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Original Article



# Interlocking passive brick set: the design of interlocking building components with connecting air cavities for heat dissipation and as a complement to the Heating, Ventilation, and Air Conditioning (HVAC) system

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**Abstract:** This dissertation explores the design and implementation of the "Interlocking Passive Brick Set," a building component aimed at enhancing thermal efficiency and optimising the performance of Heating, Ventilation, and Air Conditioning (HVAC) systems. The bricks demonstrate thermal resistance and low thermal transmittance, reflecting their ability to manage heat flow and dissipation effectively. The research focuses on the interaction between the exterior and interior surfaces of the brick set, where the exterior is exposed to a hot environment, and the interior remains cooler. The design incorporates a central air cavity with lower thermal transmittance than solid surfaces. This cavity facilitates a heat dissipation cycle: hotter air rises and is expelled through the top compartment, while cooler air descends, cooling the space. This convective process enhances the overall thermal regulation within the structure. The data explain the discrepancy between predicted and measured thermal performance in interlocking brick systems and how the integrated air cavity addresses these issues. Heat-flux measurements were correlated in a general form to enable designers to account for convection at both the interior and exterior surfaces.

**Keywords:** passive brick set, heat dissipation, HVAC

## 1. Introduction

In the realm of building design and energy efficiency, traditional insulation materials have long been engineered to act as passive barriers, limiting temperature exchange between the interior and exterior of structures (Li et al., 2023; Fawaier and Bokor, 2022). While this approach has been effective to some extent, it fails to leverage the full potential of building materials in actively contributing to a building's thermal management system (Budaiwi et al., 2002; Thakur et al., 2023). A more innovative approach to insulation would incorporate dual functions: serving as part of the building's structural integrity while also enhancing the performance of heating, ventilation, and air conditioning (HVAC) systems (Sadri & Mohseni, 2023). Beyond these primary roles, such materials could also fulfil various secondary functions that further optimise energy use and indoor comfort. This paper introduces a novel method for designing building materials that integrate a heat dissipation cycle into their very structure. The concept is simple yet transformative: hotter air naturally rises and is expelled through the upper compartments of a building's envelope, while cooler air descends, contributing to a cooling effect within the occupied space. This dynamic process can be embedded into any base material capable of being manufactured with interlocking air cavities and channels, making the material both a passive insulator and an active participant in the building's overall energy management. The research is divided into two primary experimental phases, each providing critical insights into the material's potential for thermal efficiency in hot climates. The first experiment involves a detailed theoretical calculation of the thermal properties of an interlocking passive brick set, focusing particularly on the middle horizontal section. This analysis is conducted using a range of materials, including aerated concrete, different types of conventional concrete, and clay. These materials are specifically engineered with parallel channels to facilitate various modes of heat transfer between the external environment and the interior spaces. The significance of this experiment lies in the need for the interconnecting material component to effectively absorb and transfer heat across its surfaces, enabling the air within these channels to carry out the desired heat exchange processes. The results from this experiment validate existing methods from the thermal sciences literature and offer new insights into how these principles can be applied to the design of thermally efficient buildings, particularly in regions characterised by hot climates.

| Abbreviations and symbols used in the text | | | |
|---|---|---|---|
| A | Area [$m^2$] | Q' | Heat dissipation rate [W] |
| ρ | Density [$kg/m^3$] | q | Heat flux [$W/m^2$] |
| cρ | Specific Heat Capacity [$JKg^{-1}$ $K^{-1}$] | Qc | Heat transfer rate at air channel [W] |
| C | Constant on fluid properties [$m/s{\cdot}K^{-0.5}$] | Qt | Heat transfer rate at air cavity [W] |
| λ | Thermal Conductivity [$Wm^{-1}K^{-1}$] | T | Temperature [K] |
| d | Thickness of the material [m] | △T | Temperature difference [K] |
| h | Heat transfer coefficient [$W/m^2{\cdot}K$] | R | Thermal Resistance [K/W] |
| L | Characteristic length [m] | U | Thermal transmittance [$W/m^2{\cdot}K$] |
| Nu | Nusselt Number | V˙ | Air flow rate [CFM] |
| n | Velocity scales with temperature | v | Air velocity [FPM] |
| m | Mass flow rate [$kg/m^3$] | NTU | Number of Transfer |
| Q | Heat transfer rate [W] | BTU | British Thermal Unit |

### 1.1. Heat dissipation insulation

In 1701, Sir Isaac Newton published his work on cooling in a paper on thermal science titled Scala Graduum Caloris (Scale of the Degree of Heat), which is now known as Newton's law of cooling (Maruyama & Moriya, 2021). Newton stated that the rate at which a body loses heat is directly proportional to the temperature difference between the body and its surrounding environment (Newton, 1701). Although Newton's law originally focused solely on conduction-type cooling, it was later revised in 1817 by Dulong and Petit to account for heat convection at temperature differentials by including an exponent (Whewell, 1866).

These insights laid the groundwork for one of the earliest understandings of how materials dissipate heat and highlighted the importance of insulation in buildings.

In 1822, Fourier published his work on heat flow in Théorie analytique de la chaleur (The Analytical Theory of Heat) (Arago, 1857). Fourier formalised the concepts of heat transfer through conduction (heat transfer through materials) and convection (heat transfer through fluid movement). He stated that the rate of heat transfer through a material is proportional to the negative gradient of the temperature and the area perpendicular to that gradient through which the heat flows (Maruyama and Moriya, 2021; Fourier, 1822). These principles are fundamental in designing effective insulation systems that manage airflow and heat dissipation. In the 1960s, ’70s, and ’80s, engineers in Norway, Canada, Sweden, Denmark, Finland, and Switzerland developed a new ventilation system for livestock buildings based on a novel idea for recovering heat (Bartussek, 1986). A layer of insulation divided the shed into a room and an attic. The attic space extended halfway down the walls to form a wrap-around cavity. Using a fan, fresh air from the cavity was drawn into the room through the insulation. As the air passed through the pores, it was warmed by heat conducting through the material in the opposite direction. The Norwegian term Motstrømstak highlighted the novelty of counter-current exchange (Uvsløkk, 2008), while the German term Porenlüftung alluded to the idea of ‘breathing’ with ventilation through pores (Bartussek, 1981). British researchers later adopted the term dynamic insulation (Taylor et al., 1996). A new series of studies were conducted in 2015 and 2016. Researchers examined micro-scale (Alongi and Mazzarella, 2015), latent, and transient (Ascione et al., 2015) heat transfer; the filtration of particulates (Di Giuseppe et al., 2015); and the use of buoyancy to replace fans (Park, Kim, & Yoon, 2016). One group even developed custom apparatus to test some of these aspects in combination (Alongi and Mazzarella, 2015). Despite the renewed interest, today's designs share two common features worth questioning. First, they rely on stock insulation materials, necessitating additional materials to complete a given envelope design. Second, they incorporate an air-mixing cavity to cover the interior surface, which seems to mitigate the impact of the surface temperature rather than resolving the issue conclusively.

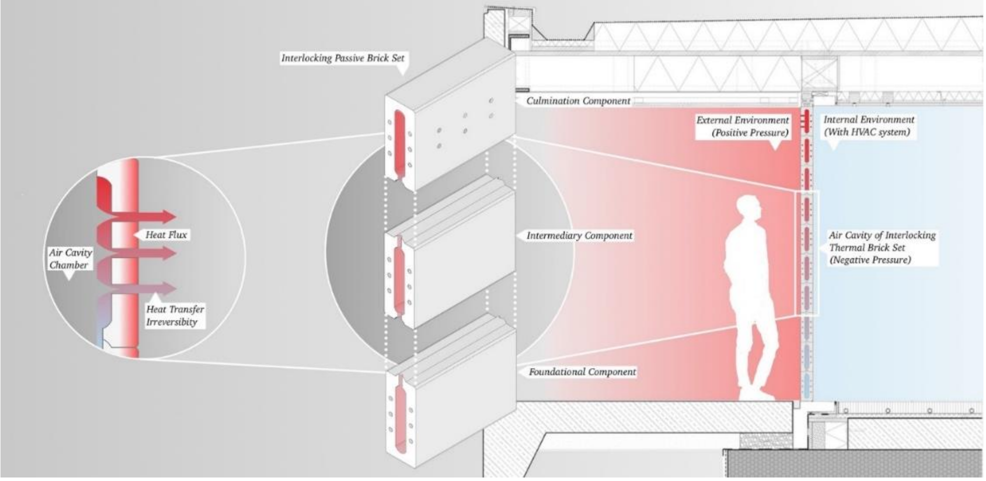


Fig. 1. The building envelope featuring the interlocking passive brick set is optimised to control heat dissipation and circulate airflow within the air cavity chamber while expelling hot air outward. An integrated air circuit within the brick set regulates temperature, functioning as dynamic insulation while also serving as a structural component

This study revisits the basic premise of dynamic insulation but takes a different approach, using a method from the thermal sciences literature (Alongi and Mazzarella, 2015). The method demonstrates how to optimise parallel channels in any material to counteract exterior heating by forcing a coolant through the channels at a given pressure. Kim, Lorente, and Bejan (Kim et al, 2007) employed analytical methods and numerical simulations to develop a set of design correlations applicable to a wide range of scenarios and base materials. Our experiment validates their results, which we present in standard notation for heat exchanger design, enabling the design of building envelopes that exchange heat efficiently.

### 1.2. Interlocking building component

Brick masonry has long been a cornerstone of construction, with its roots tracing back to many of the ancient civilizations (Cajamarca-Zuniga et al., 2023). The traditional brick-making process, which involves the mixing of raw materials, molding, drying, and firing the bricks to achieve the necessary strength, has served humanity well for millennia. However, this conventional approach is not without its drawbacks, particularly concerning energy efficiency, material waste, and the labor-intensive nature of the production process. Over the past two decades, the construction industry has seen a significant shift towards innovative brick manufacturing methods designed to address these limitations (Balaji et al., 2022). This evolution has given rise to various classifications of bricks, among which solid bricks and interlocking blocks are particularly noteworthy.

Interlocking blocks, as highlighted by researchers like Ali et al. (2013), Latha and Santhanakumar (2015), and Palios (2016), represent a modern advancement in brick technology. These blocks are produced in specialized molds, where the compaction process can be either mechanical or manual, depending on the specific requirements of the block, the materials used, and the desired quality. This adaptability in production methods allows for the creation of interlocking blocks either directly at the construction site or on a larger scale in a dedicated production yard, making them a versatile solution for various building projects.

There are two primary types of interlocking blocks: soil interlocking blocks and concrete interlocking blocks. The latter, particularly when reinforced with concrete, has demonstrated remarkable resilience, maintaining structural integrity even after multiple earthquake events, as evidenced by studies conducted by Tang et al. (2014). This resilience is further enhanced by the development of semi-interlocking masonry (SIM), which introduces a level of flexibility within the wall structure. SIM is designed to reduce stiffness, allowing for relative sliding between brick courses within the plane of the wall while preventing out-of-plane movement. This feature is particularly beneficial in seismic zones, where energy dissipation is crucial for maintaining the structural integrity of buildings. Research by Totoev and Harthy (2016) and Jeslin and Padmanabam (2020) has shown that SIM with an open gap offers reduced energy dissipation compared to SIM without a gap or with a closing gap, highlighting the importance of design variations in achieving optimal performance.

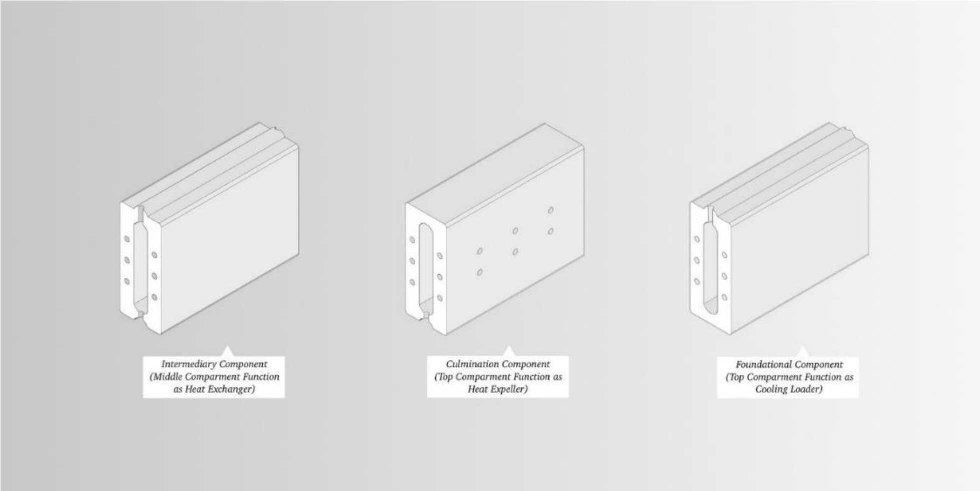


Fig. 2. The design of the Interlocking Passive Brick Set consists of three components (from left to right): the Intermediary Component positioned in the middle of the brick layering composition (functions as a heat exchanger), the Culmination Component positioned at the top (functions as a heat expeller), and the Foundational Component positioned at the bottom (functions as a cooling loader)

In the context of this study, the focus is on the use of concrete interlocking blocks, particularly within the framework of the Interlocking Passive Brick Set. This innovative approach to brick design aligns with the broader trend of optimizing building materials for enhanced thermal efficiency. The Interlocking Passive Brick Set is engineered to incorporate parallel channels within the material, a feature that significantly improves heat dissipation and the airflow management within (Chaimoon et al., 2013). This design enhances the thermal performance of the brick and complements the operation of HVAC systems, contributing to a more energy-efficient building envelope.

The development of the Interlocking Passive Brick Set revisits and expands upon the basic premise of dynamic insulation. By integrating advanced principles of thermal science, this approach offers a novel solution to the challenges of heat management in modern buildings. The research draws on foundational studies by Dalehaug et al. (1993), as well as more recent advancements by Koenders et al. (2018), to create a building material that actively participates in thermal regulation. This represents a significant departure from traditional static insulation methods, positioning the Interlocking Passive Brick Set as a forward-thinking solution in the pursuit of sustainable and resilient building design.

In extending this research, it becomes clear that the implications of such advancements are far-reaching. The use of interlocking blocks offers practical benefits in terms of construction efficiency and structural resilience and contributes to the broader goal of creating buildings that are better equipped to adapt to environmental challenges. As the global climate continues to change, the need for building materials that can respond dynamically to temperature fluctuations and reduce energy consumption becomes increasingly critical (Benyahia et al., 2023). The Interlocking Passive Brick Set, with its innovative design and integration of advanced thermal management principles, offers a promising pathway towards achieving the goals.

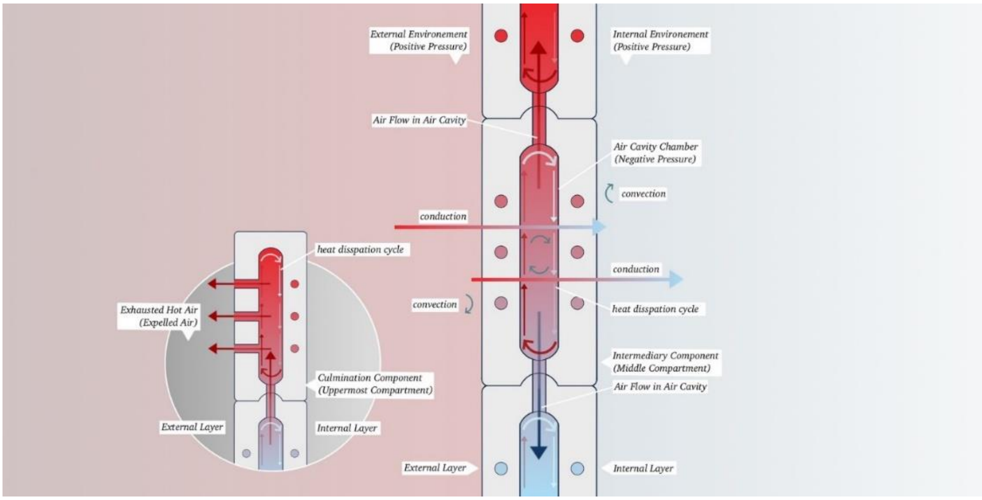


Fig. 3. The schematic of the heat transfer, heat dissipation cycle, and heat expelling process of the Interlocking Passive Brick Set. On the right side of the diagram illustrated the schlieren imaging of thermal movement in the intermediary component and on the left side illustrate the thermal movement of the culmination component

### 1.3. The outline

Before translating the results of the building envelope, particularly in the context of material design, it is imperative to evaluate the boundary conditions that influence thermal performance lied within heat transfer and radiation (Howell et al., 2020). Understanding how heat transfer occurs from the interior space to the external environment—and specifically, how it interacts with the dynamic insulation and structural components—is crucial for optimizing building efficiency (Tang et al., 2022). Central to this understanding is the role of the connecting air cavity chamber, a key element in regulating temperature and airflow within the building envelope (Zhang et al., 2023).

This evaluation determines the heat transfer rate and assesses how effectively the building can dissipate heat through airflow and convection (d’Ambrosio Alfano et al., 2021). To characterize this heat transfer, we conducted convection measurements within a custom-designed air cavity chamber (Bağcı et al., 2015). This chamber, featuring strategically placed air holes at its culmination component, plays a vital role in controlling both the temperature and airflow circulation within the building envelope (Alrwashdeh et al., 2022). By utilizing the schlieren imaging technique, we gained valuable insights into the physical interactions between natural and forced convection within the core of the structural component (Gao et al., 2022). This advanced imaging method provided a clearer understanding of the dynamics at play, revealing the complexities of heat exchange in such environments (Korobiichuk et al., 2022).

The results from these investigations are significant for several reasons. First, they elucidate why dynamic insulation systems often exhibit lower-than-expected heat recovery rates. The findings suggest that direct contact heating could be a more effective method for improving thermal management in buildings. Specifically, the interlocking passive brick set, which has been engineered to optimize heat dissipation and airflow management, demonstrates how an integrated air circuit within the bricks can regulate temperature more effectively (Field et al., 2019, Chaimoon et al., 2013). This dual functionality – as both dynamic insulation and a structural component – marks a significant advancement in building material design (Fig. 1). The implications of this research extend beyond the immediate findings of material. These findings underscore the critical importance of optimizing the design of interlocking passive bricks to enhance their performance in modern construction. By refining the integration of airflow channels and thermal properties, these bricks can contribute significantly to the overall energy efficiency of a building, especially in climates where temperature control is paramount (Alaloul et al., 2020).

Table 1. Physical parameters of the materials in test sample

| Materials | Density (kg/m$^3$) | Specific heat J/(kgK) | Thermal Conductivity (W/mK) |
|---|---|---|---|
| Aerated Concrete Block | 750 | 1000 | 0.23 |
| Brickwork (Clay) | 1700 | 800 | 0.62 |
| Concrete Block (heavy) | 2300 | 1000 | 1.63 |
| Concrete Block (medium) | 1400 | 1000 | 0.50 |
| Concrete Block (light) | 600 | 1000 | 0.19 |

The research presented here is divided into distinct sections to facilitate a comprehensive understanding of the experiments conducted. The experimental study is detailed separately in Sections 2 and 3 to ensure clarity and precision in discussing the results. Section 4 then provides a broader overview of the challenges and opportunities for future research, with a particular focus on how the findings from these experiments can be applied to real-world building construction. This section also explores the potential for further innovations in dynamic insulation and structural design, aiming to push the boundaries of what is possible in creating thermally efficient, sustainable buildings.

## 2. Interlocking passive brick set

An interlocking Passive brick is a building material used to make walls, building envelope and other elements in masonry construction. The dimension of the testing brick is 300 x 90 x 200 mm. The composition of brick is tabulated below (Fig. 2).

### 2.1. The design of the interlocking passive brick set

Each brick component features a concave semicircular indentation at the strategic locations and providing thermal insulation. Component Number 1 includes a concave semicircular indentation at its lower end, spanning the entire length, serving as both an interlocking element with underlying bricks and a thermal insulation zone as the design of the brick set incorporates thermal insulation features, enhancing its performance in this aspect (Wu et al., 2023). Additionally, semicircular cylinders with a radius of 5 mm and midsection heights of 10 mm are positioned to facilitate ventilation and connect adjacent bricks. Component Number 2 has concave semicircular indentations at both the upper and lower regions, serving a dual purpose of enhancing thermal performance and interlocking with adjacent bricks. Component Number 3 features a concave semicircular indentation at its uppermost region, spanning its entire length, which serves as an interlocking element and thermal insulation. The brick set's design includes a central airgap characterized by a symmetrical semi-circular edge airgap within the brick's structure, contributing to its functional versatility and structural attributes. The central airgap measures 30 mm in width and 150 mm in height, while the symmetrical semi-circular airgap has a radius of 15 mm and an elevation of 10 mm. Additionally, the design incorporates six small airgaps, each with a uniform radius of 5 mm, culminating in a combined surface area of 480 $mm^2$. These airgaps are strategically positioned, with a central small airgap located 10 mm from the midpoint of the expansive airgap, and upper and lower small airgaps precisely situated 30 mm from the upper and lower extremities of the semi-circular airgap.

Table 2. Theoretical calculation of the interlocking passive brick set numerical data that set as variable based as physical dimension, material density, specific heat, and thermal conductivity. To calculate the following variable in this table

| | P (kg) | λ ($Wm^{-1}K^{-1}$) | △T (K) | R (K/W) | Q (W) | Q ($W/m^2$) | H ($W/m^2 \cdot K$) |
|---|---|---|---|---|---|---|---|
| A.1 | 3.0488 | 0.0554 | 13.0435 | 1.6245 | 8.0292 | 13.3820 | 1.0260 |
| A.2 | 2.8793 | 0.0554 | 13.0435 | 1.6245 | 8.0292 | 13.3820 | 1.0260 |
| A.3 | 2.9696 | 0.0554 | 13.0435 | 1.6245 | 8.0292 | 13.3820 | 1.0260 |
| B.1 | 6.9105 | 0.0616 | 4.8387 | 1.4604 | 3.3133 | 5.5221 | 1.1412 |
| B.2 | 6.5263 | 0.0616 | 4.8387 | 1.4604 | 3.3133 | 5.5221 | 1.1412 |
| B.3 | 6.7310 | 0.0616 | 4.8387 | 1.4604 | 3.3133 | 5.5221 | 1.1412 |
| C.1 | 9.3495 | 0.0643 | 1.8405 | 1.4004 | 1.3142 | 2.1904 | 1.1901 |
| C.2 | 8.8297 | 0.0643 | 1.8405 | 1.4004 | 1.3142 | 2.1904 | 1.1901 |
| C.3 | 9.1066 | 0.0643 | 1.8405 | 1.4004 | 1.3142 | 2.1904 | 1.1901 |
| D.1 | 5.6910 | 0.0607 | 6.0000 | 1.4836 | 4.0441 | 6.7402 | 1.1234 |
| D.2 | 5.3746 | 0.0607 | 6.0000 | 1.4836 | 4.0441 | 6.7402 | 1.1234 |
| D.3 | 5.5432 | 0.0607 | 6.0000 | 1.4836 | 4.0441 | 6.7402 | 1.1234 |
| E.1 | 2.4390 | 0.0536 | 15.7895 | 1.6794 | 9.4017 | 15.6695 | 0.9924 |
| E.2 | 2.3034 | 0.0536 | 15.7895 | 1.6794 | 9.4017 | 15.6695 | 0.9924 |
| E.3 | 2.3756 | 0.0536 | 15.7895 | 1.6794 | 9.4017 | 15.6695 | 0.9924 |

### 2.2. The principle of the interlocking passive brick set

The primary configuration of the Interlocking Passive Brick Set introduces a groundbreaking approach to building design, particularly in the context of energy-efficient and sustainable construction (Ahmed and Sugini, 2021) (Xi and Cao, 2022). This system consists of a series of interlocking bricks that form an integrated network of air cavities and channels, meticulously designed to facilitate an efficient heat dissipation cycle (Sadri and Mohseni, 2023). In this cycle, warmer air is guided to rise through the channels and is expelled through small air channelings at the top compartments, while cooler air descends, creating a natural cooling effect within the space (Solovyov and Solovyov, 2020, Keven, 2023). This innovative design offers significant advantages in thermal regulation, making it a highly valuable addition to modern construction, especially in buildings equipped with mechanical ventilation and air-conditioning systems (Fig. 3). The flexibility of the Interlocking Passive Brick Set lies in its adaptability to various construction materials (Gardner et al., 2018). The effectiveness of heat control within this system is not solely dependent on the materials used but is significantly enhanced by the design of the air cavities and channels within the bricks (Ingebretsen et al., 2022). These features are key to improving both thermal resistance and thermal transmittance, which are critical factors in achieving efficient energy use within buildings (Dai et al., 2022). The incorporation of an air circuit within the bricks serves as dynamic insulation, regulating temperature by allowing controlled airflow through the building envelope (Zhang et al., 2023). This ensures that the internal temperature remains stable, even in the face of external temperature fluctuations (Cojocaru et al., 2020).

Table 3. Theoretical calculation of the interlocking passive brick set numerical data of the variable that required for additional numerical input ranging from U-value, Nusselt number, airflow, heat dissipation, etc

| | U ($W/m^2 \cdot K$) | Q' (W) | Nu | v (FPM) | $V^{\cdot}$ (CFM) | Qc (W) | Qt (W) |
|---|---|---|---|---|---|---|---|
| A.1 | 0.1969 | 0.2348 | 5.5560 | 1.8058 | 0.0163 | 10.5116 | 24.5718 |
| A.2 | 0.1969 | 0.2348 | 5.5560 | 1.8058 | 0.0163 | 10.5116 | 24.5718 |
| A.3 | 0.1969 | 0.2348 | 5.5560 | 1.8058 | 0.0163 | 10.5116 | 24.5718 |
| B.1 | 0.0873 | 0.0871 | 5.5578 | 1.0999 | 0.0099 | 4.3376 | 9.1154 |
| B.2 | 0.0873 | 0.0871 | 5.5578 | 1.0999 | 0.0099 | 4.3376 | 9.1154 |
| B.3 | 0.0873 | 0.0871 | 5.5578 | 1.0999 | 0.0099 | 4.3376 | 9.1154 |
| C.1 | 0.0354 | 0.0331 | 5.5526 | 0.6783 | 0.0061 | 1.7205 | 3.4672 |
| C.2 | 0.0354 | 0.0331 | 5.5526 | 0.6783 | 0.0061 | 1.7205 | 3.4672 |
| C.3 | 0.0354 | 0.0331 | 5.5526 | 0.6783 | 0.0061 | 1.7205 | 3.4672 |
| D.1 | 0.1056 | 0.1080 | 5.5537 | 1.2247 | 0.0110 | 5.2944 | 11.3030 |
| D.2 | 0.1056 | 0.1080 | 5.5537 | 1.2247 | 0.0110 | 5.2944 | 11.3030 |
| D.3 | 0.1056 | 0.1080 | 5.5537 | 1.2247 | 0.0110 | 5.2944 | 11.3030 |
| E.1 | 0.2246 | 0.2842 | 5.5545 | 1.9868 | 0.0179 | 12.3084 | 29.7449 |
| E.2 | 0.2246 | 0.2842 | 5.5545 | 1.9868 | 0.0179 | 12.3084 | 29.7449 |
| E.3 | 0.2246 | 0.2842 | 5.5545 | 1.9868 | 0.0179 | 12.3084 | 29.7449 |

Furthermore, the integration of these bricks into the building's structural framework improves thermal efficiency and yet supports the overall integrity of the construction. The interlocking mechanism is designed to ensure a precise and secure fit between the bricks, minimizing the need for additional adhesives or fasteners, which could potentially compromise the thermal insulation properties (Chaib and Kriker, 2022). This tight interlocking system enhances the durability and energy efficiency of the building, offering a practical solution to some of the challenges posed by traditional insulation methods.

The Interlocking Passive Brick Set also addresses several common issues associated with conventional insulation techniques. Traditional insulation often struggles with effectively counteracting exterior heat, particularly in regions with extreme temperatures (Ahmed and Sugini, 2021). By optimizing the design of the parallel channels within the bricks, this system ensures that heat transfer is managed with high efficiency (Chaimoon et al., 2013). Recent studies have validated this approach, demonstrating that the strategic design of these channels significantly enhances the building's overall thermal performance (Delouei et al., 2022). Additionally, the system incorporates features specifically aimed at controlling convection and airflow, which are crucial for maintaining an efficient heat cycle within the building.

# 3. Experiment: theoretical calculation of thermal properties on interlocking passive brick set

Before the Interlocking Passive Brick Set can perform its intended functions, the material must first absorb heat on one surface. The significance and complexity of this initial stage appear to have been underestimated in the dynamic insulation literature, as demonstrated by the experiment reported in this section.

## 3.1. Thermal dynamic process

The heat transfer processes within the Interlocking Passive Brick Set involve conductive heat transfer, convective heat transfer, external heat transfer, and enthalpy flow in the ventilated cavity (Verma and Singh, 2022), as shown in Fig. 3. Heat conduction occurs in both the internal and external structures. Convective heat exchange exists between all solid surfaces and the adjacent air (Gizzatullina et al., 2021). The heat exchange takes place in the air cavity between the exterior surface of the internal structure and the interior surface of the external structure. Relevant simplifications and assumptions are adopted as follows:

1) Heat conduction along the vertical direction (y direction) is neglected in both the internal layer and external structure, and the conductive heat flux is assumed to occur only in the horizontal direction (x direction) (Woodbury et al., 2023).
2) The air flow path in the air cavity chamber is considered two-dimensional (along the vertical and cyclical directions), and the variation of air humidity during the air and heat exchange process is neglected. Since the outward exhaust airflow is warmed when passing through the interlocking Passive brick, no condensation is expected to occur.
3) The thermal properties of all solid materials are assumed to be constant, and the materials are considered homogeneous and isotropic (Zhang et al., 2022).

## 3.2. Numerical model for theoretical thermal calculation

With the information provided in Table 1, variables are set based on physical dimensions, material density, specific heat, and thermal conductivity (Wang et al., 2022). For this calculation, we will focus on the middle section of the brick set, consisting of three types of components in the following sequence: first culmination component, intermediary component, and foundational component. The objective is to determine the airflow and heat dissipation that occurs within the air cavity chamber and the overall thermal transmittance to demonstrate the insulating ability of the brick (Qin et al., 2023). The following steps will be used to calculate all variables:

Firstly, calculate thermal resistance of the material on the outer layer which can be written as eq. (1):

$$R_1 = \frac{d_1}{\lambda_1} \tag{1}$$

where $R_1$ is the thermal resistance of the solid material, W/K; $d_1$ is the density of the solid material, kg/m^3; $\lambda_1$ is the thermal conductivity of the solid material; W/m·K.

Calculate thermal resistance of the material on the outer layer, which can be written as eq. (2):

$$R_2 = \frac{d_2}{\lambda_2} \tag{2}$$

where $R_2$ is the thermal resistance of the air, W/K; $d_2$ is the density of the air, kg/m$^3$; $\lambda_2$ is the thermal conductivity of the air; W/m·K.

Determines the total thermal resistance, which can be written as eq. (3):

$$R_{total} = R_1 + R_2 + R_1 \tag{3}$$

where $R_{total}$ is the total thermal resistance of the Interlocking Passive brick, W/K; $R_1$ is the thermal resistance of the solid material, W/K; $R_2$ is the thermal resistance of the air, W/K.

Calculate the overall thermal conductivity, which can be written as eq. (4):

$$\lambda_{total} = \frac{d_{total}}{R_{total}} \tag{4}$$

where $\lambda_{total}$ is the total thermal conductivity of the interlocking Passive brick; W/m·K. $d_{total}$ is the total density of the Interlocking Passive brick, kg/m$^3$; $R_{total}$ is the total thermal resistance of the Interlocking passive brick, W/K;

Use Fourier's Law of Heat Conduction which can be written as eq. (5):

$$Q = \frac{\triangle T}{R} \tag{5}$$

where Q is the heat transfer rate, W; $\triangle T$ is the difference of temperature between 2 opposite surfaces of the Interlocking Passive Brick, K; R is the thermal resistance of the Interlocking Passive brick, W/K;

Rearrange to solve for temperature difference which can be written as eq. (6):

$$\triangle T = Q \times R \tag{6}$$

where $\triangle T$ is the difference of temperature between 2 opposite surfaces of the Interlocking passive brick, K; Q is the heat transfer rate, W; R is the thermal resistance of the Interlocking passive brick, W/K.

Find temperature on the other side of the brick which can be written as eq. (7):

$$T_2 = T_1 - \triangle T \tag{7}$$

where $T_2$ is the temperature on the exterior surface of the Interlocking passive brick, K; $T_1$ is the temperature on the interior surface of the Interlocking Passive brick, K; $\triangle T$ is the difference of temperature between 2 opposite surfaces of the Interlocking Passive brick, K.

Calculate heat flux which can be written as eq. (8):

$$q = \frac{Q}{A} \tag{8}$$

where q is heating flux, W/m$^2$; Q is the heat transfer rate, W; A is cross sectional area of the interlocking Passive brick, m$^2$.

Find heat transfer coefficient of the component which can be written as eq. (9):

$$h = \frac{q}{\triangle T} \tag{9}$$

where h is heat transfer coefficient, W/m$^2$·K; q is heating flux, W/m$^2$; $\triangle T$ is the difference of temperature between 2 opposite surfaces of the Interlocking passive brick, K.

Assuming that one side of the brick is subjected to a higher temperature due to sunlight or an external heat source, we do not consider the radiant temperature. Instead, we assume the surface temperature (T1) on the external layer to be 313.15 K, reflecting the average temperature of concrete-based materials in an equatorial climate.

The results of the calculations to find these variables are presented in Table 2, ranging from left to right: density per unit, overall thermal conductivity, temperature difference between the two sides of the brick, total thermal resistance, heat transfer, heat flux, and heat transfer coefficient. With the provided information, we can further calculate the thermal transmittance using the following eq. (10):

$$U = \frac{1}{R_{total}} \tag{10}$$

where U is the U-value as known as Thermal transmittance, W/m$^2$·K; $R_{total}$ is the total thermal resistance of the Interlocking Passive brick, W/K.

Where heat dissipation occurs within the air cavity chamber, the variable we seek is $Q'$ (heat transfer rate). Although we have $Q$ in Fourier's law of heat conduction, which has been applied to the temperature difference, $Q$ =100 W is used for a constant heat transfer rate of air. To find heat dissipation rate is defined as:

$$Q' = hA \triangle T \tag{11}$$

where $Q'$ is the heat dissipation rate within the air cavity chamber, W; h is the heat transfer coefficient, W/m$^2$·K; A is cross sectional area of the interlocking passive brick, m$^2$; △T is the difference of temperature between 2 opposite surfaces of the Interlocking passive brick, K, and the local convective heat transfer coefficient is normalized to limit of pure conduction, giving the local Nusselt number:

$$Nu = \frac{hL}{\lambda} \tag{12}$$

where $Nu$ is Nusselt number the ratio of total heat transfer to conductive heat transfer at a boundary in air cavity chamber; h is heat transfer coefficient, W/m$^2$·K; Characteristic length, m; λ is the thermal conductivity of the Interlocking passive brick; W/m·K.

Heat exchange and disputation correlated to the movement of the air that occur within the brick. So, to calibrate airflow rate, define the average air velocity and C and n are empirical constants in this C ≈ 0.5 and n ≈ 0.25 for small temperature differences). is defined as:

$$v = C \cdot (\triangle T)^n \tag{13}$$

where $v$ is the air velocity, feet per minute; $C$ is Constant on fluid properties, m/s·K$^{-0.5}$; △T is the difference of temperature between 2 opposite surfaces of the interlocking passive brick, K.

With air velocity provided, the air flow rate of the air cavity chamber and air channelings on culmination component can be estimated using the following formula based on natural convection:

$$V^{\cdot} = A \cdot v \tag{14}$$

where $V^{\cdot}$ is the air flow rate, cubic feet per minute; A is cross sectional area of the interlocking passive brick, $m^2$; $v$ is the air velocity, feet per minute.

Lastly finding the heat transfer that occur on the culmination component and the air cavity chamber, and since the flow is equally distributed among the upmost 6 air channels, the total heat transfer rate is already calculated for the entire system.

$$Q_{c/t} = m^{\cdot} \cdot cp \cdot \triangle T \tag{15}$$

where $Q_{c/t}$ is Heat transfer rate at air channel and air cavity chamber, W; $m^{\cdot}$ is Mass flow rate, $kg/m^3$; $cp$ is Specific heat of the material, J/(kg·K); $\triangle T$ is the difference of temperature between 2 opposite surfaces of the Interlocking passive brick, K.

The value provided for mass flow rate of an air which is 1.2 $kg/m^3$ combined with the volumetric of air within the air cavity chamber. This calculation assumes for a uniform temperature difference and equal distribution of air flow among the channels.

## 4. Result

The understanding of the material and component should be read in conjunction with Table 1 and section 2, which given set of variable information such as physical dimension, material density, specific heat, and thermal conductivity. The measurement we used to find the value of variable based on the x-axis section of the brick.

### 4.1. Thermal properties analysis

The significance of the U-values within the Interlocking Passive Brick Set cannot be overstated, as they provide critical insight into the insulation properties of each component. The U-values, which range from 0.0354 to 0.2246 $W/m^2 \cdot K$, indicate varying levels of thermal insulation among the different components. Component C, with the lowest U-value of 0.0354 $W/m^2 \cdot K$, demonstrates superior insulation capabilities, effectively minimizing heat transfer through the material. Conversely, Component E, with the highest U-value of 0.2246 $W/m^2 \cdot K$, shows a relatively lower level of insulation, allowing more heat to pass through. This range in thermal transmittance is not just a statistical observation but a strategic element in the design of the building envelope. By carefully selecting and placing components with specific U-values, it is possible to optimize the overall thermal performance of a structure, balancing insulation needs with other design considerations such as structural integrity and cost.

In parallel, the calculated airflow rates within the brick's cavity, which range from 0.0061 to 0.0179 CFM, are of particular interest in the context of dynamic insulation. Although these airflow rates might appear modest compared to open environmental conditions, they are significant when considering the brick's dual role in thermal regulation and structural support. The presence of controlled air movement within the brick's cavity is indicative of its potential for passive cooling and heat dissipation, key functions in reducing the building's reliance on active HVAC systems. This airflow not only contributes to the cooling process but also enhances the overall energy efficiency of the building by facilitating the removal of heat from the building envelope.

The heat dissipation values, which range from 1.7205 W for Component C to 12.3084 W for Component E, further highlight the varied thermal management capabilities of the Interlocking Passive Brick Set. The correlation between higher heat dissipation and increased airflow rate within the brick underscores the importance of design in enhancing the thermal performance of building materials. This relationship suggests that by increasing air movement within the brick's channels, it is possible to significantly improve the brick's ability to remove heat from the building envelope, thereby contributing to a cooler and more comfortable indoor environment. The design principle of the brick, which integrates these thermal and airflow dynamics, offers a novel approach to building envelope design that could lead to more energy-efficient and climate-responsive structures (Fig. 3).

### 4.2. Component performance analysis

1) Component C exhibits the best insulation properties (lowest U-value) but the lowest heat dissipation and airflow. This suggests its suitability for areas requiring high thermal resistance.
2) Component E, with the highest U-value, airflow, and heat dissipation, may be most effective in areas where enhanced heat removal is desired.
3) Components A, B, and D are offering intermediate performance, providing flexibility in design and placement to balance insulation and heat dissipation needs.

### 4.3. Discussion

The concept of dynamic insulation, as demonstrated by the Interlocking Passive Brick Set, represents a significant evolution in how thermal dynamics are managed within buildings. Traditional insulation methods, which have historically relied on static barriers to prevent heat flow, are being increasingly challenged by adaptive and responsive systems (Fawaier and Bokor, 2022). The Interlocking Passive Brick Set exemplifies this new approach, where the building envelope itself becomes an active participant in regulating temperature, rather than merely functioning as a passive thermal barrier. This shift toward dynamic insulation aligns with sustainable design trends and raises important questions about the future of building technology and its integration with the surrounding environment.

Dynamic insulation systems like the Interlocking Passive Brick Set are designed to respond to environmental changes in real-time, offering a solution to the challenges of energy efficiency and thermal comfort in buildings. As global emphasis on sustainability grows, so too does the demand for adaptive systems that can optimize energy performance under varying climate conditions. The Interlocking Passive Brick Set serves as both an insulating material and a dynamic thermal regulator, adjusting its heat retention and dissipation properties depending on environmental factors.

The U-values of the Interlocking Passive Brick Set components, which range from 0.0354 to 0.2246 $W/m^2 \cdot K$, provide critical insights into the system’s dual capability as both a static and dynamic thermal barrier. For instance, Component C, with a U-value of 0.0354 $W/m^2 \cdot K$, demonstrates strong insulation performance, aligning with global trends in sustainable architecture that emphasize minimizing heat loss in colder climates or reducing heat ingress in hotter climates. In contrast, Component E, which exhibits higher heat dissipation (12.3084 W) and airflow (0.0179 CFM) but a higher U-value (0.2246 $W/m^2 \cdot K$), highlights a balanced approach between insulation and active heat removal in hot environments.

One of the most significant implications of dynamic insulation is its potential to reduce dependency on energy-intensive HVAC systems (Fawaier and Bokor, 2022). HVAC systems are responsible for a substantial proportion of building energy consumption, particularly in climates with extreme temperatures (Olu-Ajayi et al., 2023). The calculated heat dissipation rates and airflow within the Interlocking Passive Brick Set cavities suggest that this system can contribute to passive cooling and ventilation (Zhu et al., 2023). This would not only improve thermal comfort but also offer a sustainable solution to the growing energy demands of modern buildings (Bangsbo, 2019). By reducing the load on HVAC systems, the Interlocking Passive Brick Set could significantly lower the overall energy consumption of buildings, making it a crucial component in the global effort to reduce carbon emissions and energy costs.

The integration of passive and active systems is a key trend in sustainable building design, where reducing overall energy consumption is prioritized. The Interlocking Passive Brick Set provides a novel approach by leveraging heat dissipation and controlled airflow within its cavities to alleviate the pressure on HVAC systems (Budiyani and Prastyatama, 2020). This is particularly pertinent as global temperatures continue to rise, necessitating building designs that are more energy-efficient and adaptable to environmental fluctuations.

The adaptability of the Interlocking Passive Brick Set to different climate conditions is another critical aspect of its design. The system's U-value range (0.0354 to 0.2246 $W/m^2 \cdot K$), airflow, and heat dissipation characteristics allow it to be customized for various environmental needs. In hot climates, components with higher heat dissipation and airflow rates, such as Component E, can be prioritized to reduce cooling loads. Conversely, in colder climates, components with lower U-values, such as Component C, can be utilized to retain heat while still allowing for some degree of passive heat dissipation. This flexibility ensures that the Interlocking Passive Brick Set is aligned with current global trends toward climate-responsive and resilient building designs, especially in regions experiencing increased temperature variability.

From a material science perspective, the Interlocking Passive Brick Set represents a significant innovation in sustainable building materials. The system's dynamic insulation properties, combined with its structural capabilities, reflect broader efforts in the research community to develop multi-functional materials that reduce energy use while improving building performance. The variation in U-values across the Interlocking Passive Brick Set components is a direct result of careful material selection and design, aimed at optimizing thermal performance in a sustainable manner. Furthermore, the heat dissipation and airflow properties of the Interlocking Passive Brick Set suggest that it could reduce the need for additional systems such as external fans or supplementary insulation layers, further enhancing its sustainability.

Beyond energy efficiency, the integration of dynamic insulation systems like the Interlocking Passive Brick Set into building envelopes could lead to the development of more responsive and resilient structures (Garriga et al., 2020). As buildings become more attuned to environmental conditions, they are better equipped to maintain stable indoor environments with reduced energy input (Liu et al., 2023). This capability is particularly valuable in regions facing the dual challenges of rising temperatures and energy scarcity, where the need for sustainable and climate-resilient building technologies is critical (Mosadeghrad et al., 2023).

The Interlocking Passive Brick Set thus represents a significant opportunity for innovation in both material science and sustainable building technology. By incorporating adaptive thermal management systems into the core structure of buildings, the Interlocking

Passive Brick Set sets a new standard for energy-efficient, resilient, and sustainable architecture (Li et al., 2021). The implications of this approach extend beyond immediate energy savings to include broader impacts on the design and construction of future buildings, particularly in the context of global climate change (Holsman, 2023). The development and implementation of dynamic insulation systems such as the Interlocking Passive Brick Set could transform the building industry, making it more responsive to environmental conditions and less reliant on energy-intensive systems (Setaki and van Timmeren, 2022).

## 5. Conclusion

The heat dissipation capabilities of the Interlocking Passive Brick Set offer compelling possibilities for integration with active HVAC systems, illustrating a synergistic relationship between passive and active thermal management strategies (Peng et al., 2023). For instance, during cooling cycles, the brick's air cavities could serve as a pre-cooling pathway for the HVAC system. By lowering the temperature of incoming air before it enters the active cooling mechanism, this pre-cooling process could reduce the energy load on the HVAC system, enhancing overall efficiency. Conversely, in heating scenarios, the same air cavity system could be leveraged to improve the distribution and retention of heat throughout the building, thereby optimizing thermal comfort with minimal energy expenditure.

This dual functionality underscores the concept of dynamic insulation, a key innovation demonstrated by the Interlocking Passive Brick Set. Unlike traditional building envelopes, which function as static barriers to heat flow, this system reimagines the building envelope as an active participant in thermal regulation. This shift is in line with broader trends in sustainable architecture that emphasize working with, rather than against, natural thermal processes. The Interlocking Passive Brick Set thus represents a convergence of material science, building technology, and environmental design principles, paving the way for more resilient and adaptable buildings.

However, it is crucial to recognize that the effectiveness of this dynamic insulation and heat dissipation system is likely to vary based on several factors, including climate, building design, and usage patterns. In hot, humid climates, the system's heat dissipation properties could be particularly advantageous, potentially reducing cooling loads and, consequently, the energy demand of the building (Peng et al., 2023). In contrast, in colder climates, the system’s ability to provide effective insulation while still allowing for controlled heat dissipation could help maintain indoor comfort without excessive reliance on heating systems. This flexibility suggests that the Interlocking Passive Brick Set could be tailored to meet the specific needs of diverse climatic regions, making it a versatile tool in the pursuit of sustainable building design.

The theoretical findings from this research indicate that the Interlocking Passive Brick Set has the potential to significantly transform approaches to building insulation and thermal management (Chaimoon et al., 2013). By offering a system that provides variable insulation properties and actively participates in heat dissipation, this innovation could redefine the role of the building envelope. Such a system is not merely reactive but rather anticipates and responds to environmental conditions, aligning with the principles of adaptive architecture (Chaimoon et al., 2013).

This innovative approach could lead to the development of more energy-efficient buildings that are better equipped to adapt to changing environmental conditions and the evolving needs of occupants (Yin et al., 2023). As the global climate continues to change, and as the demand for energy-efficient and resilient buildings grows, the Interlocking Passive Brick Set could play a crucial role in shaping the future of building design (Ahmed and

Sugini, 2021). Further research and development in this area could unlock new possibilities for integrating dynamic insulation systems into a wide range of building types, enhancing their thermal performance and sustainability (Firrdhaus Mohd-Sahabuddin et al., 2023).

Thermal comfort studies suggests that this innovation could serve as a foundation for future advancements in building technology (Fard et al., 2021). For example, integrating smart sensors and controls could enhance the responsiveness of the Interlocking Passive Brick Set, allowing it to adjust its thermal properties in real-time based on environmental conditions (Pereira et al., 2023). This could further reduce energy consumption and improve indoor environmental quality, making buildings and more efficient also more comfortable and healthier for occupants.

To conclude, the Interlocking Passive Brick Set represents a significant step forward in the evolution of building envelopes. Its potential to reduce reliance on active HVAC systems, improve thermal efficiency, and adapt to various environmental conditions makes it a promising candidate for future research and application in sustainable building practices. As the construction industry continues to seek innovative solutions to the challenges posed by climate change and resource constraints, dynamic insulation systems like the Interlocking Passive Brick Set will be essential in creating the next generation of energy-efficient, resilient, and adaptive buildings.

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