourier number is a dimensionless number that represents the ratio of heat conduction to heat storage in a material given by:

$$F_o = \frac{\alpha t}{L^2}$$

Where F_o is Fourier number, α is thermal diffusivity of the material [m^2/s], t is time [s] (time period of 3600 seconds), and L is characteristic length (thickness of the building envelope) [m]. Fourier number is approximate 4.932×10^{-3} . Another dimensionless number is Biot Number that represents the ratio of conduction resistance within a solid to convective resistance at its surface given by:

$$B_i = \frac{hL}{k}$$

Where B_i is Biot number, h is Convective heat transfer coefficient [$\text{W}/\text{m}^2\cdot\text{K}$], L is characteristic length (thickness of the building envelope) [m], k is thermal conductivity

[W/m²·K]. Biot number is approximate ≈ 61.91 . To calculate solve Kirchhoff's Law of Radiation state, it requires to solve heat transfer by radiation between the two-interval points Interval 1: Between the exterior (outside concrete layer) and the air cavity. Interval 2: Between the air cavity and the interior (another outer layer of concrete), the Stefan-Boltzmann law is used:

$$q_{\text{rad}} = \sigma \cdot F_{12} \cdot A \cdot (T_1^4 - T_2^4)$$

Where q_{rad} is heat transfer by radiation [W], σ is Stefan-Boltzmann constant equal $5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4$, A is surface area (m²), T_{th} is the surface temperatures in Kelvin. The interval 1 is $T_1 = 312.834 \text{ K}$, $T_2 = 312.787 \text{ K}$, and interval 2 is $T_3 = 293.242 \text{ K}$, and $T_4 = 293.195 \text{ K}$. Assume $F_{12} = 1$ for full view exchange. The heat transfer by radiation of interval 1 equal 0.408 W and interval 2 equal 0.272 W. To apply Kirchhoff's Law of Radiation states, it needs to determine emissivity and absorptivity.

$$\epsilon(\lambda, T) = \alpha(\lambda, T)$$

$\epsilon(\lambda, T)$ is the ability of a surface to emit thermal radiation at a specific wavelength and temperature, $\alpha(\lambda, T)$ is the ability of a surface to absorb radiation at a specific wavelength and temperature, λ is wavelength of radiation [m], T is Absolute temperature of the surface [K]. Where Emissivity of concrete equal 0.85 (typical value for concrete). Absorptivity of concrete equal 0.85 (based on Kirchhoff's law). If emissivity ϵ of the material is known, the radiation heat transfer equation can be expressed as:

$$q_{\text{rad}} = \epsilon \cdot \sigma \cdot F_{12} \cdot A \cdot (T_1^4 - T_2^4)$$

Where q_{rad} is heat transfer by radiation [W], σ is Stefan-Boltzmann constant equal $5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4$, A is surface area (m²), T_{th} is the surface temperatures in Kelvin. The interval 1 is $T_1 = 312.834 \text{ K}$, $T_2 = 312.787 \text{ K}$, and interval 2 is $T_3 = 293.242 \text{ K}$, and $T_4 = 293.195 \text{ K}$. Assume $F_{12} = 1$ for full view exchange. The heat transfer by radiation of interval 1 equal 0.347 W and interval 2 equal 0.231 W.

Since the core of this dynamic building envelope is the integration of active ventilation system embedded at the base of the building envelope's air cavity. Assume that there is

an air blower that produce 0.1 m/s (an average speed of small air blower) with opening of 0.1 m². For the relative humidity is 73% as it is an average humidity in hot-humid climate region. The mass flow rate equation is given as:

$$\dot{m} = \rho \cdot V \cdot A$$

Where $\dot{m}$ is mass flow rate [kg/s], ρ is air density [kg/m³], V is air velocity [m/s], and A is opening area [m²]. With provided information mass flow rate is equal 0.0126 kg/s. To predict fluid flow patterns in different situations by measuring the ratio between inertial and viscous forces, incorporate Reynolds number given as:

$$Re = \frac{\rho \cdot V \cdot D_h}{\mu}$$

Where Re is Reynolds Number, ρ is air density [kg/m³], V is air velocity [m/s], D_h is characteristic of linear dimension of Hydraulic diameter, μ is dynamic viscosity of air at room temperature [1.85×10⁻⁵Pa·s]. First step is finding D_h using the following:

$$D_h = \frac{4A}{P}$$

Where D_h is characteristic of linear dimension of Hydraulic diameter [m], A is opening area [m], P is Wetted perimeter (depends on geometry). Assuming the opening is a square for simplicity where side length $L = \sqrt{A} = \sqrt{0.1} \approx 0.316$ m² with wetted perimeter equal 1.264 m². Where characteristic of linear dimension of Hydraulic diameter is 0.316 m. As the result Reynolds number approximate at 2,091. With the context of the building envelope with air cavity, stack effect would be applied to the design of it. Pressure difference due to the stack effect:

$$\Delta P = \rho \cdot g \cdot h \cdot \frac{T_i - T_o}{T_i}$$

Where ΔP is Pressure difference [Pa], ρ is Air density [kg/m³], g is Acceleration due to gravity [9.81m/s²], h is height of the column of air [m], T_i is inside temperature [K], T_o is outside temperature [K]. As the Height of the building envelope (h): 2.4 m, with inside

temperature of 293.242 K, and outside temperature of 312.834 K. Air density is 1.225 kg/m³, Cross-sectional area of the opening is 0.18 m, Discharge coefficient is 0.6. The result of Pressure difference is $\Delta P \approx 0.97 \text{ Pa}$

$$Q = C_d \cdot A \cdot \sqrt{\frac{2\Delta P}{\rho}}$$

Where Q is volumetric airflow rate [m³/s], C_d is discharge coefficient (typically ~0.6–0.65 for most openings), A is Cross-sectional area of the opening [m²], ΔP is pressure difference [Pa], ρ is air density [kg/m³]. In this case Discharge coefficient is 0.65 (typical for openings), Opening area is 0.1 m², Pressure difference is 0.979 Pa from the previous equation. The result of Volumetric Flow Rate approximate is 0.0823 m³/s. With this information the Prandtl number as the ratio of momentum diffusivity to thermal diffusivity

$$Pr = \frac{\mu \cdot C_p}{k}$$

Where Pr is Prandtl number, μ is the dynamic viscosity of air [Pa·s], C_p is the specific heat capacity of air [J/kg·K], k is the thermal conductivity of air [W/m·K]. Where C_p approximate is 1005 J/kg·K, k approximate is 0.026 W/m·K, μ is dynamic viscosity of air at room temperature [1.85×10⁻⁵ Pa·s]. The Prandtl number (Pr) for air is approximately 0.715. With the Prandtl number Nusselt number which the ratio of total heat transfer to conductive heat transfer at a boundary in a fluid could be given by the following empirical correlation:

$$Nu = 0.023 \cdot Re^{0.8} \cdot Pr^{0.4}$$

Where Nu is Nusselt number, Re is the Reynolds number, Pr is Prandtl number. Reynolds number approximate at 2,091, and the Prandtl number for air is approximately 0.715. The Nusselt number (Nu) is approximately 9.114513. With the provided information the heat transfer coefficient (h) can be calculated from the Nusselt number (Nu) and the hydraulic diameter (D_h) be given by the equation:

$$h = \frac{Nu \cdot k}{D_h}$$

Where h is heat transfer coefficient [W/m²K], Nu is the Nusselt number, k is the thermal conductivity of the fluid (air in this case) [W/m·K], D_h is the hydraulic diameter [m]. The Nusselt number (Nu) is approximately 9.114513, k approximate is 0.026 W/m·K, and $D_h \approx 0.316$ m. The result of heat transfer coefficient approximate is 0.749928303 W/m²K

Write a formula to find Thermal resistance over time, and over speed of wind. for wall envelope that has integral of time heat that gradually transfer and the wind is pumping in at the bottom. To see how speed of wind pumping interacts with the heat transfer and thermal resistance

$$R_{cond} = \frac{L}{k}$$

Where L is the wall thickness [m], and k is its thermal conductivity [W/m·K]. L determined as 0.2 m, and using total thermal conductivity as 0.0323 W/m·K the convective resistance, which is strongly influenced by wind speed, is defined as

$$R_{conv}(V) = \frac{L}{h(V) A}$$

with A representing the surface area available for convection [m²], and the convective heat transfer coefficient $h(V)$ [W/m²K], modeled as a function of wind speed V [m/s]. A common empirical relationship for $h(V)$ is.

$$h(V) = h_0 + aV^n$$

where h_0 is the baseline convective coefficient under natural convection, and a and n are empirical constants that capture the enhancement of convection due to wind. In this parameter, the exponent n represents how sensitive the convective heat transfer coefficient is to changes in wind speed. In many cases, experiments have shown that for turbulent forced convection over flat surfaces or building facades, n typically falls in the range of 0.5 to 0.8. A value of 0.6 is a common representative value under typical outdoor conditions where the flow is moderately turbulent. Similarly, a is an empirical coefficient that quantifies the magnitude of the enhancement of convection due to wind. Its value

depends on several factors such as the surface geometry, roughness, and the specific environmental conditions. A value of $a=0.5$ is often used as an approximate parameter based on regression analysis of experimental data for similar scenarios. In this equation, the baseline convective coefficient under natural convection assumed to 2 W, n as 0.6 and a equal of 0.5. As the result the convective heat transfer coefficient is 2.125594 W/m²K. Thus, the overall steady-state thermal resistance is

$$R_{\text{total}}(V) = \frac{L}{k} + \frac{1}{A(h_0 + \alpha V^n)}$$

Where $R_{\text{total}}(V)$ is Total thermal resistance [W/K]. When considering the transient response of the wall envelope, the energy balance for a lumped system is written as

$$C \frac{dT}{dt} = \frac{T_{\infty} - T(t)}{R_{\text{total}}(V)}$$

Where C is the thermal capacitance of the wall [J/K], $T(t)$ is its temperature at time t [K [s]], and T_{∞} is the ambient temperature [K]. Solving this first-order differential equation yields. Where T_{∞} is 313.15 K according to the surface on one side, and $T(t)$ is 307.390 K from the following equation and R total as 3.781 W/K. Which thermal capacitance is equivalent to 0.6594 J/K.

To find Ambient temperature conditions, using convective heat transfer equation. For

$$q_{\text{conv}} = hA(T_s - T_{\text{amp}})$$

Where q_{conv} is convective heat transfer [W/m²K], h is Heat transfer coefficient [W/m²K], A is Area exposed to air [m²] T_s is Surface temperature [K], T_{amp} is Ambient temperature [K], Rearrange to;

$$T_{\text{amp}} = T_s - \left(\frac{q_{\text{conv}}}{hA} \right)$$

Where T_{amp} is ambient temperature [K] (this variable will be used in the part of temperature at that time in the other equation. As the convective coefficient under natural convection is 25 W at wind speed outside of 1 m/s, n as 0.6 and a equal of 0.5. As the result the convective heat transfer coefficient is 5.5 W/m²K. With surface temperature of 313.5 K, the ambient temperature (temperature at that time) equal to 311.2561 K.

$$T(t) = T_{\infty} + (T(0) - T_{\infty}) \exp\left(-\frac{t}{\tau}\right)$$

In this equation, $T(t)$ is the temperature of the system at time t . The term T_{∞} represents the steady-state temperature that the system will eventually reach when it has fully equilibrated with its surroundings. The value $T(0)$ is the initial temperature of the system at time $t = 0$. The exponential term, $\exp\left(-\frac{t}{\tau}\right)$, describes the decay of the temperature difference between the system and its surroundings over time. Here, τ is the time constant, a key parameter that determines how fast the temperature approaches T_{∞} . As $\text{EXP}(x)$ returns the natural exponential of x , where e is the base of the natural logarithm, 2.71828 (Euler's number). EXP is the inverse function of the LN function. Steady-state temperature equal to 310.881 K with initial temperature at 313.15 K. t is equal to 1800s and τ as 3600s. Temperature at time constant equal 312.4048 K. With the time constant τ defined as

$$\tau = R_{\text{total}}(V)C = \left[\frac{L}{k} + \frac{1}{A(h_0 + \alpha V^n)} \right] C$$

This formula illustrates that an increase in wind speed V increases the convective heat transfer coefficient $h(V)$, thereby reducing R_{conv} and consequently the overall thermal resistance $R_{\text{total}}(V)$. As a result, the time constant τ decreases, meaning that the wall envelope will respond more quickly to changes in ambient conditions. In summary, the transient temperature behavior of the wall envelope, influenced by wind-induced convection, is given by

$$T(t) = T_{\infty} + (T(0) - T_{\infty}) \exp\left\{ -\frac{t}{C \left[\frac{L}{k} + \frac{1}{A(h_0 + \alpha V^n)} \right]} \right\}$$

An increase in cavity airflow enhances convective heat removal from the internal cavity surfaces, thereby increasing the overall thermal resistance of the wall assembly. The resulting increase in equivalent thermal resistance is reflected as a lower equivalent U -value, indicating reduced heat transfer through the wall. The resulting equivalent U -values

(Phaiboonnukulkij, 2025) represent the overall thermal transmittance of the airflow-enhanced wall assembly and provide the interface between the wall-level thermal analysis and the whole-building energy assessment conducted in the EDGE App. The present analysis is based on prescribed airflow conditions and does not explicitly model transient airflow behavior, wind-driven effects, or variations in outdoor climatic conditions. Consequently, the reported U-values should be interpreted as equivalent performance indicators for comparative evaluation rather than direct predictions of field performance.

5. Experiment

The energy performance of a two-storey residential building was evaluated using the EDGE App, with the project location set to Thailand (Bangkok climate) in order to apply location-specific climatic data, energy baselines, and default assumptions consistent with EDGE methodology. This location setting ensures that weather files, cooling degree days, and typical residential energy use patterns are representative of the project context. The analysis assessed the impact of a hollow lightweight concrete wall system under varying wind-speed conditions. The simulation procedure consisted of two stages. First, equivalent wall U-values were determined using the thermal-analysis methodology described in Section 4. Second, the resulting U-values were incorporated into the EDGE App to evaluate their influence on annual building energy performance. Three airflow scenarios (0 m/s, 0.1 m/s, and 1.0 m/s) were assessed while maintaining all other building parameters constant.

5.1 Building Energy Simulation Setup

To implement the ADLP system within the building energy model, the exterior wall areas incorporated into the simulation were identified and quantified from the architectural model. Figures 6–8 illustrate the façade elevations used to determine the distribution of opaque wall surfaces, fenestration elements, and ADLP wall segments included in the EDGE assessment.

This simulation is conducted on a two-storey modern residential building located in Bangkok, Thailand, representing typical construction in a hot-humid tropical climate. The building has a gross floor area (GFA) of 265 m² (Figures 2 and 3), which establishes the scale for evaluating envelope-related energy measures within the EDGE framework. Wall areas, window areas, and wall-between-floor segments are documented individually for each

façade and are treated according to EDGE conventions, with no additional summation performed. The southern façade consists of a 51.87 m² exterior wall area, a 1.73 m² window area, and a 12.48 m² wall-between-floor segment that is excluded from Window-to-Wall Ratio (WWR) calculations (Figure 7).

To implement the ADLP system within the building energy model, the exterior wall areas incorporated into the simulation were identified and quantified from the architectural model. Figures 5–8 illustrate the façade elevations used to determine the distribution of opaque wall surfaces, fenestration elements, and ADLP wall segments included in the EDGE assessment.

The northern façade includes wall areas of 26.2 m², 10.67 m², and 5.67 m². The window area is identified as 27.44 m², from which 10.67 m² and 5.67 m² (corresponding to wall segments) are excluded to obtain the effective glazing area. The façade also includes a 12.48 m² wall-between-floor portion, which is excluded from WWR calculations (Figure 5).

The eastern façade includes wall areas of 47.97 m², 16.01 m², and 4.48 m², along with a window area of 41.03 m², from which 16.01 m² and 4.48 m² (non-glazed portions) are excluded to determine the net window area. The façade also contains a 21.04 m² wall-between-floor segment that is excluded from WWR evaluation (Figure 6).

The western façade is composed of 55.57 m² and 16.35 m² wall areas. The window area is described as 33.93 m², from which 16.35 m² is excluded to define the effective glazing area. This façade also includes a 21.04 m² wall-between-floor segment that is not used in the WWR calculation (Figure 8).

The facade areas illustrated in Figures 6–8 were used to define the exterior envelope within the EDGE model. The equivalent U-values derived from the thermal analysis were applied to the ADLP wall areas, while all other envelope parameters remained unchanged. This approach enabled the influence of airflow-enhanced wall performance on annual building energy consumption to be evaluated.

Table 2. Simulation Parameters:

Parameter	Value	Status
WWR	16.90%	Constant
SRI	30	Constant
COP	3.16	Constant
Airflow velocity	0, 0.1, 1.0 m/s	Variable
Wall U-value	Calculated	Variable

Source: Author

Airflow velocity was the only variable modified between simulation scenarios; all other building and system parameters remained unchanged.

5.2 EDGE App Simulation: Lightweight Concrete Wall – No cavity ventilation (0 m/s)

The simulation study evaluates the energy performance of the case study building, using the EDGE App. The analysis focuses specifically on the building’s exterior walls, with the objective of quantifying the influence of a lightweight concrete wall on cooling-energy demand under typical tropical conditions. Other envelope components and internal systems are maintained at baseline or default EDGE settings to isolate the effects of the wall.

The primary parameters used in the simulation include the thermal transmittance of the wall, the window-to-wall ratio, the reflective properties of the exterior surface, and the efficiency of the cooling system. The wall U-value (EEM08 – Insulation of Exterior Walls) is set at 0.590 W/m²·K, representing the thermal performance of a conventional unventilated lightweight concrete wall. The window-to-wall ratio (EEM01) is defined as 16.9% based on the building design, reflecting the proportion of glazing to total opaque wall area on the building façades according to the architectural design. The reflective properties of the exterior wall (EEM03) are represented by a Solar Reflectance Index (SRI) of 30, corresponding to a light-colored concrete finish. The building’s HVAC system efficiency (EEM13) is set at 3.16 COP (W/W), consistent with typical equipment in residential

applications. These values are compared to the base-case reference inputs, which feature a higher U-value of 1.86 W/m²·K, an SRI of 45, and a slightly higher WWR of 18%, providing a benchmark for evaluating relative energy savings.

The simulation process begins with the input of the wall U-value into EDGE, representing the passive insulation characteristics of the lightweight concrete wall. The window-to-wall ratio is applied per façade based on the design configuration, ensuring accurate representation of solar gains and envelope distribution. The solar reflectance is set at 30 to reduce solar absorption and moderate heat gain. The cooling system efficiency is fixed at 3.16 COP, isolating envelope performance effects. Additionally, the influence of ambient wind on the wall is assessed at per-second intervals to capture the convective enhancement of heat transfer and its impact on the effective U-value, which in turn influences the calculated cooling-energy reduction.

The objectives of this simulation are threefold. First, it quantifies the cooling-energy demand of the building when constructed with a standard lightweight concrete wall under Bangkok’s hot-humid climate. Second, it evaluates the extent to which wind-induced convective effects can modify the effective thermal performance of the wall. Finally, it establishes a baseline performance scenario against which the Active Double-Layered Precast Wall System can later be compared, thereby isolating the contribution of envelope improvements to overall building energy savings as calculated by EDGE.

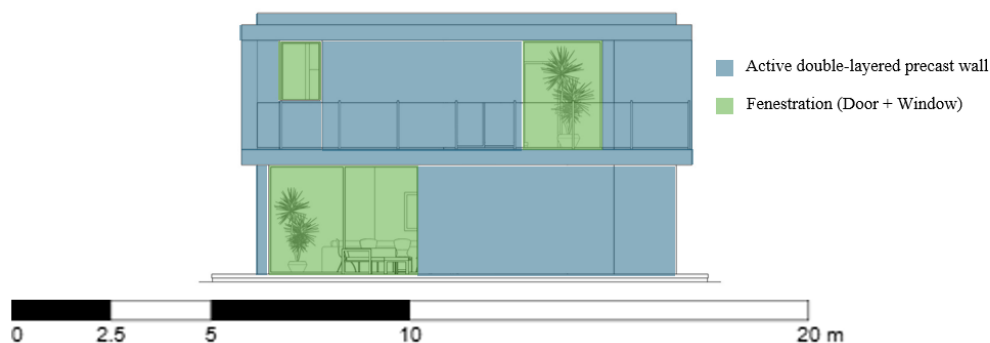


Figure 5. North-facing façade of the case-study building, illustrating the distribution of opaque wall areas, fenestration elements, and the wall-between-floor band; regions highlighted in blue indicate the Active Double-Layered Precast Wall system, while regions highlighted in green represent fenestration components, including doors and windows, incorporated in the envelope analysis.

Source: Author

5.3 EDGE App Simulation: Lightweight Concrete Wall – Low-Speed Cavity Ventilation (0.1 m/s)

This simulation evaluates the energy performance of the case study building, using the EDGE App, focusing specifically on the impact of a lightweight concrete wall enhanced by low-speed airflow within the envelope. The study isolates the effect of the wall system on cooling-energy demand while maintaining all other envelope components and internal systems at baseline or default EDGE settings.

The primary simulation parameters reflect the wall's improved thermal performance and include wall U-value, window-to-wall ratio, solar reflectance, and cooling-system efficiency. The wall U-value (EEM08 – Insulation of Exterior Walls) is set at 0.256 W/m²-K, representing the effect of low-speed airflow (0.1 m/s) within the hollow cavity, which enhances convective heat removal. The window-to-wall ratio (EEM01) is fixed at 16.9%, reflecting the architectural design. The exterior wall reflectance (EEM03) is set at SRI 30, representing a light-colored finish. The cooling system efficiency (EEM13) remains 3.16 COP (W/W), unchanged from the baseline, to ensure that observed energy reductions are solely due to envelope improvements. Base-case comparisons are maintained with a U-value of 1.86 W/m²-K, SRI of 45, and WWR of 18%.

The simulation process begins with inputting the wall U-value into EDGE to represent the combined effect of the lightweight concrete and cavity airflow. The influence of ambient wind at 0.1 m/s is incorporated to capture the enhanced convective heat removal, allowing EDGE to reflect the improved thermal behavior as a reduced effective U-value.

5.4 EDGE App Simulation: Lightweight Concrete Wall – Moderated Cavity Ventilation (1 m/s)

To evaluate the effect of moderate cavity airflow, a simulation was conducted with 1 m/s airflow applied within the wall cavity of the hollow lightweight concrete wall system. This scenario represents stack-driven ventilation induced by temperature differences, rather than forced mechanical ventilation. The two-storey residential building in Bangkok, Thailand, was modeled in the EDGE App with the same architectural and system parameters as previous simulation.

Key input parameters included: wall U-value (EEM08) of 0.177 W/m²·K, reflecting the improved thermal performance under 1 m/s airflow; window-to-wall ratio (EEM01) of 16.9%; reflective exterior wall (EEM03) with a Solar Reflectance Index of 30; and cooling system efficiency (EEM13) of 3.16 COP (W/W). All other building and system characteristics were maintained at baseline EDGE values to ensure that changes in energy performance could be attributed solely to the active envelope enhancement.

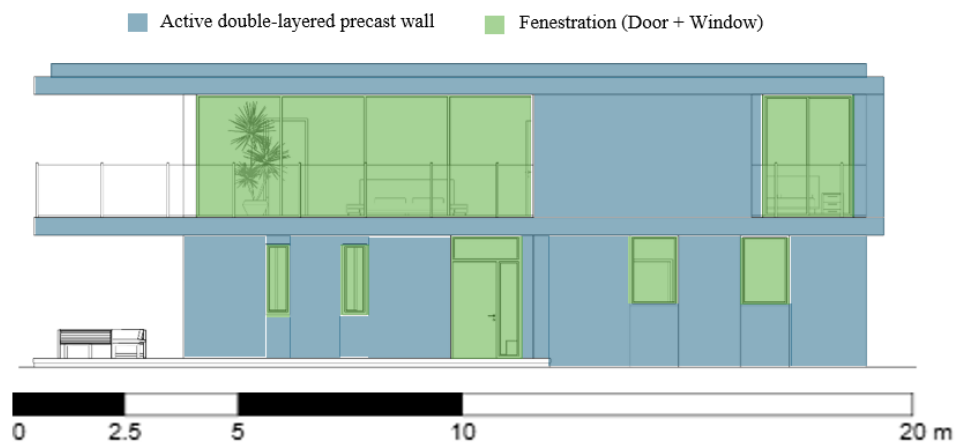


Figure 6. West-facing façade of the case-study building, illustrating the distribution of opaque wall areas, fenestration elements, and the wall-between-floor band; regions highlighted in blue indicate the Active Double-Layered Precast Wall system, while regions highlighted in green represent fenestration components, including doors and windows, incorporated in the envelope analysis.

Source: Author

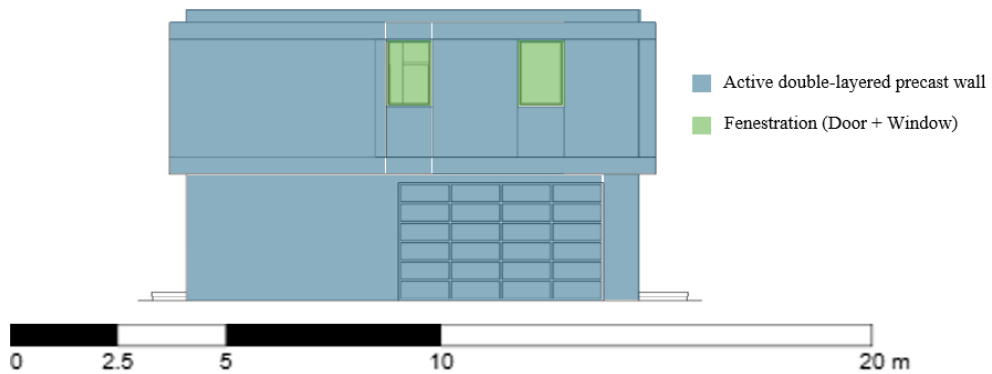


Figure 7. South-facing façade of the case-study building, illustrating the distribution of opaque wall areas, fenestration elements, and the wall-between-floor band; regions highlighted in blue indicate the Active Double-Layered Precast Wall system, while regions highlighted in green represent fenestration components, including doors and windows, incorporated in the envelope analysis.

Source: Author

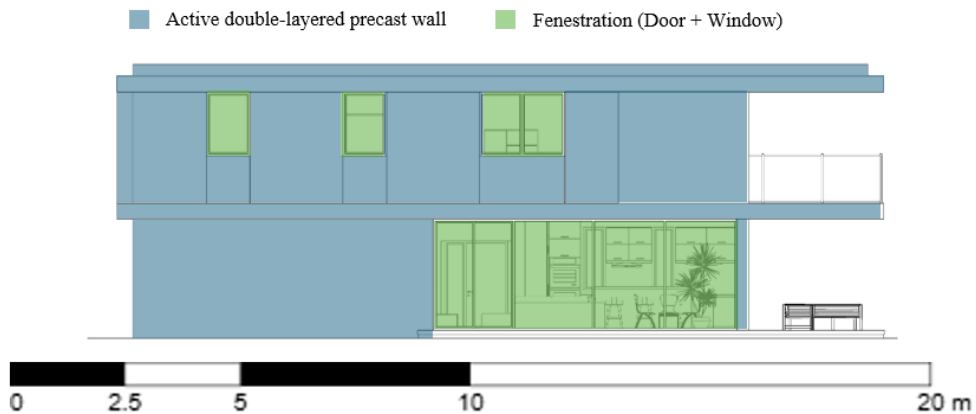


Figure 8. East-facing façade of the case-study building, illustrating the distribution of opaque wall areas, fenestration elements, and the wall-between-floor band; regions highlighted in blue indicate the Active Double-Layered Precast Wall system, while regions highlighted in green represent fenestration components, including doors and windows, incorporated in the envelope analysis.

Source: Author

6. Results

The results are presented using two performance indicators: (1) effective wall U-value, representing envelope-level thermal performance, and (2) annual energy savings predicted by the EDGE App, representing whole-building energy performance relative to the EDGE baseline building. While the U-value reflects the thermal behavior of the wall

assembly, the energy-saving percentage quantifies the influence of wall-performance improvements on total building energy consumption.

The energy-saving percentages reported by EDGE represent the combined effect of all project-design parameters relative to the EDGE baseline model. Within the present study, airflow-induced improvements in wall thermal performance were incorporated through modified wall U-values, while other project inputs remained fixed across the airflow scenarios investigated. Consequently, differences observed between the 0 m/s, 0.1 m/s, and 1.0 m/s cases can be attributed primarily to changes in airflow-enhanced wall performance.

Table 3 summarizes the thermal and energy-performance results for the three airflow scenarios. The introduction of cavity ventilation improved both the effective wall U-value and the predicted annual building energy savings. The most substantial improvement occurred when airflow was increased from 0 m/s to 0.1 m/s, indicating that even low-speed ventilation can enhance convective heat removal and reduce conductive heat transfer through the wall assembly. Further increasing airflow from 0.1 m/s to 1.0 m/s continued to improve thermal performance; however, the additional reduction in U-value and corresponding increase in annual energy savings were comparatively modest. This trend suggests diminishing marginal benefits at higher airflow velocities, as a large proportion of the heat-removal potential is already achieved under low-speed ventilation conditions.

The simulation results indicate that, in the absence of cavity airflow, the building achieves a 7.23% reduction in annual energy use relative to the EDGE base case. As illustrated in Figure 9, this reflects the inherent energy-saving performance of the lightweight concrete wall combined with its reflective surface properties, without any contribution from cavity ventilation.

When low-speed airflow of 0.1 m/s is introduced into the wall cavity, the simulation results (Figure 10) show an increase in energy savings to 9.35% compared to the EDGE base-case building. In comparison, the wall configuration without cavity airflow achieved energy savings of 7.23%. Therefore, the introduction of 0.1 m/s airflow increased energy savings by 2.12 percentage points ($9.35\% - 7.23\%$). The results confirm that even minimal airflow enhances convective heat removal within the cavity, effectively reducing heat transfer through the wall and improving overall envelope performance. This

demonstrates the measurable contribution of low-speed airflow to cooling energy reduction under hot-humid tropical conditions.

The airflow-enhanced wall configuration with a cavity airflow velocity of 1.0 m/s achieved annual energy savings of 9.85% relative to the EDGE baseline (Figure 11). Although this represents the highest energy-saving value among the evaluated scenarios, the improvement over the 0.1 m/s case was limited to only 0.50 percentage points (9.85% – 9.35%). This relatively small increase indicates that the majority of the thermal benefits are already achieved at low airflow velocities. Consequently, increasing airflow beyond 0.1 m/s provides only marginal additional energy savings, demonstrating a diminishing-return effect in the relationship between cavity airflow and building energy performance.

From a thermal performance perspective, the wall U-value decreases from 0.590 W/m²·K in the no-airflow condition to 0.256 W/m²·K at 0.1 m/s, and further to 0.177 W/m²·K at 1 m/s. This substantial reduction indicates the effectiveness of cavity ventilation in enhancing convective heat transfer and reducing conductive heat flow through the wall assembly. The corresponding improvements in energy savings—from 7.23% to 9.35% and 9.85%—highlight the relationship between reduced U-value and cooling load reduction.

Table 3. U-values and energy savings across the three scenarios:

Wind Speed (m/s)	Effective Wall U-Value (W/m ² ·K)	Annual Energy Savings (%)
0 (Base case)	0.590	7.23
0.1	0.256	9.35
1	0.177	9.85

Source: Author

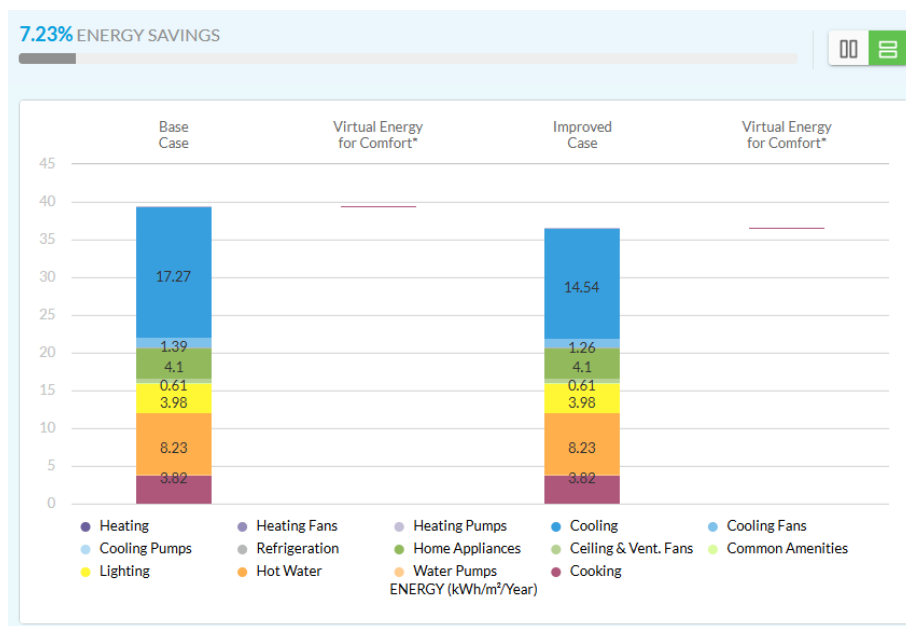


Figure 9. EDGE App Simulation – Zero Wind Speed (0 m/s) illustrates the building energy simulation results for the lightweight concrete wall with no cavity airflow.

Source: Author

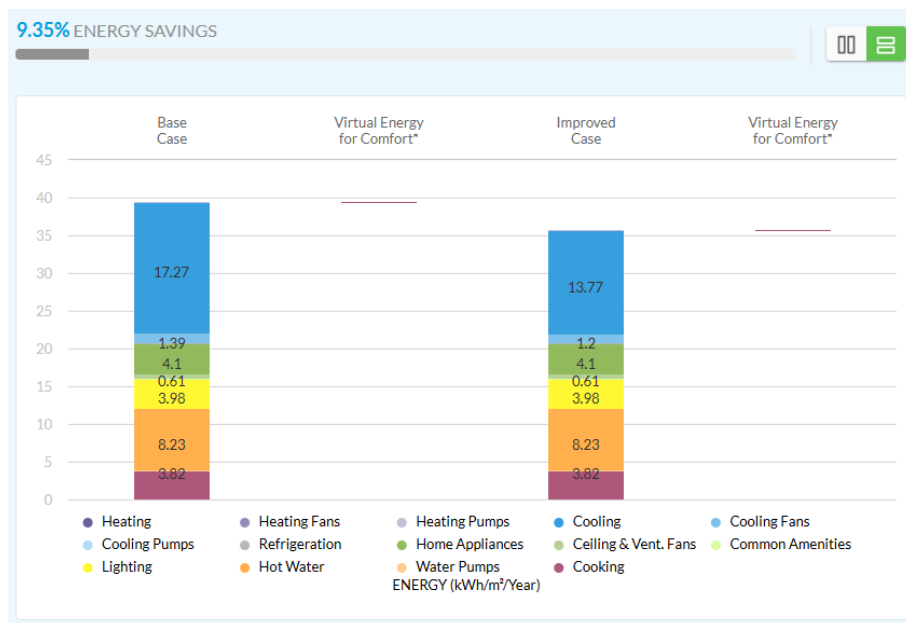


Figure 10. EDGE App Simulation – Low-Speed Cavity Ventilation (0.1 m/s) indicates the incremental energy-saving effect of low-speed active airflow within the wall cavity.

Source: Author

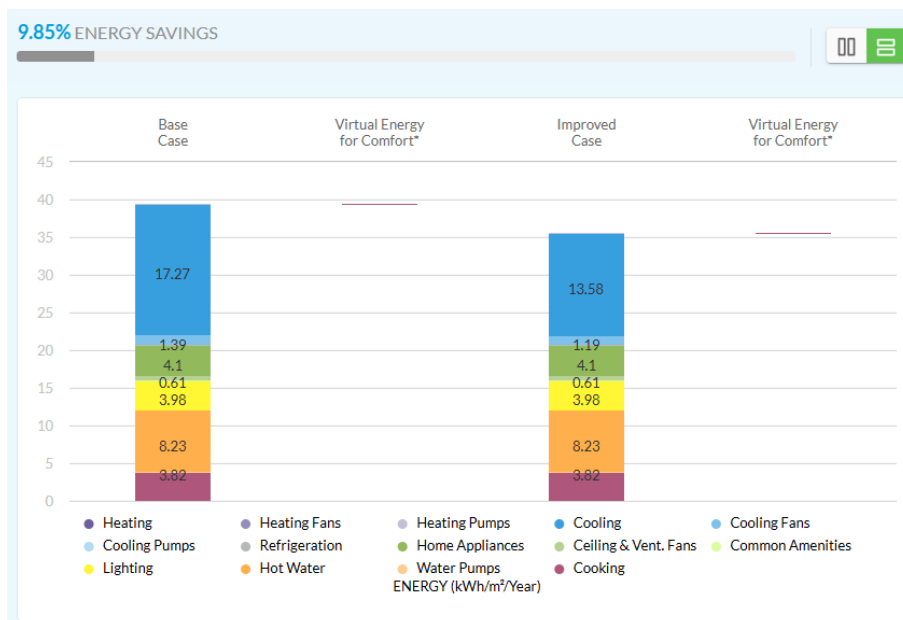


Figure 11. EDGE App Simulation – Moderate Cavity Ventilation (1 m/s)

Source: Author

Overall, the results show a clear trend of increasing energy savings with higher airflow within the wall cavity. Figures 9, 10, and 11 present the EDGE App simulation outputs for 0 m/s, 0.1 m/s, and 1 m/s, respectively, illustrating the progressive improvement in building energy performance. Even small increases in airflow produce measurable benefits, reinforcing the value of integrating airflow-assisted strategies into conventional lightweight concrete wall systems.

However, overall building energy performance is influenced by multiple factors, including window-to-wall ratio, solar reflectance, and cooling-system efficiency. While these parameters remained constant throughout the simulations, the results demonstrate how changes in airflow-enhanced wall performance affect annual building energy consumption within the EDGE framework. The findings therefore provide a quantitative basis for evaluating the contribution of cavity ventilation to building energy performance under hot-humid climatic conditions.

7. Discussion

The results indicate that the Active Double-Layered Precast (ADLP) Wall System improves both envelope thermal performance and whole-building energy performance

within the simulated scenarios. The reduction in equivalent wall U-value was associated with increased annual energy savings predicted by the EDGE App, demonstrating the relationship between wall thermal performance and cooling-energy demand. The equivalent U-value decreased from 0.590 W/m²·K under the no-airflow condition to 0.177 W/m²·K at an airflow velocity of 1.0 m/s, while predicted annual energy savings increased from 7.23% to 9.85%.

It should be noted that the reported energy savings are not solely attributable to cavity ventilation. The case-study model incorporated a different window-to-wall ratio and solar reflectance index relative to the EDGE baseline model, both of which influence cooling demand. However, these parameters remained constant across all airflow scenarios. Therefore, the differences observed between the 0 m/s, 0.1 m/s, and 1.0 m/s cases can be associated primarily with changes in airflow-enhanced wall thermal performance represented through the equivalent wall U-value.

The results also indicate diminishing performance gains at higher airflow velocities. The introduction of low-speed airflow (0.1 m/s) produced a substantial improvement in both U-value and annual energy savings, whereas increasing airflow from 0.1 m/s to 1.0 m/s resulted in comparatively modest additional benefits. This behavior suggests that a portion of the convective heat-removal potential can be achieved under relatively low airflow conditions, reducing the need for high ventilation rates within the cavity.

From a practical perspective, the findings suggest that airflow-assisted wall systems may provide an alternative approach to improving building-envelope performance in hot-humid climates. Rather than relying exclusively on additional insulation thickness, the ADLP concept enhances thermal resistance through convective heat removal within the wall cavity. The resulting reduction in heat transfer through the envelope may contribute to lower cooling-energy demand in buildings located in cooling-dominated climates such as Bangkok, Thailand.

The findings should be interpreted within the scope of the modeling assumptions adopted in this study. The analysis was based on prescribed airflow conditions and equivalent thermal-performance calculations rather than direct experimental measurements. Furthermore, the study considered a single residential building configuration and a limited range of airflow scenarios. Consequently, the reported U-values and energy-

saving estimates should be interpreted as comparative performance indicators within the simulation framework rather than direct predictions of field performance. Future research should include experimental validation, detailed airflow modeling, and additional building typologies to further evaluate the applicability of the proposed methodology.

8. Conclusion

This study evaluated the thermal performance and energy-saving potential of a hollow lightweight concrete wall and the Active Double-Layered Precast Wall (ADLP) System under the hot-humid climatic conditions of Bangkok, Thailand. A thermal analysis was conducted to determine equivalent wall U-values under different cavity-airflow conditions, and the resulting U-values were incorporated into the EDGE App to assess their influence on whole-building energy performance.

The results indicate that cavity airflow improves the thermal performance of the wall assembly. The equivalent wall U-value decreased from 0.590 W/m²·K under the no-airflow condition to 0.256 W/m²·K at an airflow velocity of 0.1 m/s and to 0.177 W/m²·K at 1.0 m/s. Correspondingly, the predicted annual energy savings increased from 7.23% to 9.35% and 9.85%, respectively, relative to the EDGE baseline model. The results also indicate diminishing performance gains at higher airflow velocities, suggesting that a substantial portion of the thermal benefit can be achieved under relatively low airflow conditions.

The study demonstrates a practical approach for representing airflow-enhanced wall performance within the EDGE framework using equivalent wall U-values. This methodology provides a means of evaluating airflow-assisted wall systems using a certification-oriented building energy assessment tool and contributes to the ongoing development of energy-efficient envelope strategies for cooling-dominated climates. The findings should be interpreted within the limitations of the adopted modeling approach. The analysis was based on prescribed airflow conditions and equivalent thermal-performance calculations rather than direct experimental measurements. In addition, the study considered a single building configuration and a limited range of airflow scenarios. Therefore, the reported U-values and energy-saving estimates should be regarded as comparative performance indicators within the simulation framework.

Future research should include experimental validation of the ADLP system under operational conditions and investigation of additional design parameters that may influence thermal performance, including cavity width, cavity depth, cavity geometry, and airflow optimization strategies. Further studies involving different building typologies and climatic conditions would also help evaluate the broader applicability of the proposed methodology. widespread adoption of this technology in both new and existing buildings.

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