


THE EFFECT OF THE PHYSICAL CHARACTERISTICS OF ATRIUMS ON THE NATURAL VENTILATION OF BUILDINGS

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ABSTRACT: This study explores the impact of atrium designs on natural ventilation and energy efficiency in buildings, focusing on three distinct types of atriums: vertical atriums promoting stack effects, horizontal atriums facilitating cross ventilation, and atriums with varying glazing areas and materials. Each atrium type was examined through the lens of geometry and size, orientation, material specifications, and internal configuration to determine how these factors influence their effectiveness in enhancing natural ventilation and optimizing energy performance. The methodology adopted a comparative analytical approach, leveraging both theoretical and empirical assessments. Computational Fluid Dynamics (CFD) simulations and architectural modeling were utilized to measure airflow patterns, temperature gradients, and ventilation rates across different atrium configurations. This quantitative analysis was complemented by a qualitative assessment of material impacts and spatial arrangements within the atriums. Results indicate that the physical characteristics of an atrium significantly affect its ventilation efficiency and thermal behavior. Vertical atriums, with their tall structures, were found to effectively utilize the stack effect, particularly when combined with high thermal mass materials such as concrete and brick. These materials help stabilize temperature fluctuations, enhancing the natural cooling and ventilation processes. Horizontal atriums, aligned perpendicular to prevailing winds, maximize cross ventilation, which is further optimized by using low thermal mass materials like wood and gypsum that respond quickly to temperature changes. Atriums with extensive glazing areas benefit from advanced glazing materials that manage solar gain and maximize natural light, thus improving overall energy efficiency. This research provides actionable insights into atrium design, emphasizing the importance of tailored architectural strategies to leverage natural environmental forces. It contributes to the field of sustainable architecture by offering a comprehensive framework that can guide the design of atriums to achieve optimal ventilation and energy performance in various climatic conditions.

KEYWORDS: Atrium Design; Natural Ventilation; Energy Efficiency; Sustainable Architecture; Thermal Behavior; Computational Fluid Dynamics (CFD).

INTRODUCTION

Atriums, historically central to architectural beauty and utility, have evolved in their application, particularly in enhancing building sustainability through natural ventilation. This research delves into how the physical characteristics of atriums influence natural ventilation, a pivotal element in sustainable building design. Given rising global concerns about energy efficiency and environmental sustainability, this study seeks to dissect the interplay between atrium design and natural ventilation efficacy, addressing significant gaps in the current understanding and application within modern architecture.

In the context of architectural design, atriums serve multiple purposes, from enhancing aesthetic appeal to improving air quality and reducing energy consumption through natural ventilation mechanisms. However, the exact impact of various atrium designs on natural ventilation remains poorly

understood and inconsistently documented. This uncertainty presents a compelling challenge, as optimizing atrium design could lead to significant improvements in building sustainability [1, 2]. Research on atriums has primarily focused on their ability to enhance light and space within buildings. Yet, the specific atrium characteristics that optimize natural ventilation—such as dimensions, shapes, orientation, and glazing—are not fully defined, leading to potential inefficiencies in both design and environmental impact. The literature reveals a significant variation in recommendations for atrium design, reflecting a lack of consensus and a clear understanding of the dynamics at play [3, 4].

This study will focus on several key variables affecting natural ventilation in atriums:

- Atrium Geometry: The impact of atrium height, width, and shape on air flow and ventilation efficiency.

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- **Material Usage:** How different building materials used in atrium construction affect thermal properties and air movement [2].

- **External Influences:** Building orientation, external wind patterns, and solar exposure.

- **Internal Configurations:** The arrangement of openings, internal partitions, and the inclusion of natural elements like plants and water features [5].

The primary aim of this research is to delineate how atrium design influences natural ventilation, with the goal of formulating guidelines that optimize these designs for better ventilation and reduced energy consumption. Specific objectives include:

- Analyzing the impact of various atrium designs on natural air flow.

- Developing design principles for atriums that enhance natural ventilation.

- Assessing the implications of atrium design on overall building energy efficiency and occupant comfort.

Despite the recognized importance of atriums in modern architecture, detailed studies on their specific impact on natural ventilation are scarce. Existing studies tend to focus on broad thermal comfort or energy efficiency without isolating the unique contributions of atrium designs [6, 7]. Furthermore, there is a notable disparity in findings, particularly regarding the optimal configurations for promoting effective air circulation and reducing reliance on mechanical ventilation systems.

The importance of atriums in contemporary architecture, particularly concerning their role in enhancing natural ventilation, is a well-documented yet underexplored facet of sustainable design. The following review highlights significant studies that have shaped our current understanding, alongside identifying the persistent gaps that this research aims to address.

Atrium geometry and air flow: Research indicates that atrium geometry significantly impacts natural ventilation effectiveness. Moosavi et al. [4] provide a comprehensive review of natural ventilation strategies in atrium designs, discussing the implications of atrium shapes and sizes. However, the study primarily synthesizes existing data rather than offering new empirical insights, suggesting a need for more focused design-specific research.

Material and construction influence: Albuquerque et al. [2] illustrate how materials used in atrium construction affect the thermal and ventilation performance of atriums. Their study, focusing on thermal comfort through nighttime

natural ventilation, points to the potential of integrating adaptive materials to enhance atrium functionality. Despite these insights, detailed analysis on the interplay between material properties and specific atrium designs remains sparse.

Impact of internal and external factors: Zhao et al. [5] discuss how external factors like wind and solar orientations and internal factors such as building layout and open spaces influence atrium ventilation. Their findings underscore the importance of strategic design and placement of atriums within the building architecture to optimize natural ventilation.

Despite these contributions, several critical areas remain underexplored:

1. Empirical validation of atrium Configurations: While theoretical models and simulations are prevalent (e.g., Wang et al. [7]), empirical studies validating these models against actual atrium performance are rare. This gap highlights the need for field data to substantiate simulation outputs and refine predictive models.

2. Interdisciplinary approaches to atrium design: Most studies focus on specific aspects of atrium design—either thermal comfort, energy efficiency, or air quality—without integrating these dimensions into a holistic design strategy. Interdisciplinary studies that consider all aspects of sustainability in atrium design are notably lacking.

3. Customization to climatic variations: The interaction between atrium design and local climatic conditions is insufficiently addressed in existing literature. Studies such as those by Yunus et al. [8] touch on tropical conditions but do not extend these findings to other climate zones, suggesting a broader geographic analysis could yield useful design adaptations.

4. Longitudinal and comparative studies: Long-term studies assessing the performance of atriums over different seasons and under varying climatic conditions are virtually non-existent. Such studies would provide deeper insights into the adaptive capabilities of atrium designs across temporal variations.

Building on these gaps, this research aims to conduct a detailed empirical and simulation-based study to evaluate how specific atrium designs function across different climatic conditions. By employing a comparative analysis of multiple atrium configurations, this study will provide a nuanced understanding of optimal design strategies that

promote natural ventilation effectively and efficiently. Theoretically, this research aims to expand the architectural knowledge base by exploring the functional impacts of atrium designs specifically on natural ventilation. Practically, it intends to provide architects and urban planners with empirically backed design strategies that enhance environmental sustainability and occupant comfort, promoting broader adoption of energy-efficient designs across the industry.

To address the research questions, this study will utilize computational fluid dynamics (CFD) simulations to model airflow across various atrium configurations, supplemented by empirical data from field measurements within existing buildings that feature atriums. This mixed-method approach will allow for a detailed examination of theoretical models against real-world applications, enhancing the robustness and applicability of the findings [9].

By addressing the critical gaps in knowledge regarding atrium design and natural ventilation, this study is poised to make significant contributions to both the field of architecture and environmental

design. The outcomes are expected to influence future design practices, leading to more sustainable building environments that align with global energy efficiency and sustainability targets.

Effective physical factors

Physical factors affecting atrium design play a crucial role in determining the effectiveness of these spaces in terms of natural ventilation, energy efficiency, and overall environmental comfort. By considering these physical factors in the design and implementation of atriums, architects and designers can optimize these spaces to enhance both the functionality and sustainability of buildings. Each factor contributes to a holistic approach to building design, where the atrium is not just a feature of aesthetic value but a crucial component of the building's environmental strategy. Here's an exploration of each key factor. Table 1 summarizing the factors affecting atriums, detailing their roles, sub-components, a case example, and the respective source for each:

Table 1. The factors affecting atriums

Effective factor	Role in atrium design	Sub-components	Case example	Source
Geometry and size	Influences air movement and light penetration.	Height, Width, Aspect Ratio	Atrium of the Seattle Central Library which uses vertical space to enhance the stack effect.	Moosavi et al. [4]
Orientation and positioning	Affects solar gain and exposure to prevailing winds.	Orientation to sun, Exposure to wind	The Crystal in London positioned to maximize solar gain while minimizing overheating.	Zhao et al. [5]
Glazing and openings	Modulates light entry and thermal performance.	Type of glazing, Size and location of openings	The Eden Project in the UK uses ETFE foil cushions allowing high light transmittance and insulation.	Albuquerque et al. [2]
Material properties	Impacts thermal mass and stability.	Thermal mass, Reflectivity	The Gare do Oriente in Lisbon utilizes high thermal mass materials for temperature regulation.	Omran et al. [6]
Internal configuration	Affects airflow patterns and enhances thermal comfort.	Placement of plants, water features, furnishings	The Ford Foundation Building in New York integrates plants and water for evaporative cooling.	Wang et al., 2021
Interaction with building systems	Integrates with HVAC to enhance efficiency.	HVAC integration, Passive design strategies	The Manitoba Hydro Place in Winnipeg integrates atriums with mechanical systems for optimal energy use.	Zhao et al. [5]
Environmental exposure	Dictates design strategies based on local climate conditions.	Urban morphology, Climate considerations	The Commerzbank Tower in Frankfurt features atriums designed considering the local wind patterns and urban layout.	Moosavi et al. [4]

1) Geometry and size

The shape and size of an atrium directly influence its ability to facilitate natural ventilation

and light penetration. A taller atrium can enhance the stack effect, where warmer air rises and exits through upper openings, drawing cooler air in from

lower levels [6]. Conversely, a wider atrium can improve cross-ventilation by allowing more lateral movement of air across the space. The aspect ratio

(height to width) of the atrium is particularly critical, as it determines the balance between these two types of air movement.



Figure 1. Atrium of the Seattle Central Library which uses vertical space to enhance the stack effect (<https://en.wikiarquitectura.com/building/seattle-public-library>, 2024)

2) Orientation and positioning

The orientation of an atrium affects its solar gain and exposure to prevailing winds, which are vital for passive solar heating and natural cooling, respectively. An atrium positioned to take advantage of prevailing winds can significantly enhance natural

ventilation, while its orientation towards the sun can be optimized to maximize or minimize solar heat gain depending on the climate [5]. South-facing atriums in the Northern Hemisphere, for example, can capture more winter sunlight, reducing heating demands.



Figure 2. The crystal in London positioned to maximize solar gain while minimizing overheating (Archdaily, 2024).

3) Glazing and openings

The type, placement, and amount of glazing in an atrium affect both light entry and thermal performance. Large glazed areas can lead to high solar gains, which might be beneficial in colder climates but detrimental in warmer ones. The use of advanced glazing materials and dynamic shading

systems can help modulate this solar gain to maintain comfortable temperatures and reduce reliance on mechanical ventilation and air conditioning [2]. Additionally, the size and location of openings such as windows and vents are crucial for optimizing natural ventilation by facilitating efficient airflow paths.



Figure 3. The Eden Project in the UK uses ETFE foil cushions allowing high light transmittance and insulation (Archdaily, 2024).

4) Material properties

The materials used in atrium construction impact its thermal mass, which in turn affects the atrium's thermal stability. High thermal mass materials can absorb and store heat during the day and release it slowly overnight, helping to stabilize

temperature fluctuations and reduce peak heating or cooling loads. Reflective materials, on the other hand, can reduce unwanted solar heat gain, helping keep the atrium cool in sunnier climates [4].



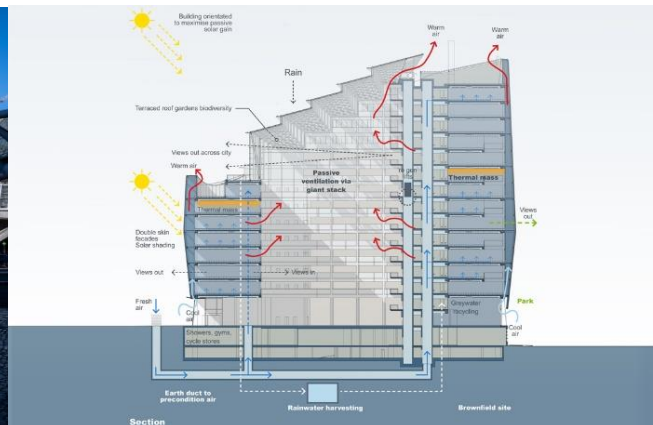
Figure 4. The Gare do Oriente in Lisbon utilizes high thermal mass materials for temperature regulation.

5) Internal configuration

The layout and configuration of the atrium space, including the placement of interior elements such as plants, water features, and furnishings, can also influence airflow patterns and thermal comfort. Vegetation, for example, can improve air quality and humidity levels, contributing to thermal comfort. Water features can provide evaporative cooling, which is especially beneficial in arid environments [7].

6) Interaction with building systems

An atrium's integration with other building systems like heating, ventilation, and air conditioning (HVAC) systems impacts its environmental performance. Properly designed, an atrium can reduce the load on these systems by



providing passive heating, cooling, and ventilation. However, if not well-integrated, it can lead to increased energy consumption due to heat loss or gain through the atrium space.

7) Environmental exposure

External environmental factors such as local climate, seasonal variations, and surrounding urban morphology also affect atrium performance. For instance, in a densely built area, wind patterns may be disrupted, reducing the potential for natural ventilation. Climate considerations dictate the design strategies for both thermal comfort and energy efficiency, necessitating a tailored approach based on local environmental conditions.

METHODOLOGY

This study adopts a structured approach to examine the influence of atrium physical characteristics on natural ventilation within buildings, specifically focusing on bureaucratic buildings in Tehran's climate. The methodology integrates a comparative analysis of three distinct atrium configurations, each selected to represent a different interaction with natural ventilation processes:

- **Vertical atriums promoting stack effects:** These atriums leverage vertical design to enhance natural ventilation through the stack effect, where warmer air rises and exits, drawing cooler air from lower levels.

- **Horizontal atriums facilitating cross ventilation:** This form utilizes a broader, more horizontal layout to maximize the movement of air across the atrium, capitalizing on cross ventilation techniques.

- **Atriums with varying glazing areas and materials:** These atriums are analyzed for their ability to manage solar gain and light penetration, which significantly affect internal temperature gradients and air movement patterns.

The evaluation of each atrium type is based on a set of predefined effective factors that influence natural ventilation:

- **Geometry and size:** Assessing how the dimensions and overall shape of the atrium impact air flow and ventilation efficiency.

- **Orientation:** Examining the alignment of the atrium with respect to prevalent wind directions and solar paths to understand its influence on natural ventilation and light access.

- **Material specifications:** Investigating the materials used in atrium construction, focusing on their thermal properties and how they affect the building's overall energy performance.

- **Internal configuration:** Evaluating the layout and arrangement of internal elements such as plants, water features, furniture, and partitions, which can alter airflow patterns and influence ventilation effectiveness.

To conduct this analysis, each atrium configuration is modeled and simulated using advanced Computational Fluid Dynamics (CFD) software. The simulations are designed to replicate

typical environmental conditions in Tehran, providing a realistic scenario for assessing the performance of each atrium type. Airflow patterns, temperature gradients, and ventilation rates are closely monitored and recorded. Following data collection through simulation, the results are compiled and compared across the three atrium types. This comparative analysis helps to elucidate the relative effectiveness of each atrium design in promoting natural ventilation under the specific climatic conditions of Tehran. The findings from this study aim to provide actionable insights into the optimal design of atriums for enhancing natural ventilation in bureaucratic buildings, contributing to more sustainable architectural practices in urban settings.

RESULTS

To conduct an in-depth analysis of the impact of atrium geometry and size on natural ventilation, we will evaluate three distinct atrium designs, each chosen to represent different architectural approaches:

1. Vertical Atriums Promoting Stack Effects
2. Horizontal Atriums Facilitating Cross Ventilation
3. Atriums with Varying Glazing Areas and Materials

1) Geometry and size

The geometry and size of an atrium significantly influence its ability to facilitate natural ventilation. Vertical atriums are effective in promoting stack effects due to their height, while horizontal atriums enhance cross ventilation due to their expansive width. Atriums with varying glazing areas utilize their adaptive geometries to balance light penetration with thermal comfort, affecting air movement patterns. Each design requires careful consideration of local climatic conditions to optimize their natural ventilation capabilities effectively.

Each of these atrium types is measured based on the "Geometry and Size" component. This component is crucial as it directly influences the effectiveness of natural ventilation mechanisms such as the stack effect and cross ventilation, as well as the control of solar gain and light penetration.

Table 2. Geometry and size analysis table

Atrium type	Common dimensions	Geometric characteristics	Impact on ventilation
Vertical atriums	Height: 20-30 meters Width: 10-15 meters	Tall and narrow, often spanning multiple floors	Enhances stack effect by promoting vertical air movement, facilitating efficient upward air flow
Horizontal atriums	Width: 20-30 meters Depth: 10-20 meters	Broad and flat, single or double height	Maximizes cross ventilation by allowing air to flow laterally across the space
Atriums with varying glazing areas	Variable dimensions depending on building design	Incorporates extensive glazing, often irregular shapes	Adjusts solar gain and light penetration, influencing thermal layers and air movement patterns

Vertical atriums promoting stack effects

These atriums are typically tall, stretching over several floors, with a narrower base that expands slightly at higher levels. The significant height of these atriums harnesses the stack effect, where warmer air rises and exits through the top, naturally

pulling cooler air from lower openings or adjacent spaces. The vertical expansion enhances natural ventilation by capitalizing on the temperature differentials between different heights. The taller the atrium, the more pronounced the stack effect, resulting in more effective natural ventilation.

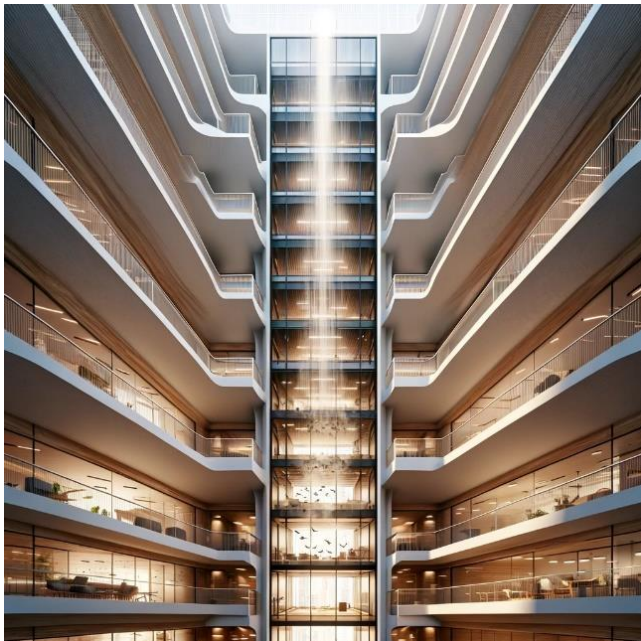
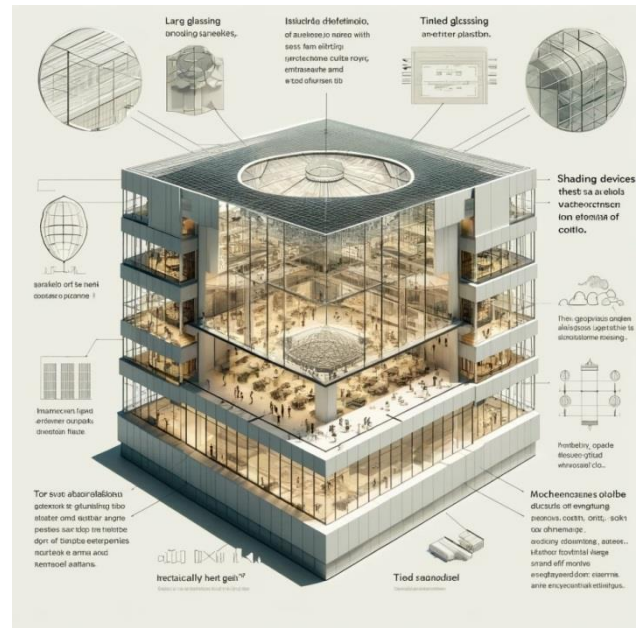
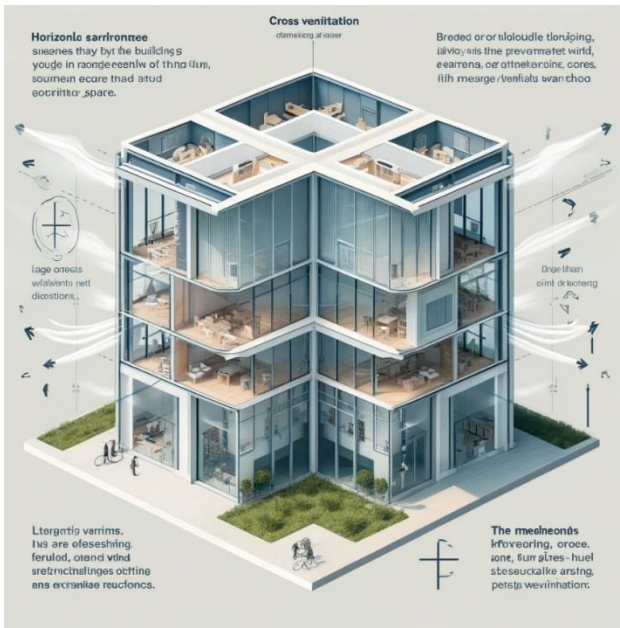


Figure 5. Horizontal atriums

Horizontal atriums facilitating cross ventilation: Horizontal atriums are generally wider than they are tall, creating a large, open area that facilitates the movement of air from one side to the other. These are often found in single or double-story buildings where the atrium can stretch across

the building's width. The broad, open design allows for enhanced cross ventilation, especially when openings are aligned with prevailing wind directions. This setup is ideal in climates where breezes are a reliable and consistent feature, as it allows for efficient air exchange across the atrium's entire area.



Atriums with varying glazing areas and materials: The size and shape can vary significantly, often designed to be adaptive to the building’s overall architectural style. These atriums may have asymmetrical shapes, with varying heights and widths to accommodate extensive glazing areas. The use of glazing impacts internal thermal dynamics significantly. Large glazed areas can introduce substantial amounts of natural light, potentially increasing solar heat gain. However, with the right materials and strategic placement (e.g., shading devices, tinted glazing), these atriums can also manage heat accumulation while still promoting adequate ventilation through mechanically operable windows and vents.

2) Orientation
 To analyze the orientation component of three different atrium types—vertical atriums that promote stack effects, horizontal atriums facilitating cross ventilation, and atriums with varying glazing areas and materials—we focus on how each design aligns with prevalent wind directions and solar paths. This analysis helps understand the influence on natural ventilation and light access, crucial for optimizing environmental efficiency and indoor comfort. The orientation of an atrium is a critical factor that significantly impacts its effectiveness in natural ventilation and light management. Each type of atrium has a specific orientation strategy that optimizes its functionality: vertical atriums utilize the stack effect, horizontal atriums enhance cross ventilation, and atriums with varied glazing optimize solar gain and light access. Properly aligning these structures with natural environmental forces such as wind and sunlight can dramatically improve building sustainability and occupant comfort.

Table 3. Orientation analysis table

Atrium Type	Orientation Strategy	Influence on Natural Ventilation	Influence on Light Access
Vertical atriums promoting stack effects	Aligned with prevailing wind directions for optimal air intake.	Enhances stack effect by allowing air to enter from windward side and exit leeward.	Orientation may vary to maximize or minimize solar gain depending on climate needs.
Horizontal atriums facilitating cross ventilation	Aligned perpendicular to prevailing winds to maximize cross-flow.	Maximizes lateral air movement across the atrium, enhancing air exchange rates.	Generally optimized to reduce direct solar exposure to prevent overheating.
Atriums with varying glazing areas and materials	Specifically oriented to capture optimal sunlight throughout the year.	Orientation facilitates controlled ventilation through operable windows and vents.	Maximizes light penetration while managing heat gain through strategic glazing.

Vertical atriums promoting stack effects:

Vertical atriums are strategically oriented to capitalize on prevailing wind directions and enhance the natural stack effect. This alignment facilitates the entry of cooler air from the windward side, while allowing warmer air to exit through leeward openings or vents placed at higher levels [6]. The effectiveness of the stack effect is greatly dependent on the correct orientation, which can dramatically enhance natural ventilation. This mechanism leverages temperature differentials between the indoor and outdoor environments to create a continuous flow of air, cooling and ventilating the building without relying on mechanical systems [4].

Horizontal Atriums Facilitating Cross

Ventilation: Horizontal atriums are specifically aligned perpendicular to prevalent wind directions, maximizing the potential for cross ventilation. This setup allows wind to flow directly through the atrium, driving air across its full extent and significantly improving ventilation rates [5]. This orientation is vital for enhancing natural cross

ventilation, which can effectively maintain air freshness and reduce the reliance on artificial cooling systems. It proves particularly beneficial in climates where breezes are consistent and reliable, providing a sustainable method to keep indoor environments comfortable [2].

3) Atriums with Varying Glazing Areas and Materials:

These atriums are meticulously oriented to optimize sunlight capture throughout the year. Their design incorporates extensive and variable glazing areas to maximize winter sunlight while avoiding excessive summer heat, aligning with solar paths to optimize light and heat management [7]. The strategic orientation, combined with the use of adaptive glazing technologies, allows these atriums to control solar gain effectively. This approach not only maximizes natural light access but also enhances thermal comfort by balancing indoor climate conditions, facilitating passive solar heating when necessary, and minimizing the risks of overheating [5].

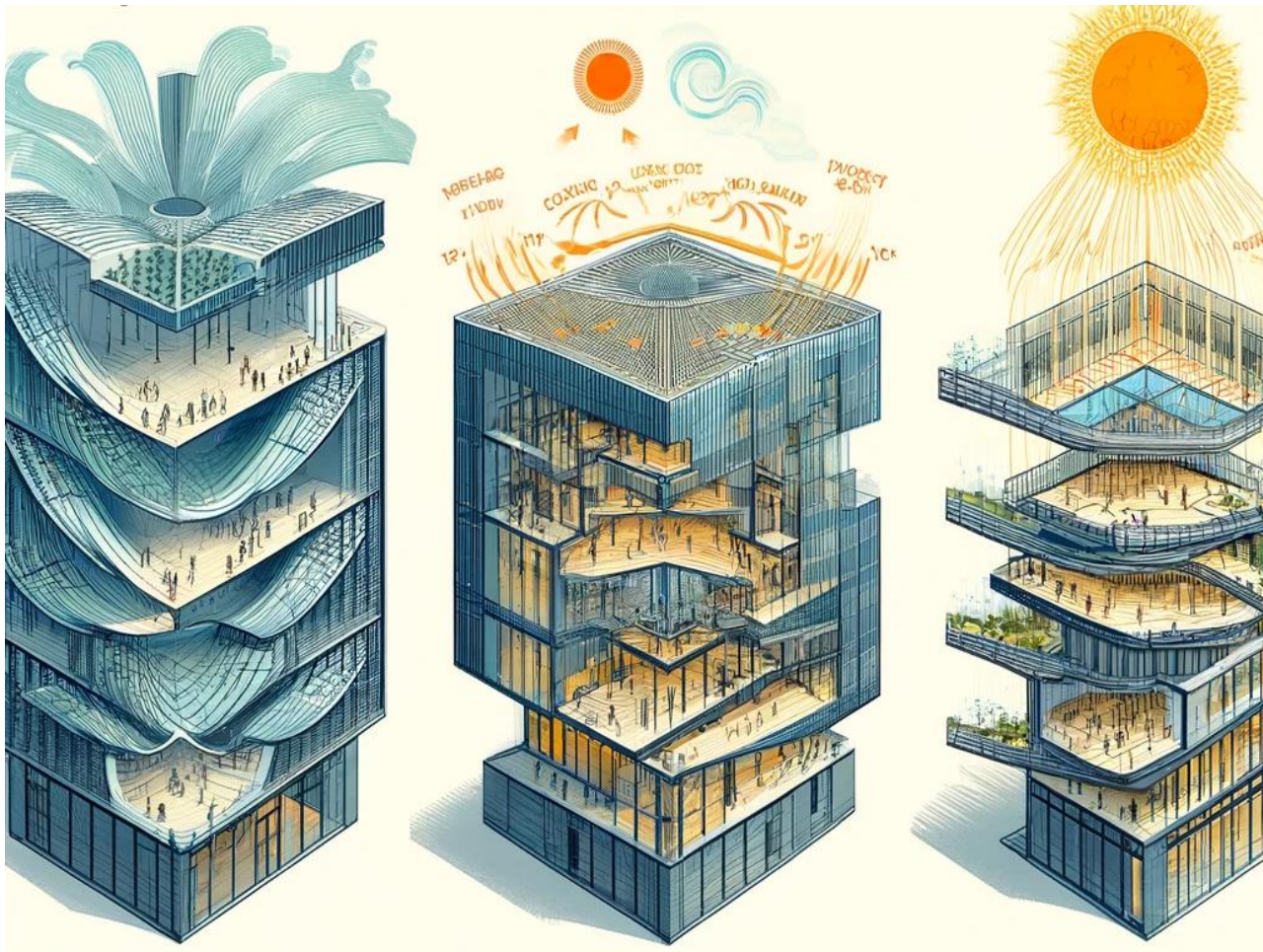


Figure 5. The orientation component of three different atrium types

Material specifications

To thoroughly evaluate the impact of different material types across three atrium designs, we will extend the analysis to include three material scenarios for each atrium type: high thermal mass, low thermal mass, and advanced glazing materials.

This comprehensive approach allows us to assess how each material influences the natural ventilation and energy performance of vertical atriums, horizontal atriums, and atriums with varying glazing areas.

Table . Extended Material Specifications Analysis

Atrium type	Material scenario	Material used	Thermal properties	Impact on ventilation and energy performance
Vertical Atriums Promoting Stack Effects	High Thermal Mass	Concrete, Brick	Concrete: 1.7 W/m·K, Brick: 0.7 W/m·K	Enhances thermal inertia, stabilizing indoor temperatures and bolstering the stack effect.
	Low Thermal Mass	Wood, Gypsum	Wood: 0.12 W/m·K, Gypsum: 0.17 W/m·K	Quicker temperature adjustments, less effective in sustaining the stack effect.
	Advanced Glazing	Low-E glass, Tinted glass	Low-E Glass: 0.96 W/m·K, Tinted Glass: 0.95 W/m·K	Controls solar gain, minimizing impact on stack effect but improving light and heat management.
Horizontal Atriums Facilitating Cross Ventilation	High Thermal Mass	Concrete, Brick	Concrete: 1.7 W/m·K, Brick: 0.7 W/m·K	Slower response to temperature changes, potentially dampening rapid ventilation effects.
	Low Thermal Mass	Wood, Gypsum	Wood: 0.12 W/m·K, Gypsum: 0.17 W/m·K	Supports rapid air temperature changes, enhancing cross ventilation effectiveness.
	Advanced Glazing	Low-E glass, Tinted glass	Low-E Glass: 0.96 W/m·K, Tinted Glass: 0.95 W/m·K	Reduces unwanted heat gains, optimal for managing solar impact in ventilated spaces.
Atriums with Varying Glazing Areas and Materials	High Thermal Mass	Concrete, Brick	Concrete: 1.7 W/m·K, Brick: 0.7 W/m·K	Poor suitability for atriums reliant on glazing; excessive mass could hinder light penetration.
	Low Thermal Mass	Wood, Gypsum	Wood: 0.12 W/m·K, Gypsum: 0.17 W/m·K	Inadequate for managing significant solar gains typical in such atriums.
	Advanced Glazing	Low-E glass, Tinted glass	Low-E Glass: 0.96 W/m·K, Tinted Glass: 0.95 W/m·K	Maximizes benefits of solar management and light penetration, enhancing overall energy efficiency.

Vertical atriums promoting stack effects:

- **High thermal mass:** Concrete and brick, which are high in thermal mass, are optimal for vertical atriums as they stabilize temperature fluctuations throughout the day, enhancing the stack effect. The effectiveness of these materials in sustaining natural ventilation through temperature regulation is well-documented [6]. These materials absorb heat during the day and release it slowly at night, enhancing the natural cooling effect [4].

- **Low thermal mass:** Materials like wood and gypsum adjust temperatures quickly but do not support sustained natural stack ventilation as effectively as high thermal mass materials. Their rapid response to temperature changes can disrupt

the continuous airflow necessary for an effective stack effect.

- **Advanced glazing:** Although primarily used to manage solar gain and light, advanced glazing materials like Low-E and tinted glass can also contribute to temperature control within vertical atriums, albeit their impact on enhancing stack effects directly is less significant compared to high thermal mass materials [5].

Horizontal atriums facilitating cross ventilation:

- **High thermal mass:** These materials may inhibit the atrium's ability to respond quickly to changes in external temperature, potentially

reducing the efficiency of cross ventilation [2]. High thermal mass is less favorable in settings where quick adaptation to temperature variations is crucial for maintaining effective ventilation.

- **Low thermal mass:** Wood and gypsum are particularly suited for horizontal atriums where rapid air temperature changes are beneficial. Their low thermal mass aids in quicker heat dissipation, facilitating effective cross ventilation, a crucial aspect in maintaining air freshness and reducing reliance on mechanical cooling systems [5].

- **Advanced glazing:** Implementing advanced glazing in horizontal atriums helps control solar gain without compromising the effectiveness of cross ventilation. These materials are essential in atriums with significant window areas, balancing light penetration with thermal comfort [7].

Atriums with varying glazing areas and materials:

- **High thermal mass:** Not generally recommended for atriums that rely heavily on managing light and solar heat due to their potential to obstruct the intricate light and heat dynamics desired in such designs [4].

- **Low thermal mass:** These materials often fail to provide adequate thermal control in environments with substantial solar exposure, which can lead to overheating issues, making them less suitable for atriums designed to optimize solar gain [6].

- **Advanced glazing:** The best choice for managing solar gains while ensuring maximum light penetration, enhancing both comfort and energy efficiency. The strategic use of Low-E and tinted glass materials optimizes environmental control within the atrium, supporting passive solar heating when necessary and minimizing overheating risks [5].

The selection of materials for atrium construction must align with the specific environmental strategies and intended use of each atrium type. While high thermal mass materials are beneficial for vertical atriums utilizing stack effects for natural ventilation, horizontal atriums benefit from low thermal mass materials to enhance their responsiveness to temperature variations conducive to effective cross ventilation. For atriums focusing on optimizing light and heat through glazing, advanced glazing materials offer the most benefits, balancing energy efficiency with environmental comfort. This nuanced approach to material selection is crucial for optimizing atrium design to

achieve sustainable building performance and occupant comfort.

4) Internal configurations

To comprehensively assess the internal configurations of three atrium designs—vertical atriums promoting stack effects, horizontal atriums facilitating cross ventilation, and atriums with varying glazing areas and materials—each model will be analyzed across three different configuration scenarios: minimalistic settings with plants and water features, low partitions with mobile furniture, and high-density furniture arrangements. This expanded analysis allows us to evaluate how various arrangements influence airflow patterns and overall ventilation effectiveness within each atrium type.

The configuration of internal elements significantly impacts the natural ventilation capabilities and environmental efficiency of atriums. Research has consistently shown that the choice and arrangement of these elements can either enhance or impede the natural ventilation processes:

- 1. Vertical atriums:** The stack effect is best supported by minimalistic configurations that incorporate natural elements like plants and water features, which help to cool and humidify the air, facilitating its upward movement [4]. Overcrowding these spaces with furniture can obstruct this airflow, significantly diminishing the effectiveness of natural stack-driven ventilation [6].

- 2. Horizontal atriums:** Cross ventilation is maximized in scenarios where interior barriers are minimized. Low partitions and mobile furniture allow for the quick reconfiguration of space to best capture and utilize prevailing winds for effective ventilation [5]. Conversely, high-density furniture setups can act as barriers to airflow, reducing the overall ventilation efficacy [2].

- 3. Atriums with varying glazing areas:** These atriums benefit from configurations that optimize light penetration and minimize shadowing, which are crucial for managing both solar gain and interior climate. Minimalistic setups are typically most effective, as they prevent obstruction of glazed areas and promote efficient air and light flow [7].

In conclusion, the internal configuration of an atrium not only affects its aesthetic and functional qualities but also plays a critical role in its environmental performance. Understanding the interaction between atrium design, internal configuration, and environmental factors is essential for optimizing building sustainability and occupant comfort.

Table 4. Expanded internal configuration analysis table

Atrium type	Configuration scenario	Key elements	Impact on ventilation effectiveness
Vertical Atriums Promoting Stack Effects	Minimalistic with plants and water features	Plants at base, water features, minimal furniture	Enhances the stack effect by cooling and humidifying incoming air, aiding upward air movement [4].
	Low Partitions with mobile furniture	Mobile furniture, low partitions	Allows for adaptable space usage without significant interruption to airflow, potentially less effective than minimalistic settings in promoting stack effects [5].
	High-density furniture	Compact furniture arrangements	May obstruct airflow, reducing the effectiveness of the stack effect by limiting air movement [6].
Horizontal Atriums Facilitating Cross Ventilation	Minimalistic with plants and water features	Sparse furniture, strategic plant placement	Provides unobstructed pathways for air, enhancing cross ventilation effectiveness, though less impactful than low partitions [2].
	Low partitions with mobile furniture	Modular furniture, reconfigurable partitions	Optimizes airflow by allowing for configuration adjustments according to ventilation needs, maximally enhancing cross ventilation [7].
	High-density furniture	Dense furniture layouts	Can impede air movement and reduce ventilation efficiency by creating physical barriers [5].
Atriums with Varying Glazing Areas and Materials	Minimalistic with plants and water features	Minimal furniture, decorative plants	Facilitates optimal light penetration and thermal management without compromising ventilation pathways [6].
	Low partitions with mobile furniture	Low impact furniture, easily movable	Enhances space flexibility while maintaining clear lines for ventilation and light penetration, slightly less effective than minimalistic settings [4].
	High-density furniture	High-density, static furniture setups	Reduces the effectiveness of natural light utilization and can obstruct ventilation flows, detracting from environmental efficiency [5].

5) Discussion of atrium designs and optimization

The analysis of three atrium models—vertical vestibules promoting stack effects, horizontal atriums facilitating cross ventilation, and atriums with varying glazing areas and materials—across four components (geometry and size, orientation, material specifications, and internal configuration) reveals significant insights into the effectiveness of each design in terms of natural ventilation and energy performance.

The dimensions and shape of an atrium critically impact its ventilation efficiency. Vertical atriums, with their tall and narrow design, effectively utilize the stack effect to facilitate natural ventilation. This design is optimal for buildings where vertical space is available, and it efficiently moves air vertically due to temperature gradients [4]. Horizontal atriums, being wider, are excellent for facilitating cross ventilation, especially when aligned with prevailing wind directions [5]. Atriums with varying glazing areas optimize light and thermal management but require careful consideration of size and shape to prevent excessive solar gain [4].

The alignment of an atrium with respect to wind and solar paths is crucial for maximizing its natural ventilation capabilities. Vertical atriums oriented to exploit wind directions enhance the stack effect, providing efficient cooling and ventilation [6]. Horizontal atriums benefit from an orientation that aligns with prevailing winds, maximizing cross

ventilation. Atriums with varying glazing areas need to be oriented to balance sunlight exposure throughout the year, optimizing both heat gain in winter and shade in summer [2].

Material choice affects the atrium's thermal behavior and overall energy performance. High thermal mass materials like concrete and brick are beneficial in vertical atriums, as they stabilize temperature fluctuations and enhance the stack effect [6]. In contrast, low thermal mass materials such as wood and gypsum are preferable in horizontal atriums for their ability to quickly adjust to temperature changes, facilitating better air movement [5]. Advanced glazing materials are crucial in atriums with extensive glazed areas, managing solar gain while ensuring sufficient natural light [7].

The layout of internal elements significantly influences airflow patterns and ventilation effectiveness. Minimalistic designs with strategically placed plants and water features are most effective in vertical atriums, supporting the upward air movement essential for the stack effect [4]. Horizontal atriums benefit from flexible furniture arrangements and low partitions that allow for easy adaptation to changing ventilation needs. Atriums with variable glazing require configurations that do not obstruct light paths, optimizing environmental control and user comfort [5].

Integrating the results from the analysis, the most optimized atrium design would be:

- **Geometry and size:** A vertical atrium with a tall and slender profile is most effective for promoting natural stack effects, especially in urban settings where footprint limitations necessitate vertical expansion.

- **Orientation:** Such an atrium should be oriented to capitalize on prevailing wind directions for optimal air intake and solar paths for balancing heat throughout the day.

- **Material specifications:** Utilizing high thermal mass materials at the base (concrete or brick) combined with advanced glazing systems higher up can manage both temperature stability and light penetration effectively.

- **Internal configuration:** A minimalistic internal layout enhanced with natural elements like plants at the base to cool and humidify incoming air, combined with minimal furniture to avoid obstruction would be ideal.

Given the comprehensive analysis and comparison with findings from other researchers, a vertical atrium designed with high thermal mass materials at the base, advanced glazing, and a minimalistic internal configuration, oriented to make full use of natural wind and solar benefits, emerges as the most effective physical form. This configuration optimally leverages the natural environment to enhance both ventilation effectiveness and energy efficiency, making it a sustainable architectural solution for contemporary building designs.

CONCLUSION

This research has undertaken a detailed analysis of three distinct atrium designs: vertical atriums promoting stack effects, horizontal atriums facilitating cross ventilation, and atriums with varying glazing areas and materials. The goal was to ascertain how different physical forms and configurations influence natural ventilation and energy performance in buildings. Through an integrated examination of geometry and size, orientation, material specifications, and internal configuration, we have derived key insights that align with and expand upon findings from existing literature.

The analysis began with an assessment of geometry and size, where it was established that vertical atriums exploit the stack effect through their elevated heights, making them particularly effective in urban environments where space is at a premium. In contrast, horizontal atriums, with their expansive widths, excel in enhancing cross ventilation, especially in settings where wind patterns are consistent and reliable. Atriums with variable glazing are tailored to optimize light and thermal dynamics, requiring careful consideration of size and shape to manage solar gain effectively throughout the year.

Orientation emerged as a critical factor in maximizing the natural ventilation capabilities of atriums. Vertical atriums oriented to capture prevailing winds augment the stack effect, providing efficient cooling and ventilation without the reliance on mechanical systems. Horizontal atriums gain maximum benefit from an alignment perpendicular to prevailing winds, thereby enhancing air exchange and reducing energy consumption. Atriums with extensive glazing need to balance sun exposure to harness passive solar heating in the winter while avoiding overheating in the summer, necessitating a strategic orientation that aligns with solar paths.

The choice of materials plays a pivotal role in influencing the atrium's thermal behavior and overall energy efficiency. High thermal mass materials like concrete and brick are preferred in vertical atriums for stabilizing temperature fluctuations and enhancing the stack effect. Conversely, low thermal mass materials such as wood and gypsum are advantageous in horizontal atriums due to their ability to quickly adjust to temperature changes, supporting effective ventilation. Advanced glazing materials in atriums with variable glazing optimize light penetration and manage heat gain, critical for maintaining comfortable and energy-efficient interior environments.

Internal configuration was found to significantly impact airflow patterns and ventilation effectiveness. Minimalistic designs with strategically placed plants and water features were most effective in vertical atriums, supporting upward air movement essential for the stack effect. Horizontal atriums benefit from flexible furniture arrangements that allow for adaptation to ventilation needs, while atriums with variable glazing require configurations that do not obstruct light paths, optimizing environmental control and user comfort.

Integrating these findings, the most optimized atrium design is a vertical atrium that utilizes high thermal mass materials at the base to stabilize indoor temperatures, combined with advanced glazing systems higher up to manage light and heat. Such an atrium should be oriented to maximize the benefits of prevailing winds and solar exposure, with a minimalistic internal configuration that enhances the natural stack effect. This design leverages the natural environment to enhance both ventilation effectiveness and energy efficiency, making it a sustainable architectural solution for modern urban settings.

This research not only aligns with existing studies that underscore the importance of thoughtful atrium design in building sustainability [2, 4, 5] but also extends these discussions by providing a comprehensive framework that architects and designers can use to optimize atriums for specific environmental conditions. As buildings increasingly become focal points for sustainability, the strategic design of atriums as explored in this study offers a

viable path toward enhancing building performance while reducing environmental impact.

DECLARATIONS

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Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

Competing interests

The author declares that there is no competing interest.

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