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AMAR THELIDJI UNIVERSITY - LAGHOUAT

كلية التكنولوجيا

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**ARCHITECTURAL INFLUENCE OF A LARGE ROOM ON THERMAL COMFORT
NUMERICAL ANALYSIS ►►►**

DEFENSE JURY	GRADE	QUALITY
LAKHDAR HACHANI	PROF	PRESIDENT
MOHAMED TEGGAR	PROF	EXAMINER
AMINE TOUFIK BENHOUIA	M.C.B	SUPERVISOR

PRESENTED BY:

LACRI AYMEN

BOUAZARA ABDELJALIL

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Dedication

Alhamdulillah,

All praise is due to Allah, who granted us the strength, patience, and perseverance to complete this work.

We dedicate this humble achievement to the most cherished people in our lives:

To our beloved parents, whose unconditional love, sacrifices, and heartfelt prayers have been the guiding light on our journey.

To our dear brothers and sisters, who stood by us with unwavering support and motivation throughout this path.

To our loyal friends, who shared with us both the struggles and the triumphs your presence made the journey worthwhile.

To all those who offered us help, encouragement, and belief in our potential we are deeply thankful.

To our resilient brothers and sisters in Palestine, whose courage and steadfastness continue to inspire us — you are always in our thoughts and prayers.

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May Allah reward you all.

LACRI AYMEN

BOUAZARA ABDELJALIL

Abstract

This study investigated the architectural influence of large rooms, specifically mosque prayer halls, on thermal comfort using computational fluid dynamics (CFD) simulations. Simulations of various mosque configurations, including those with open doors and windows at different distances and heights, revealed significant impacts on indoor thermal conditions. The findings provide insights into effective design strategies for enhancing thermal comfort in mosque environments during both summer and winter, contributing to the development of more sustainable and comfortable worship spaces.

Key words

thermal comfort – simulation – architectural effect – mosque

Résumé

Cette étude a étudié l'influence architecturale des grandes pièces, en particulier les salles de prière des mosquées, sur le confort thermique à l'aide de simulations de dynamique de fluide (CFD). Les simulations de diverses configurations de mosquées, y compris celles avec des portes ouvertes et des fenêtres à différentes distances et hauteurs, ont révélé des impacts significatifs sur les conditions thermiques intérieures. Les résultats fournissent un aperçu des stratégies de conception efficaces pour améliorer le confort thermique dans les environnements de mosquée pendant l'été et l'hiver, contribuant au développement d'espaces de culte plus durables et confortables.

Mots clés

Confort thermique - Simulation - Effet architectural - mosquée

ملخص

بحثت هذه الدراسة في التأثير المعماري للغرف الكبيرة، وتحديدًا قاعات الصلاة في المساجد، على الراحة الحرارية باستخدام محاكاة ديناميكا الموائع الحسابية (CFD). كشفت محاكاة تكوينات المساجد المختلفة، بما في ذلك تلك ذات الأبواب والنوافذ المفتوحة على مسافات وارتفاعات مختلفة، عن تأثيرات كبيرة على الظروف الحرارية الداخلية. تُقدم النتائج رؤى ثاقبة حول استراتيجيات التصميم الفعالة لتعزيز الراحة الحرارية في بيئات المساجد خلال الصيف والشتاء، مما يُسهم في تطوير أماكن عبادة أكثر استدامة وراحة.

الكلمات المفتاحية:

الراحة الحرارية - المحاكاة - التأثير المعماري - المسجد

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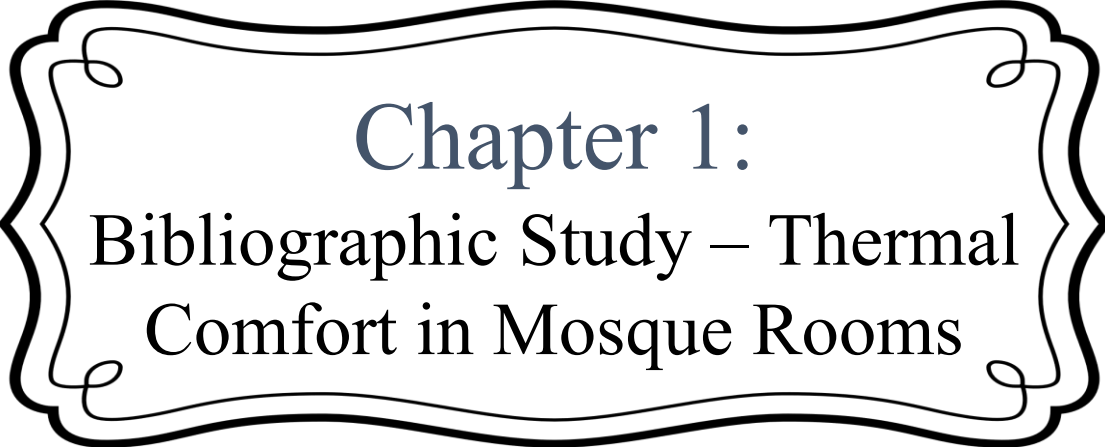
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General introduction:

Mosques are truly special places, serving as crucial centers for worship and community life. They possess a wonderful blend of unique architectural and functional features that truly set them apart from ordinary buildings. Think about those big, open prayer halls – often reaching high up with domes, or featuring lovely courtyards. They're designed specifically to welcome large groups, especially during prayer times. However, here's the thing: while these features are amazing, they also create significant challenges when it comes to maintaining the ideal temperature, particularly across different climates. Unlike typical homes or offices that often rely solely on mechanical heating, ventilation, and air conditioning (HVAC) systems, many mosques traditionally employ passive design strategies to manage their indoor environment. Getting these passive approaches right, such as harnessing natural airflow, maximizing thermal mass utilization, and utilizing strategic shading, is key to ensuring worshippers feel comfortable.

Now, thermal comfort itself is interesting; you can think of it as that feeling of satisfaction with the temperature around you. It's not simple, though. It's a complicated mix of environmental factors like air temperature, relative humidity, and air velocity, plus personal stuff like your metabolic rate and what you're wearing (clothing insulation). And when you're talking about mosques, you have extra layers of complexity, such as the crowd density during peak prayer times – that changes the thermal picture. This study delves deeply into thermal comfort, specifically in mosque rooms. The whole idea is to bridge the gap between traditional innovative architecture and what modern science tells us. The approach is as follows: First, we establish a solid foundation in the fundamentals of thermal comfort principles and the relevant standards. Then, it takes a detailed look at how the different architectural bits that are so unique to mosques impact the thermal conditions. And finally, it employs advanced simulation techniques to thoroughly analyze and suggest practical ways to enhance thermal comfort, ultimately contributing to the creation of better, more sustainable spaces for worship.

How can minarets and architectural modifications affect thermal comfort inside the mosque?

A decorative frame with a double-line border and ornate, scroll-like corners. The text is centered within this frame.

Chapter 1:
Bibliographic Study – Thermal
Comfort in Mosque Rooms

Introduction:

Mosques differ from traditional buildings in every way in their use and design. Their large, open spaces and limited occupancy especially during certain prayer times pose unique thermal challenges, particularly in hot climates. Many mosques rely on passive airflow, which must effectively interact with architectural form and local conditions.

Thermal comfort in mosques is influenced by crowd density, in addition to temperature, relative humidity, and airflow. In this chapter, we will examine the Thermophysiological Basis of Thermal Comfort and Factors Affecting Thermal Comfort and Characteristics of Mosque Architecture. [1]

1. Definition of Thermal Comfort:

Thermal comfort is a fundamental idea in environmental layout, human body structure, and architectural engineering. It refers to a nation of equilibrium between the human frame and the encircling thermal surroundings wherein a character experiences neither thermal pressure nor thermal dissatisfaction. [3]

ASHRAE Standard 55 provides the most authoritative definition of thermal comfort, which states:

Thermal comfort is a mental state that expresses satisfaction with the surrounding thermal environment. [4]

This definition intentionally highlights the subjective nature of thermal consolation: it cannot be determined solely thru objective physical measurements. Two individuals inside the same space, under identical environmental conditions, may also report vastly special thermal perceptions due to variations in metabolic rate, apparel insulation, acclimatization, mental adaptation, or even cultural norms. Therefore, thermal consolation analysis has to incorporate both measurable bodily parameters and subjective human factors. [5]

2. Thermophysiological Basis of Thermal Comfort:

Human beings are homeothermic organisms, which means they regulate their internal body temperature inside a narrow range (approximately 36.5–37.5°C) irrespective of ambient situations. This internal regulation is governed with the aid of the thermoregulatory gadget, which continues thermal stability by controlling heat exchanges between the frame and its environment via the four number one modes of heat switch:

Chapter1: Bibliographic Study – Thermal Comfort in Mosque Rooms

- Conduction: heat change through direct contact with cooler or warmer surfaces.
- Convection: heat switch to or from shifting air adjoining to the pores and skin.
- Radiation: emission or absorption of infrared heat between the body and surrounding surfaces.

When the rate of inner heat manufacturing (due to metabolism) is balanced by the fee of heat loss to the environment, the body remains in thermal equilibrium, and thermal consolation is finished. If this stability is disturbed as an instance, in a heat, poorly ventilated room the body's thermoregulatory responses (e.g. sweating or vasodilation) are activated. If these physiological responses are inadequate, A feeling of discomfort occurs. [6]

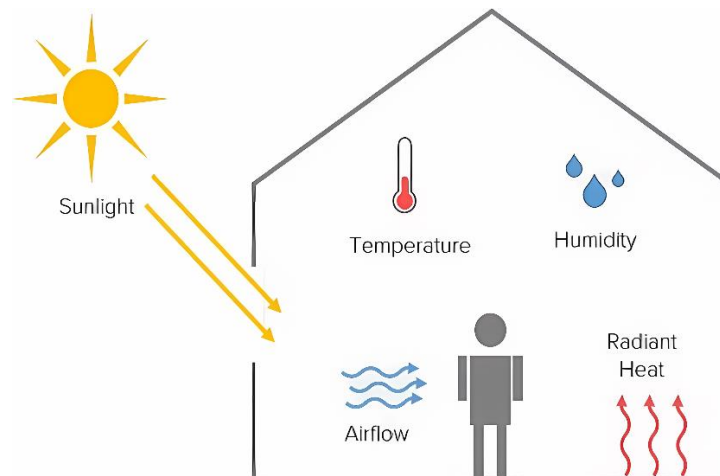


Figure 1. 1: Thermal comfort presentation.[2]

3. ASHRAE Standard 55: Overview and Scientific Rationale:

ASHRAE Standard 55 (Thermal Environmental Conditions for Human Occupancy) is the globally recognized standard that defines the acceptable thermal environmental conditions in indoor spaces. Developed by the American Society of Heating, Refrigerating and Air-Conditioning Engineers, the standard provides the scientific foundation for designing indoor environments that support occupant thermal comfort.[4]

3.1.Application to Architectural Analysis

In large, intermittently occupied spaces like mosque prayer halls, thermal comfort is highly sensitive to air stratification, ceiling height, occupancy density during peak times (e.g.,

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Friday prayers), and user clothing, which is often culturally prescribed and thermally insulating. [7]

ASHRAE 55's dual-version framework (predictive and adaptive) affords the analytical equipment vital to evaluate consolation in such spaces, whether the usage of simulation or subject measurements. [5]

Moreover, using adaptive comfort models has received growing relevance in mosque research, given their reliance on natural air flow and thermal expectations adapted to nearby climates. In hot or warm-humid regions, occupants may tolerate higher indoor temperatures without experiencing soreness, provided that air movement and mental edition are sufficient [8]

4. Factors Affecting Thermal Comfort:

Thermal comfort is decided by a complex set of variables that can be broadly categorized into classes: environmental parameters, which outline the bodily characteristics of the indoor climate, and private parameters, that are specific to every person. The interplay between these variables dictates whether or not a given indoor environment may be perceived as thermally cushty. [6]

Understanding those elements is fundamental for the architectural and thermal analysis of huge enclosed areas such as mosques, Below, we explore the six primary factors that impact thermal consolation, as mentioned in ASHRAE Standard 55 and extensively adopted in thermal comfort studies. [4]

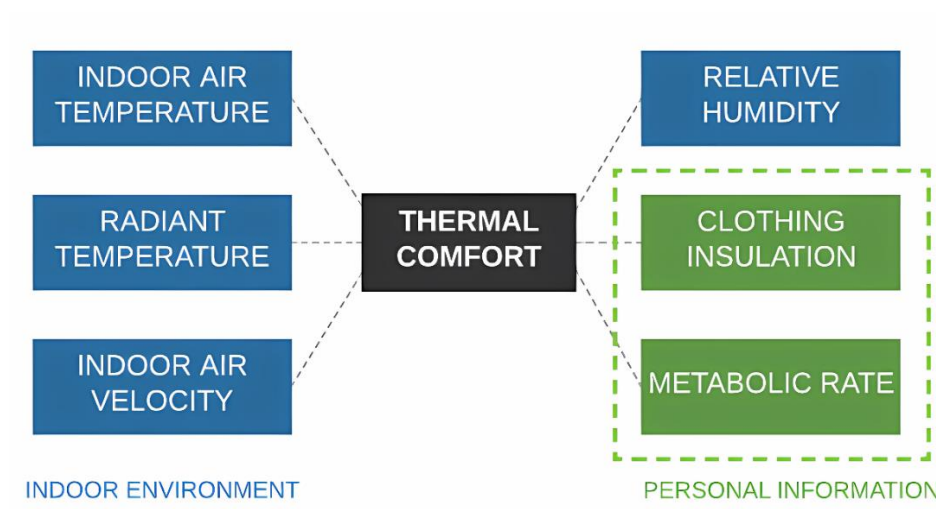


Figure 1. 2: Factors affecting thermal comfort [9]

4.1. Air Temperature (°C):

Air temperature refers back to the dry-bulb temperature of the encompassing air and is the most commonly referenced thermal variable. It at once influences the body's capability to exchange heat via convection and performs a vital position in thermal sensation. However, air temperature alone does no longer absolutely outline thermal comfort, because it does not account for radiation or humidity. In huge, high-quantity areas like mosques, temperature stratification (layering of heat air near the ceiling) is a commonplace phenomenon that may make ground-stage situations quite one of a kind from ceiling-stage measurements. [10]

4.2. Relative Humidity (%):

Relative humidity (RH) is the percentage of moisture present inside the air compared to the maximum it is able to hold at a given temperature. High humidity impairs evaporative heat loss thru sweating, growing the danger of thermal discomfort or heat pressure. Conversely, very low humidity may additionally motive dryness in the pores and skin and mucous membranes. ASHRAE 55 recommends preserving RH between 30% and 60% for comfort. In arid climate mosques, low humidity may be commonplace and might beautify the frame's evaporative cooling, which may be useful in hot climate whilst airflow is sufficient. [11]

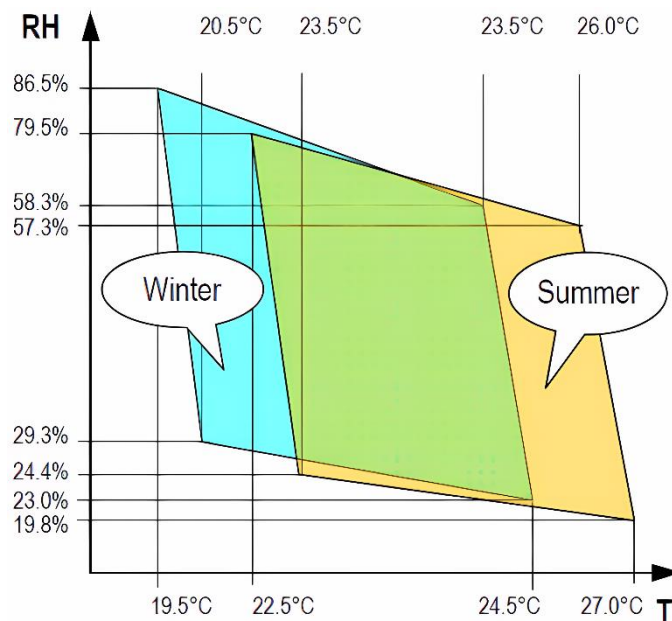


Figure 1. 3: relative humidity (RH) / temperature (T) diagram based on comfort zone according to ashrae 55-1992 [12]

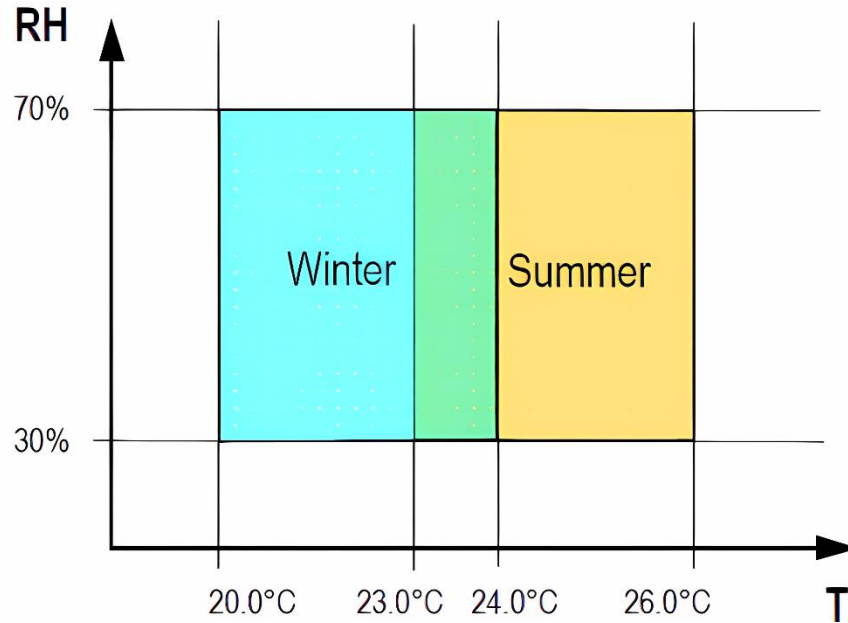


Figure 1. 4: RH/T diagram showing the comfort zone according to ISO 7730 [13]

4.3. Velocity (m/s):

Air speed refers to the charge of airflow across the body, which helps convective heat loss. Increased air motion can offset excessive temperatures, especially in obviously ventilated homes where mechanical cooling is restricted or absent. In mosques, in which windows, and passive air flow play most important roles, airflow design has to be optimized to maintain comfort without causing drafts, in particular for the duration of prayer while occupants are regularly seated on the floor. [4]

5. Characteristics of Mosque Architecture and Its Impact on Thermal Comfort:

The architectural design of a mosque is influenced via both cultural and purposeful necessities, frequently ensuing in different structural features including massive prayer halls, high ceilings, courtyards, and domes. While those features are important for the spiritual and aesthetic value of the building, in addition they have full-size implications for the thermal consolation of its occupants.

Understanding how unique architectural factors impact thermal conditions is crucial for evaluating how mosques perform beneath various climatic situations. Unlike traditional

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workplace or residential homes, mosques frequently depend on passive layout techniques for regulating indoor temperatures, such as herbal ventilation,

thermal mass, and shading. Below, we explore the main architectural characteristics of mosques and their direct impact on thermal consolation. [14]



Figure 1. 5: Oussama ibnzayed mosque Laghouat

5.1.Large Prayer Halls and Open Spaces

One of the maximum extensive characteristics of mosque architecture is the huge prayer corridor a good-sized open area designed to accommodate huge numbers of worshippers at some stage in prayer times. These spaces are usually characterized by high ceilings and minimum walls, growing expansive, unobstructed indoors volumes. [16]

Impact on Thermal Comfort:

Air Stratification: The massive extent of air in high-ceilinged areas can lead to thermal stratification, where hotter air collects close to the ceiling, whilst cooler air remains close to the ground. During less warm months, this can lead to discomfort for worshippers seated or status close to the floor, because the temperature discrepancy can be sizable.

Ventilation Challenges: The loss of walls and the quantity of air may also complicate the distribution of airflow, making it harder to preserve consistent air circulation. Natural ventilation via windows, doorways, or openings in the dome is often used, but in the absence of mechanical systems, accomplishing most reliable air distribution may be tough.

Energy Efficiency Concerns: Large prayer halls, especially those in mosques with restrained insulation, may have high power demands to maintain comfortable temperatures. Passive strategies, such as thermal mass, emerge as important for decreasing the reliance on outside power assets. [17]

5.2.Domes and Vaulted Ceilings

Another iconic characteristic of mosque structure is the dome, regularly placed immediately above the prayer hall. Domes allow for vertical expansion of the interior. Domes are generally fabricated from thick materials consisting of stone or concrete, which have considerable thermal mass.

Impact on Thermal Comfort:

Thermal Mass and Heat Storage: Materials with excessive thermal mass, like stone or concrete, soak up and shop heat throughout the day and launch it slowly in the course of the night time. This property can help hold a extra strong indoor temperature, especially in climates with extreme diurnal temperature variations (i.e., hot days and cool nights).

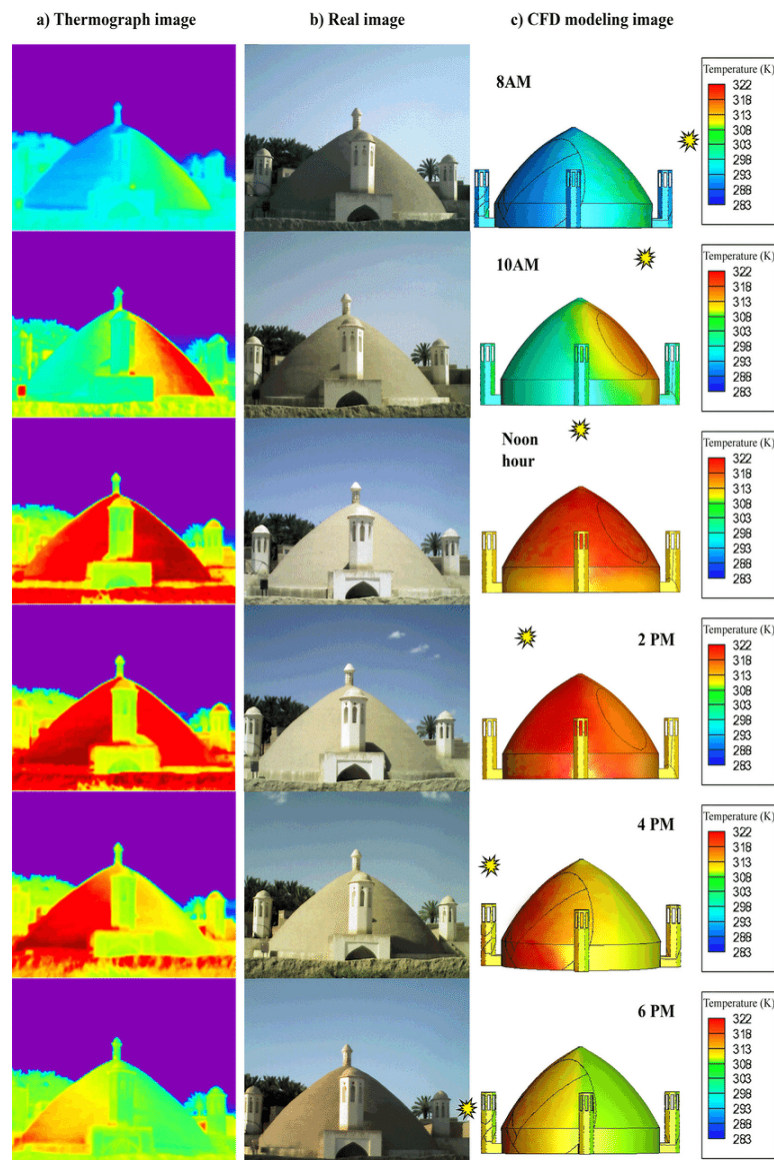


Figure 1. 6: Thermal field on the dome from numerical and experimental measurements and real image of the dome, during wind blowing (16.04.13).[34]

radiation heat: Domes with big home windows or openings permit for full-size radiation heat, in particular in regions with strong sunlight. Without powerful shading, this could result in overheating in the mosque throughout the daytime

Natural Ventilation via the Dome: Domes often feature openings or oculus that permit for hot air to escape, facilitating passive cooling. This venting mechanism is vital for maintaining air movement and lowering the accumulation of heat at the very best point of the constructing. [18]

5.3.Courtyards and Open-Air Spaces

Mosques, mainly in conventional Middle Eastern and North African designs, often include a primary courtyard surrounded via arcades or cloisters.[19]

Impact on Thermal Comfort:

Enhanced Air Circulation: Courtyards act as natural cooling structures. By facilitating pass-ventilation between the open space and surrounding rooms, they improve the airflow in the mosque, specifically in warm climates. The cool air coming into via the courtyard can lessen the general indoor temperature.

Shading and Protection from Sunlight: Courtyards offer shaded areas Shading, blended with paved stone surfaces, facilitates to keep the temperature lower by means of lowering direct exposure to sunlight.

Evaporative Cooling: Courtyards frequently include water features like fountains or pools. The evaporation of water increases humidity however additionally has a cooling effect, decreasing the perceived temperature inside the place and developing a greater comfort environment. [19]

5.4.Traditional Building Materials and Insulation

The materials utilized in mosque production play a sizable position in thermal consolation. Traditional substances which include stone, mud bricks, adobe, and mortar are frequently hired because they may be locally to be had and culturally sizeable. These substances have varying ranges of thermal mass, which influence how heat is absorbed and released through the building. [20]

Impact on Thermal Comfort:

Thermal Insulation and Mass: Materials with high thermal mass can take in heat all through the day and launch it slowly at night, providing a herbal form of temperature regulation. In warm climates, this can help to mitigate the effects of daylight hours heat, even as in cold climates, it can preserve heat in the course of the night time.

Absence of Modern Insulation Materials: Traditional Mosque buildings frequently lack present day insulation substances like foam or reflective coatings. This can lead to extra heat loss for the duration of bloodless climate and better warmth profits in the course of the

Chapter1: Bibliographic Study – Thermal Comfort in Mosque Rooms

summertime. In areas with severe climates, supplementary thermal insulation strategies may be required to improve strength efficiency and occupant consolation. [20]

5.5. Orientation and Placement of Openings

The orientation of the mosque, further to the place of home windows, doorways, and first-rate openings, plays a crucial characteristic in coping with the thermal environment. Typically, mosques are oriented within the course of the Qibla, the route of Mecca, and this often determines the alignment of key architectural talents.[21]

Impact on Thermal Comfort:

Sunlight Exposure and Shading: The orientation of domestic windows and openings can affect the amount of sun radiation the constructing receives in the direction of one-of-a-kind times of the day. For instance, massive domestic home windows handling the sun within the path of the afternoon can bring about overheating, while shaded openings can lessen sun heat gain. Strategic placement of windows can assist minimizing unwanted heat advantage.

Ventilation Pathways: The strategic placement of windows and openings allows for effective skip-air drift, an herbal method of cooling thru facilitating air movement via the mosque's indoors. However, the vicinity and size of openings must be optimized to keep away from excessive direct daylight or wind, which can bring about discomfort for the worshippers. [21]

Conclusion:

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This chapter explores thermal comfort in mosque environments, highlighting the architectural and environmental factors that affect it, particularly in large, open spaces with high ceilings. It defines thermal comfort as reliant on subjective perceptions and objective physical factors, referencing ASHRAE Standard 55 for evaluating comfort through parameters like operative temperature and humidity. The discussion includes traditional and modern mosque designs.

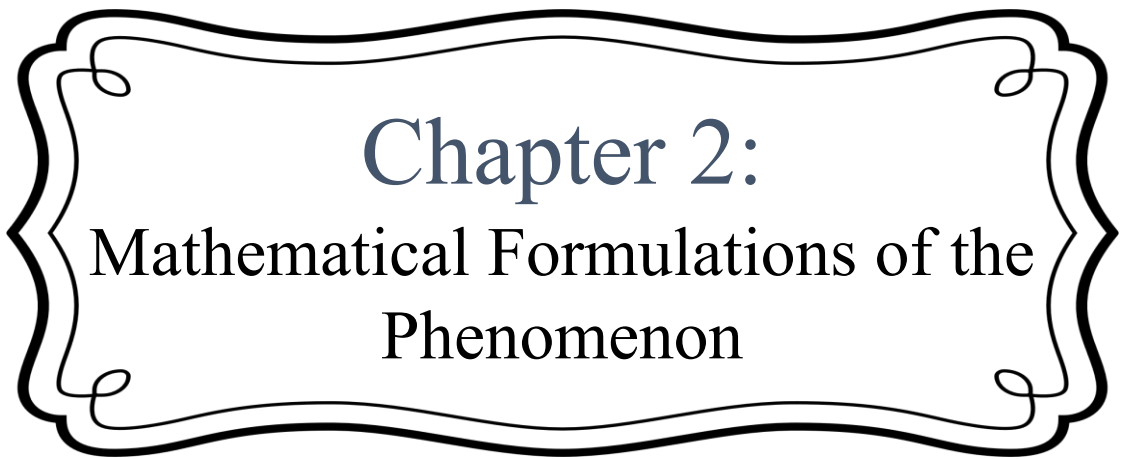
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Chapter1: Bibliographic Study – Thermal Comfort in Mosque Rooms

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Chapter 2:
Mathematical Formulations of the
Phenomenon

Chapter2: Mathematical Formulations of the Phenomenon

Introduction:

Thermal comfort is crucial for indoor environmental quality, especially in mosques with distinctive architectural features, such as high ceilings and expansive open spaces. Understanding heat transfer (conduction, convection, radiation, and evaporation) and airflow is crucial to managing indoor temperature and humidity effectively. Comfort depends not only on-air temperature, but also on humidity, which is influenced by temperature and the city's velocity. High humidity. A high heat sensation, where the same airflow can both increase or lessen comfort, depending on the individual. Mathematical modeling and simulations help examine the mosque's thermal environment, guiding design alternatives that enhance energy performance and occupant comfort. This approach is crucial in the design of eternal mosques, which aim to minimize energy consumption without compromising comfort. This chapter outlines the physical and mathematical principles basic for such analysis.[22]

Chapter2: Mathematical Formulations of the Phenomenon

1. Heat Transfer Process:

Thermal comfort within indoor surroundings is significantly influenced by the exchange of heat between the occupants, the building's surfaces, and the surrounding air in a mosque, where large areas, high ceilings, and varied architectural features, along with courtyards and airflow openings, create complex airflow patterns, understanding the mechanisms of heat transfer is essential. The ability to anticipate and manage thermal comfort in such spaces relies on a profound understanding of the fundamental heat transfer processes: conduction, convection, and radiation.

Each of these heat switch mechanisms plays a specific role in maintaining the thermal environment and distributing heat within the mosque. The interaction among these mechanisms is complex, as they often arise concurrently and have differing impacts on one another. To assess the thermal comfort of the distance, it's essential to model these heat transfer mechanisms mathematically. The following sections examine each of the primary heat switch mechanisms in the element, their significance, and their application in the context of mosque environments.[6]

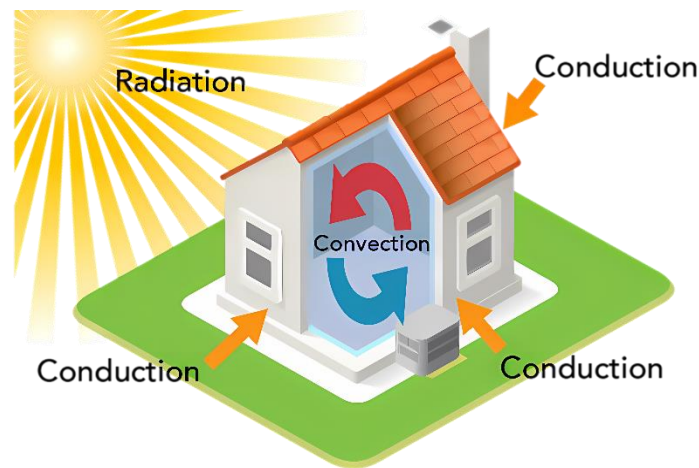


Figure 2. 1: Mechanisms of Heat Transfer in a Building: Radiation, Convection, and Conduction [23]

Example of temperature variation:

The diagram illustrates the temperature variation at a specific location within the mosque between 6 AM and 6 PM. As solar radiation increases throughout the day, the inner temperature rises due to heat gain through windows, the roof, and the walls. The high temperature is reached around 1 PM, accompanied by a sluggish decline as outside solar depth decrease. This variation highlights

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the significance of thermal mass, ventilation techniques, and passive design answers in controlling indoor comfort ranges throughout the day.[24]

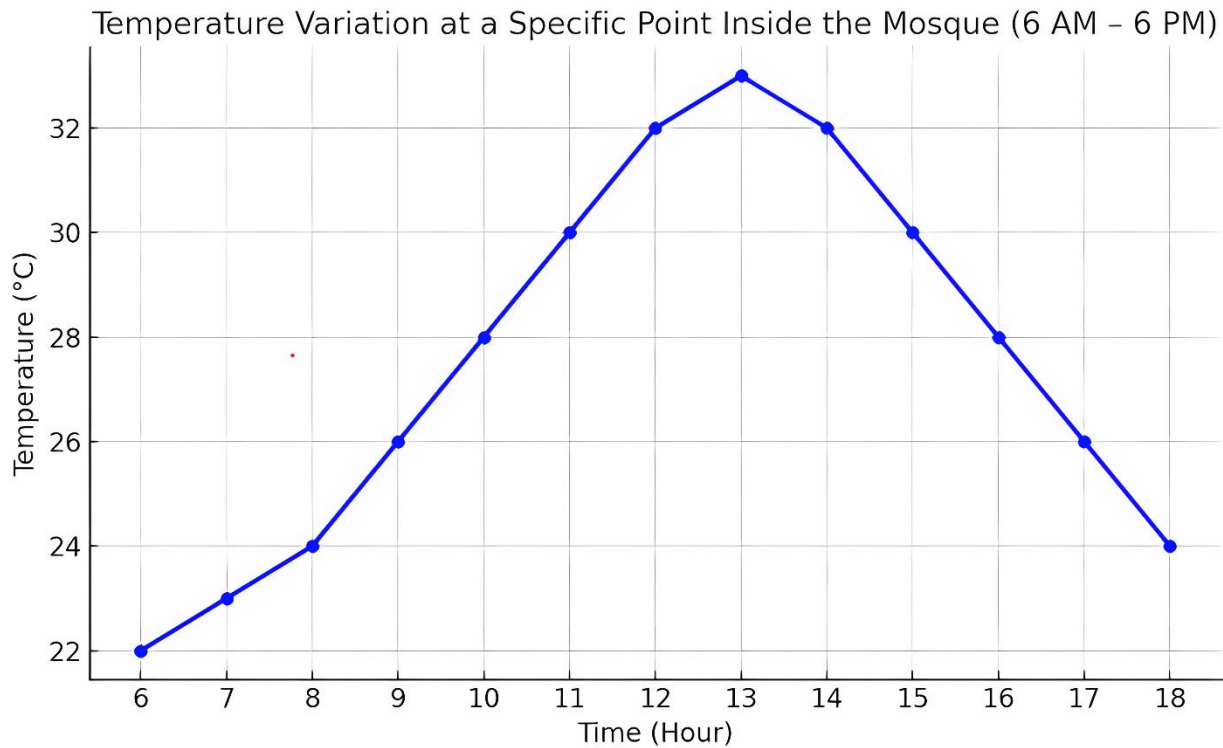


Figure 2. 2: Diurnal Temperature Variation at a Fixed Point Inside a Mosque. [24]

1.1. Conduction

Conduction is the process by which heat is transferred within a solid body from hotter regions to cooler regions. This process occurs on the microscopic scale when the kinetic energy of particles within a higher-temperature zone is transferred to particles present in a lower-temperature zone through collisions. In the case of a mosque, conduction occurs mainly through the building's solid elements, which include walls, ceilings, floors, and even furniture.

The materials used in the construction of a mosque, such as stones, concrete, and metals, have different thermal properties, which means their ability to transfer heat varies. For instance, materials with high thermal conductivity, such as metals, will transfer heat more readily compared to materials with low thermal conductivity, like wood or insulation, which will transfer heat less

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readily. The rate of heat transfer via conduction is significant to know if one wants to calculate the change in internal temperature of a mosque due to changes in outside temperature.

Fourier's Law of Conduction governs the rate of heat transfer by conduction.

$$q_{\text{cond}} = -k \frac{dT}{dx}$$

Where:

q_{cond} is the rate of heat transfer by conduction (W),

k is the thermal conductivity of the material (W/m·K),

$\frac{dT}{dx}$ is the temperature gradient within the material (K/m).[25]

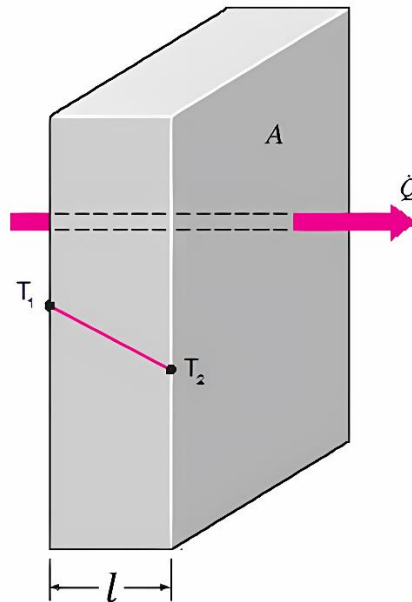


Figure 2. 3: Heat Conduction Through a Plane Wall [26]

1.2.Convection

Chapter2: Mathematical Formulations of the Phenomenon

In simple words, convection refers to the movement of heat from a solid surface to a fluid in motion. In a mosque, convection is done with the transfer of energy from the walls, windows, or floors to the air that is rotating in the compound. The hot air that is retrieved from the environment into a room loses some of its heat and therefore, while lowering its temperature will move around freely as the air mixes-up with outcoming surrounding area air.

Movement of air can greatly affect comfort from heat. In hotter regions, for example, there is natural or mechanical brisk wind systems that make air flow faster and directly enhance the feeling of comfort by removing the excess heat from the human body. Also, no movement of air in an environment makes a person feel warmer than the actual temperature which causes discomfort.

The convection heat transfer rate formula is given by:

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

Where:

q_{conv} is the rate of heat transfer by convection (W),

h is the convective heat transfer coefficient (W/m²·K),

A is the surface area through which heat transfer occurs (m²),

T_s is the temperature of the solid surface (K),

T_{∞} is the air temperature far from the surface (K). [25]

In the construction of mosques, convection is significant for distributing heat within large open spaces. For example, the stratification of temperatures within a space with high ceilings tends to have cooler air at the bottom and warmer air at the top. The design of air circulation systems, such as vents and windows, is intended to promote circulation, reduce stratification, and improve thermal comfort for occupants.

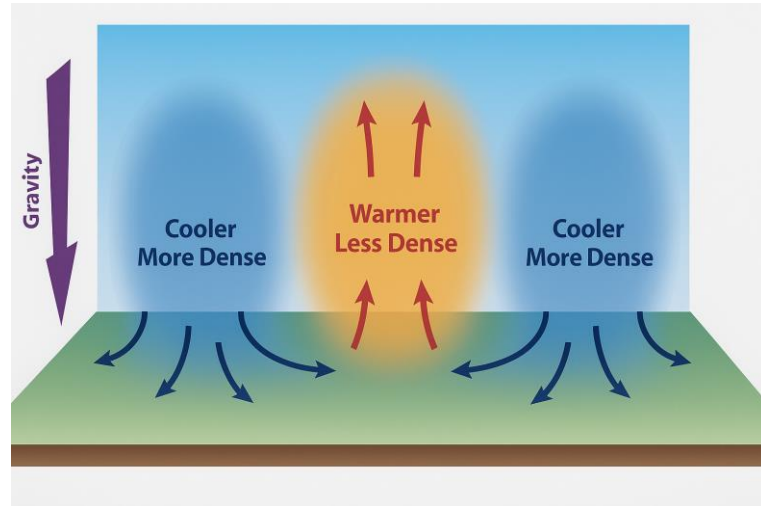


Figure 2. 4:Natural Convection in a Large Room: Density-Driven Air Movement [27]

1.3.Radiation

Radiation is the transfer of heat in the form of electromagnetic waves, typically in the infrared spectrum. Unlike conduction and convection, which require a medium (either stable or fluid) to transfer heat, radiation can occur even in a vacuum. In indoor environments, such as mosques, radiation is a crucial mode of heat transfer, particularly between the building's surfaces and its occupants.

In a mosque, radiant heat emitted by surfaces such as walls, flooring, windows, or even the roof can substantially affect the thermal comfort of worshippers. Radiant heat trade may be particularly critical in large, open spaces with high ceilings, where thermal stratification can cause discomfort if radiant heat from excessive surfaces (such as a domed ceiling or high walls) isn't well controlled.

The quantity of heat radiated via a surface is described by using Stefan-Boltzmann Law:

$$q_{\text{rad}} = \epsilon\sigma A(T_s^4 - T_{\infty}^4)$$

Where:

q_{rad} is the rate of heat transfer by radiation (W),

ϵ is the emissivity of the surface (dimensionless),

σ is the Stefan-Boltzmann constant ($5.67 \times 10^{-8} \text{ W/m}^2\text{K}^4$),

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A is the surface area (m^2),

T_s is the surface temperature (K),

T_∞ is the temperature of the surrounding environment (K).[25]

Controlling radiant heat through proper building layout, which includes the use of thermal insulation, shading devices, or reflective materials, can improve comfort levels.

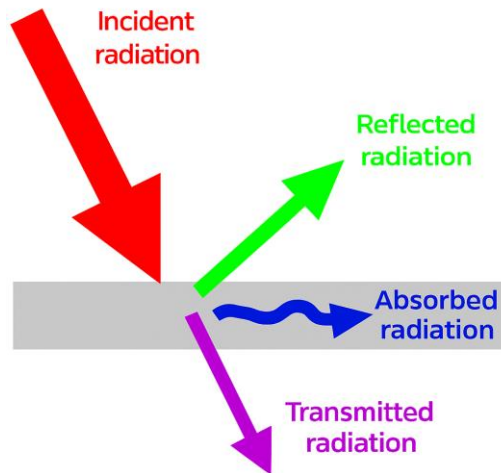


Figure 2. 5: Absorption, Reflection, and Transmission of Incident Radiation [28]

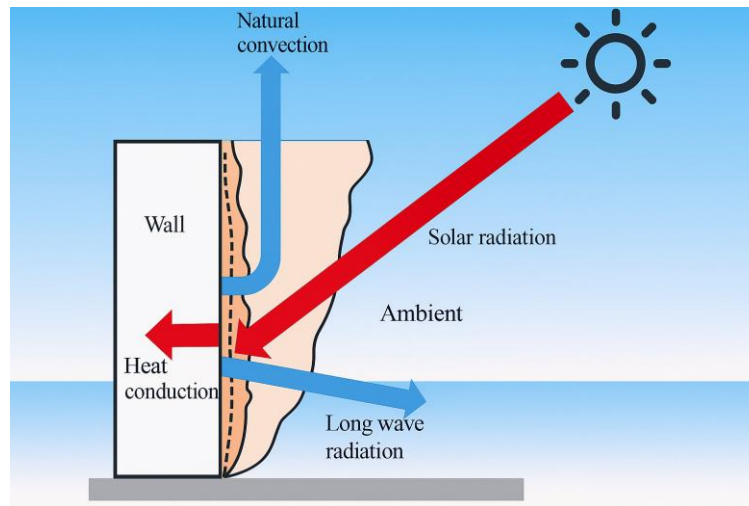


Figure 2. 6: Heat flux through the wall surface. Heat conduction, Solar radiation, Natural convection, long wave radiation [29]

2. Heat Storage in Walls and Ceiling

Chapter2: Mathematical Formulations of the Phenomenon

The materials used in the creation of the partitions and ceiling have thermal mass, allowing them to store heat during hot periods and release it gradually when the surrounding air is cooler. This thermal inertia helps regulate the internal temperature and dampens temperature fluctuations.

Energy Balance Equation (Simplified):

$$Q_{\text{radiation}} + Q_{\text{conduction}} + Q_{\text{convection}} = Q_{\text{loss}} + Q_{\text{stocked}}$$

Where:

$Q_{\text{radiation}}$: Heat input from solar and internal radiation

$Q_{\text{conduction}}$: Heat flow through walls, windows, etc.

$Q_{\text{convection}}$: Heat exchanged with air

Q_{loss} : Heat lost through ventilation or poorly insulated surfaces

Q_{stocked} : Heat stored in building materials [21]

Continuity Equation (Mass Conservation):

The continuity equation is a mathematical expression of the law of mass conservation in fluid dynamics. It states that mass can't be created or destroyed within a closed system, meaning that the change in mass inside a closed system is equal to the net mass flux throughout its boundaries..

For an incompressible fluid, the continuity equation is written as:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0$$

This equation is essential in airflow simulations within buildings to ensure that the velocity field is physically consistent and no artificial mass accumulation occurs.

$$\nabla \cdot (\rho \mathbf{v}) = 0$$

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Where:

ρ is the density of the fluid (air in your case).

\mathbf{v} is the velocity vector of the fluid. [30]

Navier-Stokes Equations:

The Navier-Stokes equations are a set of partial differential equations that describe the motion of fluids (liquids and gases) under the influence of various forces, including stress, viscosity, and gravity. These equations represent Newton's Second Law of fluid movement, accounting for the stability of forces acting on every infinitesimal detail of the fluid.

Assuming that air behaves as an incompressible Newtonian fluid, the momentum equations take the following shape in the three spatial directions (x, y, z):

In the x -direction:

$$\rho \left(\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} \right) = -\frac{\partial p}{\partial x} + \mu \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right) + \rho f_x$$

In the y -direction:

$$\rho \left(\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} \right) = -\frac{\partial p}{\partial y} + \mu \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} \right) + \rho f_y$$

In the z -direction:

$$\rho \left(\frac{\partial w}{\partial t} + u \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z} \right) = -\frac{\partial p}{\partial z} + \mu \left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} \right) + \rho f_z$$

These equations must be solved in conjunction with the continuity equation for incompressible fluids:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0$$

Notes:

u, v, w : Velocity components in the x, y, z directions respectively.

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ρ : Air density.

p : Pressure.

μ : Dynamic viscosity.

f_x, f_y, f_z : Body force components (e.g., gravity or buoyancy due to thermal effects). [30]

Energy equation:

$$\frac{\partial}{\partial t} \left(\rho \left(e + \frac{v^2}{2} \right) \right) + \nabla \cdot \left[\rho \vec{v} \left(h + \frac{v^2}{2} \right) \right] = \nabla \cdot \left(k_{\text{eff}} \nabla T - \sum_j h_j \vec{J}_j + \vec{\tau}_{\text{eff}} \cdot \vec{v} \right) + S_h$$

ρ is the fluid density.

e is the internal energy per unit mass.

$\frac{v^2}{2}$ is the kinetic energy per unit mass.

\vec{v} is the velocity vector.

h is the specific enthalpy.

k_{eff} is the effective thermal conductivity, which includes both molecular and turbulent conductivity.

T is the temperature.

h_j is the specific enthalpy of species j .

\vec{J}_j is the diffusion flux of species j .

$\vec{\tau}_{\text{eff}}$ is the effective stress tensor, accounting for viscous effects.

$\vec{\tau}_{\text{eff}} \cdot \vec{v}$ represents viscous dissipation.

S_h is a volumetric heat source term, which may include heat from chemical reactions, radiation, or other sources. [31]

2.1.Applications of the Heat Balance Equation

The heat balance equation is used in thermal comfort studies to determine the comfort level of individuals in various environments. In a mosque, for example, the heat balance equation can help determine how the building's design, ventilation systems, and occupant activity affect the thermal comfort of worshippers. By adjusting parameters such as air temperature, air velocity, and humidity, it is possible to determine whether the thermal environment is suitable or requires adjustments to achieve improved comfort.

The heat balance approach combines principles of heat transfer, thermal physiology, thermoregulation, anthropometry, and anatomy to create mathematical representations of the human body and its thermoregulatory systems (Krittiya, 2017). This approach aligns closely with the physiological thermoregulatory system of the human body. It functions on the principle that for thermal balance to be achieved, the rate of heat production through body metabolism must equal the rate of heat loss to the external environment through the body surface, respiratory system, and other physiological heat transfer mechanisms. These heat transfer mechanisms include convection, radiation, conduction, and evaporation processes. The metabolic process involves the conversion of consumed nutrients into metabolic energy through chemical and biological processes. While a portion of this energy is used for mechanical work, the majority is transformed into internal heat generation. To maintain thermal equilibrium, the heat generated by metabolism must be transferred to the surrounding environment at the same rate at which it is produced. The body consists of a central core with an average temperature, T_c , surrounded by an outer layer of tissue with an average temperature, T_{sk} , known as the mean skin temperature. The core temperature typically ranges from 36 to 38°C in a healthy body without heat strain. The skin temperature varies depending on several factors, including clothing, air temperature, air velocity, perspiration rate, and metabolic activity. In a resting person within an environment that is neither hot nor cold, the mean skin temperature is approximately 34°C, and this is termed the neutral skin temperature. However, when the environment removes heat from the human body at a rate that differs from the metabolic heat generated, a physiological response occurs. This response is an involuntary action taken by the body to restore a stable temperature balance with its surroundings, a process known as body thermoregulation. The human body contains temperature-sensitive receptors in both the core and skin, which respond to deviations of core temperature (T_c) and skin temperature (T_{sk}) from their neutral values. Heat transfer from the core to skin tissues primarily occurs through blood flow.

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When the core receptors signal a high temperature, vasodilation occurs, causing expansion of the relevant blood vessels to facilitate increased blood flow. Further increases in the high signals from core receptors trigger perspiration and evaporation, leading to cooling. When the skin receptors detect low signals indicating cold conditions, vasoconstriction occurs. This causes the blood vessels supplying the skin tissues to contract. The vital organs in the core of the body receive a continuous supply of warm blood, prioritizing their protection while allowing the skin to cool. As a result, in icy conditions, the extremities, such as fingers, toes, or ears, can be vulnerable to tissue damage from frostbite. Reduced skin temperature can also trigger involuntary muscular movements, known as shivering, in an attempt to generate additional metabolic heat. Therefore, the human body maintains its heat balance through continuous physiological heat exchange and metabolic heat production.

The heat balance equations system was developed to consider the metabolic processes involved in body-environment heat exchanges. It takes various forms but follows the same principles. Then, all equations share a common underlying concept, encompassing the balance of heat generation, heat transfer, and heat storage in the human body. The metabolic rate of the body (ϕ) provides energy for mechanical work (W), with the remaining energy released as heat ($\phi - W$). This heat is transferred from the body through conduction (ϕ^{cond}), convection (ϕ^{conv}), radiation (ϕ^{rad}), and evaporation (ϕ^{evap}) (Hensen, 1990). By combining these rates, the heat production equals the sum of heat loss rates, including heat storage (S). All terms are expressed in watts per square meter (W/m^2). The conceptual thermal balance equation is:

$$\phi - W = \phi^{evap} + \phi^{rad} + \phi^{conv} + \phi^{cond} + S \quad (1)$$

For thermal balance, the heat storage (S) should be zero ($S=0$). If $S>0$ (net heat gain), the body's core temperature will increase. Conversely, if $S<0$ (net heat loss), the heat storage will be negative and the body's core temperature will decrease. Thus, thermal balance is achieved when $S=0$.

$$\phi - W - (\phi^{evap} + \phi^{rad} + \phi^{conv} + \phi^{cond}) = 0 \quad (2) \quad [32]$$

Conclusion

The concept of thermal comfort in large indoor areas, particularly mosques, is shaped by several physical principles essential for effective design. Achieving thermal comfort requires a

Chapter2: Mathematical Formulations of the Phenomenon

deep understanding of heat transfer mechanisms and fluid dynamics. This knowledge is crucial in developing environments that promote well-being and productivity, particularly in mosques where people gather for extended periods of time.

Numerical simulations and mathematical analyses play a crucial role in evaluating thermal comfort within mosque environments. These fashions enable designers to predict how architectural functions interact with thermal performance, which is crucial for developing comfortable spaces. Understanding the primary heat transfer mechanisms, including conduction, convection, and radiation, is crucial for handling indoor climates, particularly in regions with high ceilings and diverse airflow patterns.

The precise architectural functions of mosques, which consist of expansive prayer halls and courtyards, notably affect their thermal environments. Heat transfer dynamics through surfaces, such as walls, ceilings, and flooring, along with factors including air temperature, humidity, and airflow, create complex thermal conditions. The heat balance equation for the human frame is crucial for understanding thermal comfort, as it illustrates the human response to various environmental conditions and environmental parameters that assist in optimizing individual comfort predictions.

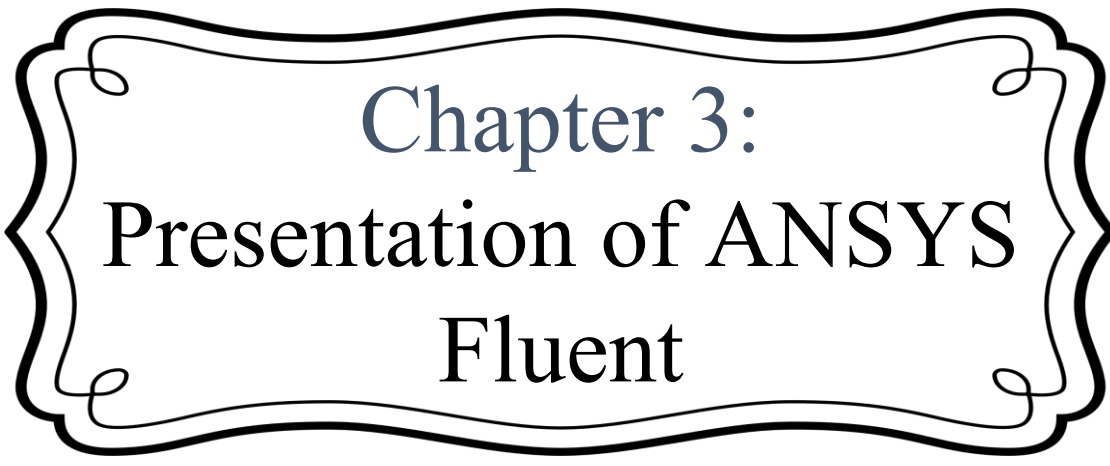
In conclusion, the mathematical formulations and indices explored provide a robust foundation for reading and optimizing thermal comfort in mosque settings. These gears align architectural functions with length, format, materials, and airflow systems to meet the thermal comfort needs of occupants.

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Chapter 3:
Presentation of ANSYS
Fluent

Introduction:

This chapter is going to dive into ANSYS Fluent, which is a super popular software package used for computational fluid dynamics (CFD). We'll walk through the main stuff: how you actually use it the usual steps you take (the workflow), what it can actually do (the core features), and how you look at your results afterward (post-processing). The idea is to give you a really solid grasp, especially if you're an advanced user or researcher.

1. What is ANSYS Fluent?

Ansys Fluent is a general-purpose computational fluid dynamics (CFD) software used to model fluid flow, heat and mass transfer, chemical reactions, and more. Fluent offers a modern, user-friendly interface that streamlines the CFD process from pre- to post-processing within a single window workflow. Fluent is known for its advanced physics modeling capabilities, which include turbulence modeling, single and multiphase flows, combustion, battery modeling, fluid-structure interaction, and much more.

Also known for its efficient HPC scaling, large models can easily be solved in Fluent on multiple processors on either CPU or GPU. Multiple solver options are available, including pressure-based and density-based CPU solvers to cover low-speed to hypersonic flows and a pressure-based native GPU solver. [33]

2. Workflow in ANSYS Fluent:

The workflow in ANSYS Fluent follows a structured, step-by-step path. It's designed to take real-world fluid flow and thermal problems and turn them into computational simulations through the use of numerical methods. The process covers several key stages: geometry creation, meshing, setting up the physics, running the solve, and then post-processing the results. Each one of these phases is absolutely essential for achieving accurate, stable, and efficient outcomes in your simulations. This systematic way of working is what allows users to simulate complex physical systems ranging from turbulent jets to heat exchangers with high fidelity and reproducibility. [33]

Chapter 3: Presentation of ANSYS Fluent

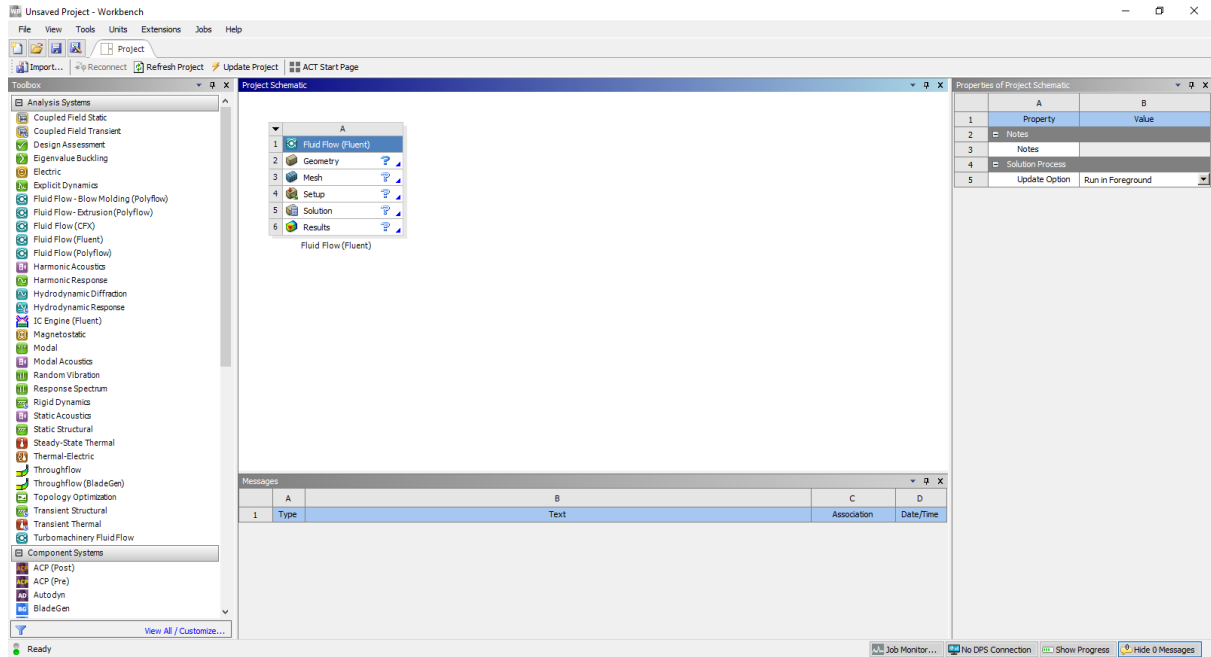


Figure 3. 1: ANSYS Fluent Workflow Stages

2.1. Geometry:

Geometry is created or imported using ANSYS DesignModeler or SpaceClaim. Engineers must simplify the geometry to remove small edges or features that may affect meshing. Clean geometries help in faster and more accurate mesh generation, especially when boundary layers and interfaces are involved. *Named selections* (inlets, outlets, walls) are defined here for ease of assigning boundary conditions later [37].

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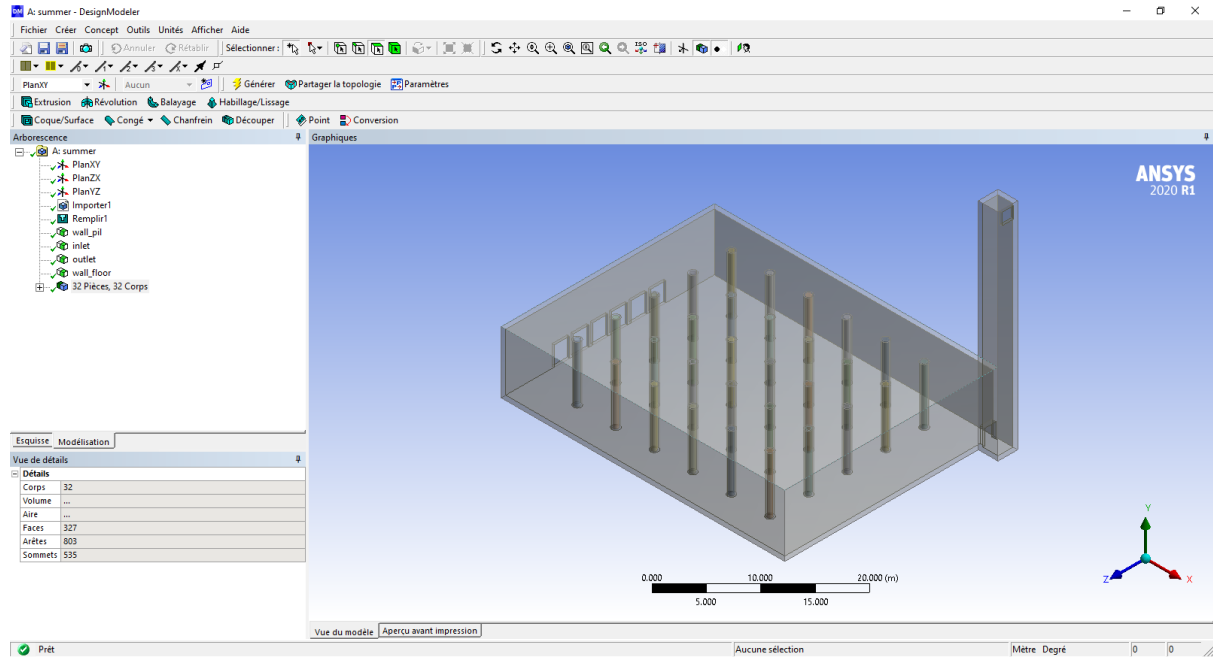


Figure 3. 2: Geometry Creation in ANSYS Fluent

2.2. Meshing

Meshing translates the geometry into discrete control volumes. Fluent supports structured (hexahedral), unstructured (tetrahedral, polyhedral), and hybrid meshes. Boundary layer refinement using inflation layers is crucial for resolving near-wall flows accurately. Good mesh quality (low skewness, good aspect ratio) ensures numerical stability and accuracy[37].

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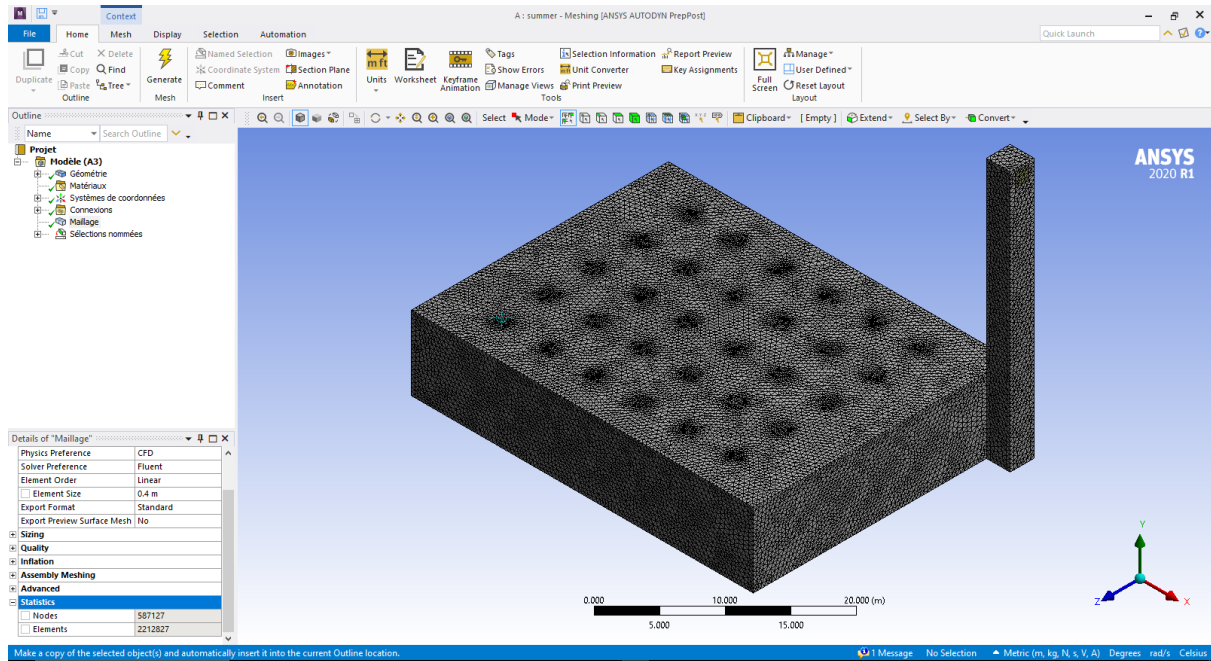


Figure 3. 3: Meshing in ANSYS Fluent

2.3. Physics Setup in Fluent

Classical Assumptions for Boundary Conditions

- Imposed Temperature or Flux**
Imposed temperature (Dirichlet): It is assumed that certain surfaces (walls, floor, ceiling) are maintained at a constant temperature, often equal to the outdoor ambient temperature or a measured value.
Imposed heat flux (Neumann): On other surfaces, a heat flux is imposed (e.g., incident solar flux, conduction losses, etc.). The assumption can also include a zero flux to model perfect insulation.
- Air Boundary Conditions**
Air Inlet: Assumption of an imposed air flow rate, temperature, and relative humidity at the inlet (e.g., fresh air at 30°C and 20% RH in summer).
Air Outlet: Often, a static pressure (usually atmospheric) or a constant mass flow rate is imposed at the outlet.
Solid walls: No-slip assumption for velocity (zero velocity at the wall) and heat exchange depending on the nature of the wall (adiabatic, conductive, etc.).
- Modelling Assumptions for Buildings**
Zone Homogeneity: Air temperature is often assumed to be uniform throughout a zone, which neglects thermal stratification or local convective phenomena in large spaces such as mosques.
Internal Loads: Thermal loads due to occupancy (number of people, activity, heat output) and lighting are set according to representative scenarios (e.g., occupant surface temperature at 37°C, lighting load at 20 W/m²).
Weather Conditions: External conditions (temperature, humidity, wind, solar

Chapter 3: Presentation of ANSYS Fluent

radiation) are assumed to be constant or variable according to hourly or seasonal profiles [RM1]. [RM1] À reservoir in Fluent:

- Select solver type (pressure-based or density-based) depending on compressibility.
- Choose steady or transient time settings.

In our case we used

- Pressure-based
- Steady
- Gravity ($Y = -9.81$)

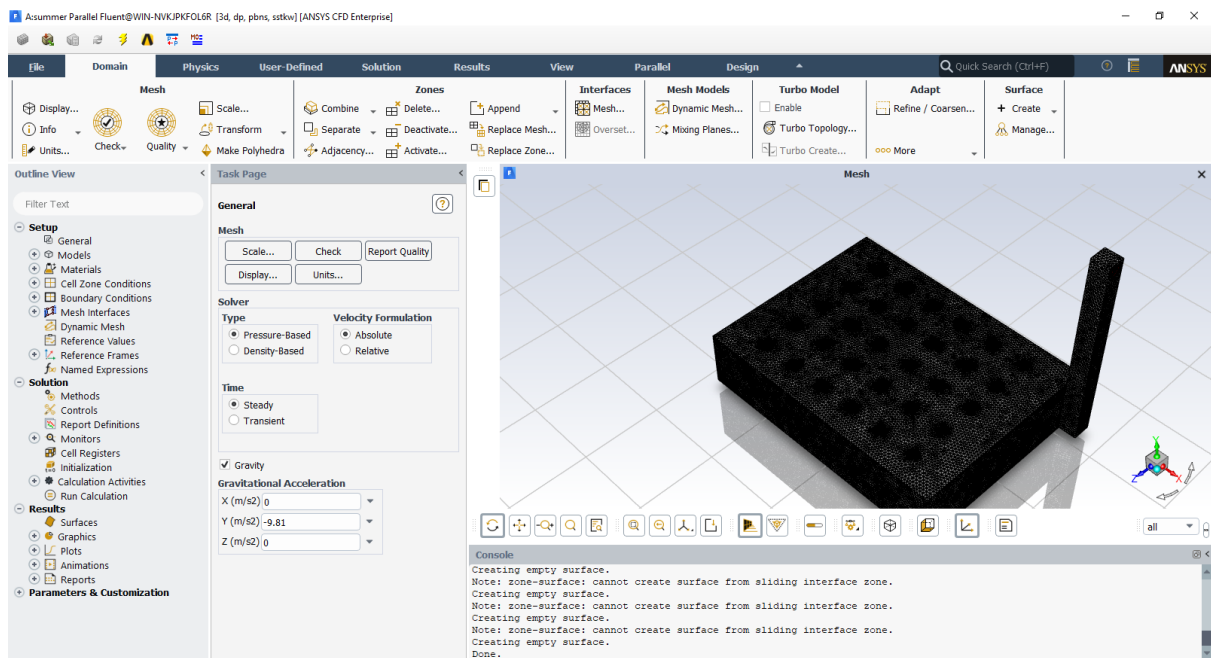


Figure 3. 4: Physics Setup in ANSYS Fluent

- Activate relevant models: energy (on/off), turbulence ($k-\epsilon$, $k-\omega$, LES), multiphase (VOF, Eulerian), heat transfer, species transport, etc.

In our case we used

- Energy (on)
- Turbulence (SST $k-\omega$)

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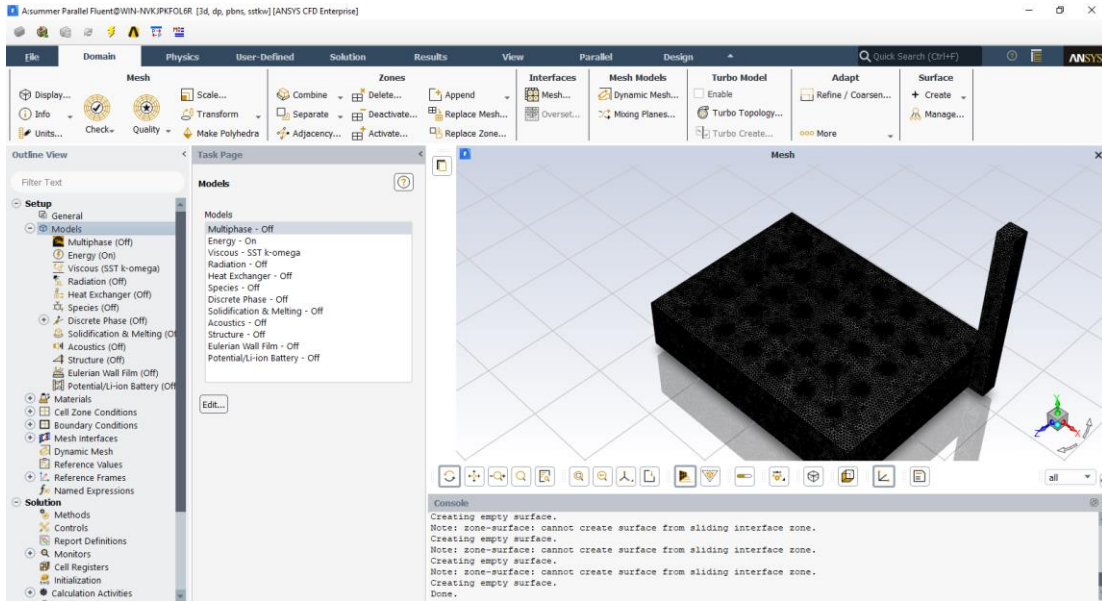


Figure 3. 5: Models in ANSYS Fluent

- Define material properties and apply them to domains.

In our case we used

- Air – boussinesq (fluid)
- Brick (Solid)

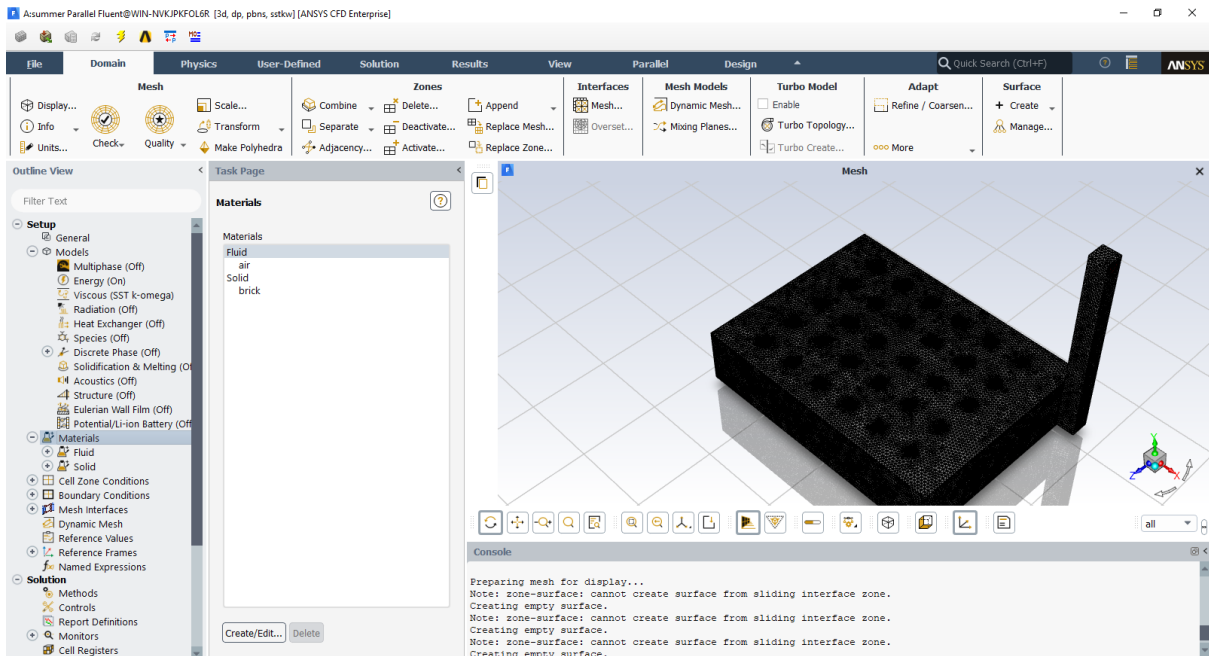


Figure 3. 6: Materials in ANSYS Fluent

Chapter 3: Presentation of ANSYS Fluent

- Assign boundary conditions based on physics (velocity inlet, pressure outlet, no-slip wall, etc.).

In our case we used

- Velocity inlet
- Pressure outlet
- Wall

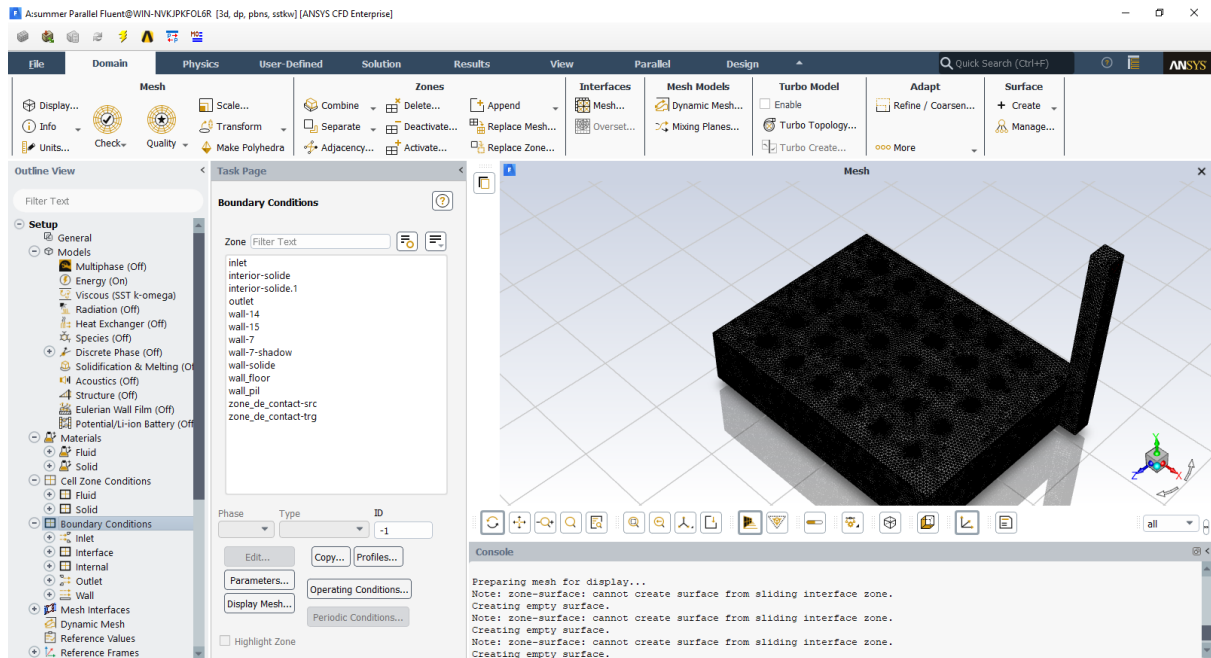


Figure 3. 7: Boundary condition in ANSYS Fluent

Advanced scripting (using text-based TUI logs) can automate complex setup steps and enable batch processing or team workflows[37].

2.4.Solution:

Control numerical accuracy via:

- Discretization schemes (1st or 2nd-order upwind),
- Under-relaxation factors
- Residual monitors for convergence.

Chapter 3: Presentation of ANSYS Fluent

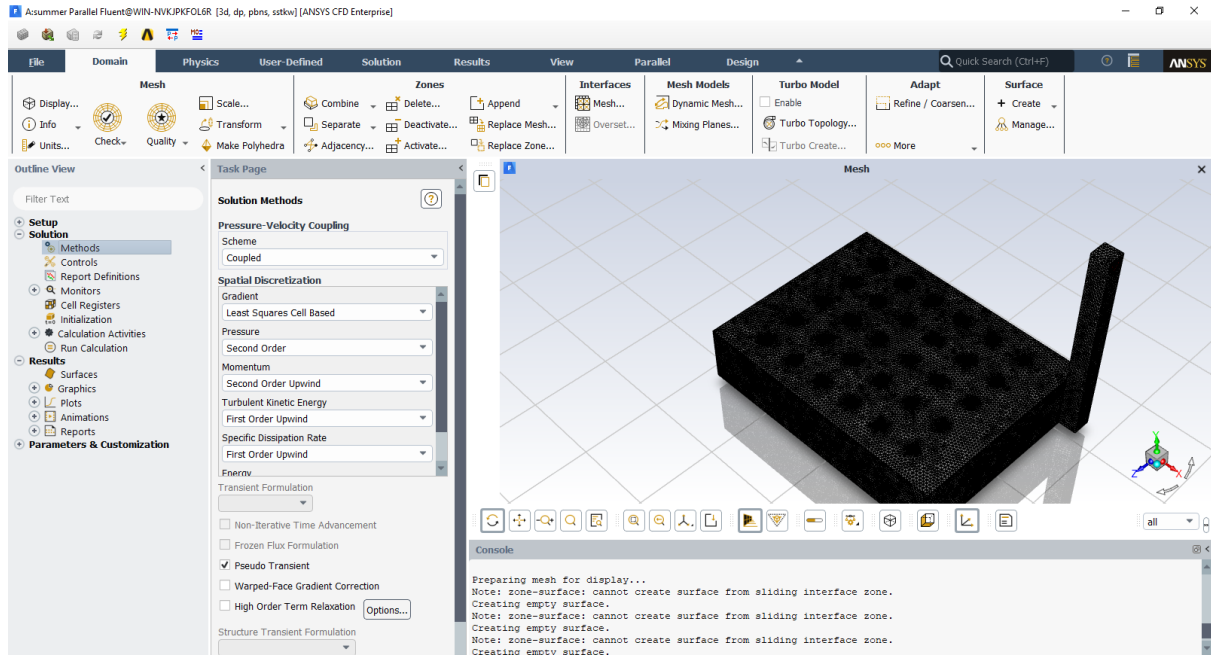


Figure 3. 8: Solution Control in ANSYS Fluent

Steady simulations run until residuals stabilize and monitored quantities (like lift, drag, or mass flow) become steady. Transient simulations require time-stepping and can simulate unsteady or periodic flows. Time-accurate modeling is essential in applications like aero-optical effects and heat-driven natural convection, both of which rely on dynamic solver settings and precise coupling[34],[36].

2.5.Post-Processing

Fluent's visualization tools allow:

- Contours (pressure, velocity, temperature)

Chapter 3: Presentation of ANSYS Fluent

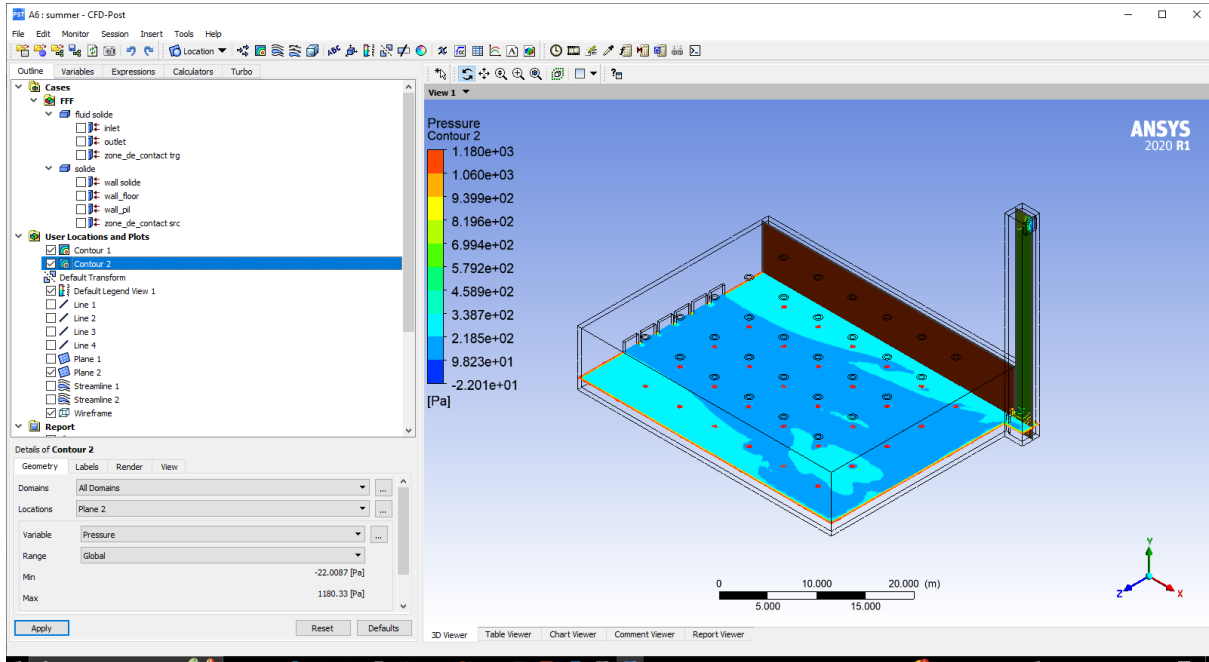


Figure 3. 9: Post-Processing in ANSYS Fluent (temperature contour)

- Streamlines, vectors, and iso-surfaces for fluid behavior visualization

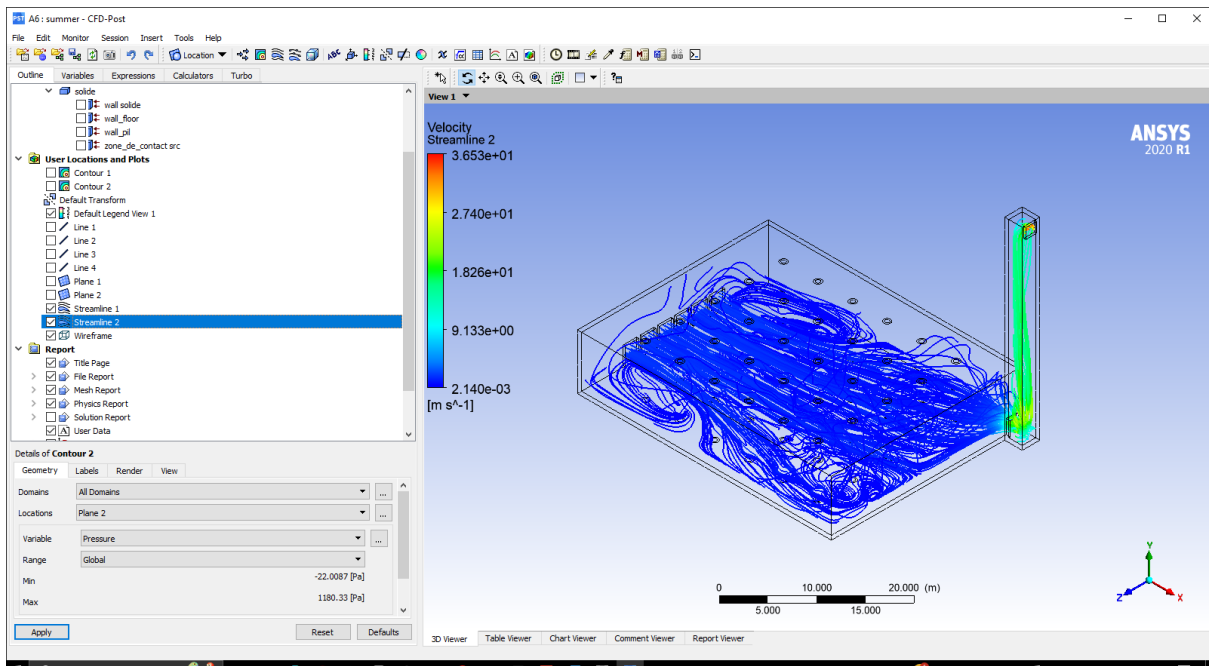


Figure 3. 10: Post-Processing in ANSYS Fluent (velocity streamline)

Chapter 3: Presentation of ANSYS Fluent

- Quantitative tools for surface integrals, force coefficients (C_l , C_d), and mass/energy balances.

For example, in solar still simulations, output such as condensation rates, heat flux, and thermal gradients are key insights provided through Fluent's post-processing modules[35].

Chapter 3: Presentation of ANSYS Fluent

Conclusion:

Each step in the Fluent workflow is validated by academic applications—from pre-processing with clean geometry and quality meshing to solver configurations that reflect the physics of the problem and rich visual/quantitative post-analysis. Efficient scripting, advanced solvers, and domain-specific models make Fluent a gold standard for CFD simulations across science and engineering.

References List:

Chapter 3: Presentation of ANSYS Fluent

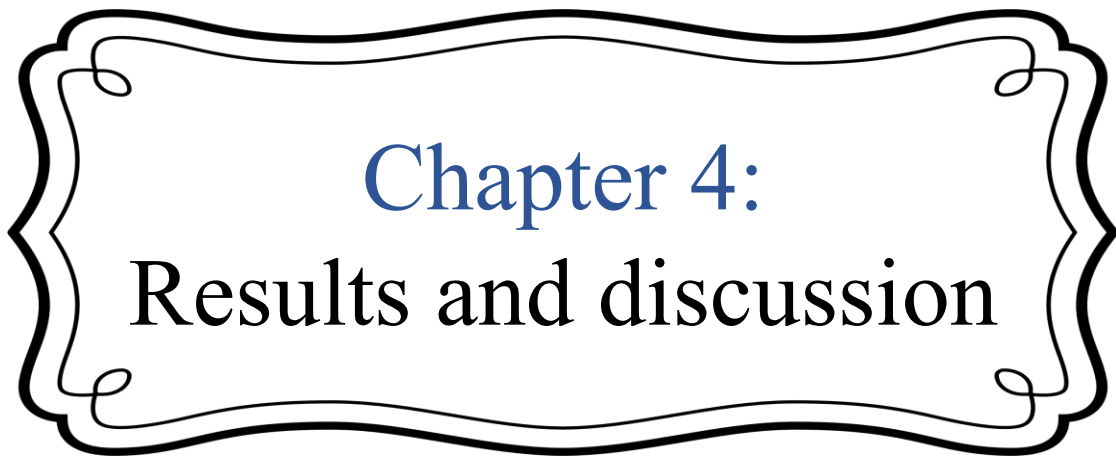
[33] ANSYS Fluent User's Guide. (2023). ANSYS, Inc.

[34] Versteeg, H. K., & Malalasekera, W. (2007). An Introduction to Computational Fluid Dynamics: The Finite Volume Method. Pearson Education.

[35] Blazek, J. (2015). Computational Fluid Dynamics: Principles and Applications. Elsevier.

[36] Ferziger, J. H., & Peric, M. (2002). Computational Methods for Fluid Dynamics. Springer.

[37] Patankar, S. V. (1980). Numerical Heat Transfer and Fluid Flow. Hemisphere Publishing Corporation.

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Chapter 4:
Results and discussion

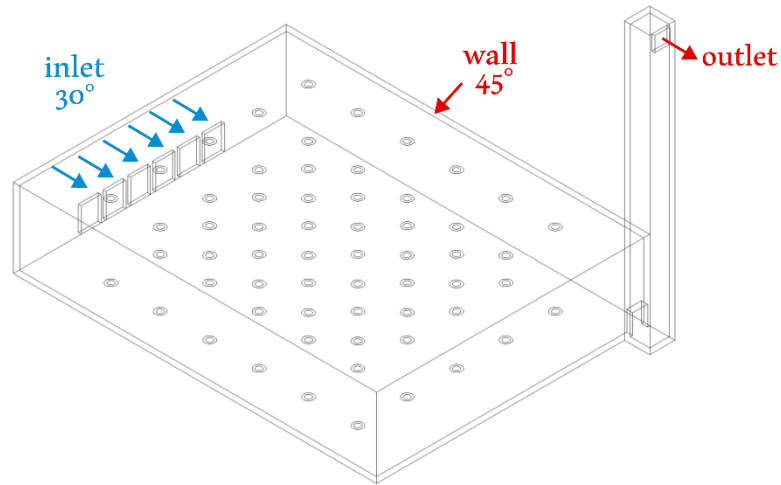
Chapter 4: Results and discussion

Introduction:

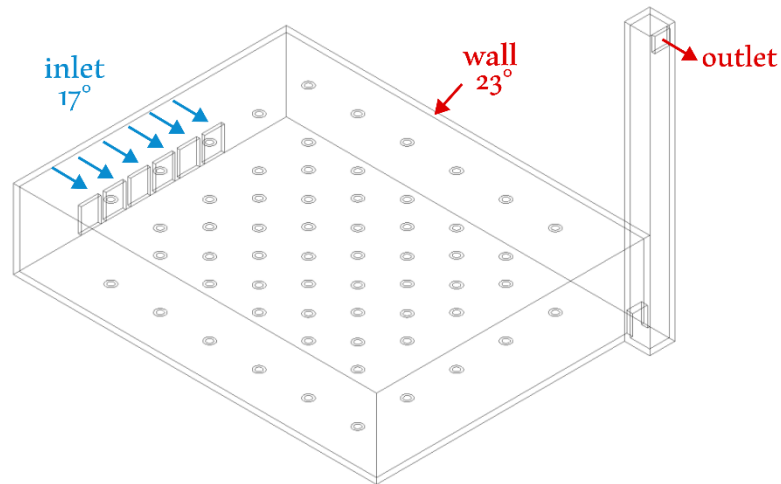
This chapter is all about sharing the results from a computational fluid dynamics (CFD) simulation we ran using ANSYS Fluent. We specifically wanted to investigate how the connection port design on the minaret impacts thermal comfort inside a mosque's prayer hall. The core goal of this study was to really explore how making architectural modifications right at that interface between the prayer space and the minaret could influence how air behaves indoors and how temperatures distribute, ultimately affecting how comfortable the people inside feel.

We simulated multiple different port configurations, making sure they were all run under identical boundary conditions. We then assessed how well each one performed by looking at key parameters derived from the CFD data – things like velocity Streamline, temperature contours, and chart. So, this chapter will take you through how these architectural changes influenced the airflow dynamics and thermal comfort within the prayer hall, backing everything up with detailed visualizations and the quantitative outputs we got straight from ANSYS Fluent.

1. Simulation results for the real case of the mosque (without modification):



(a)



(b)

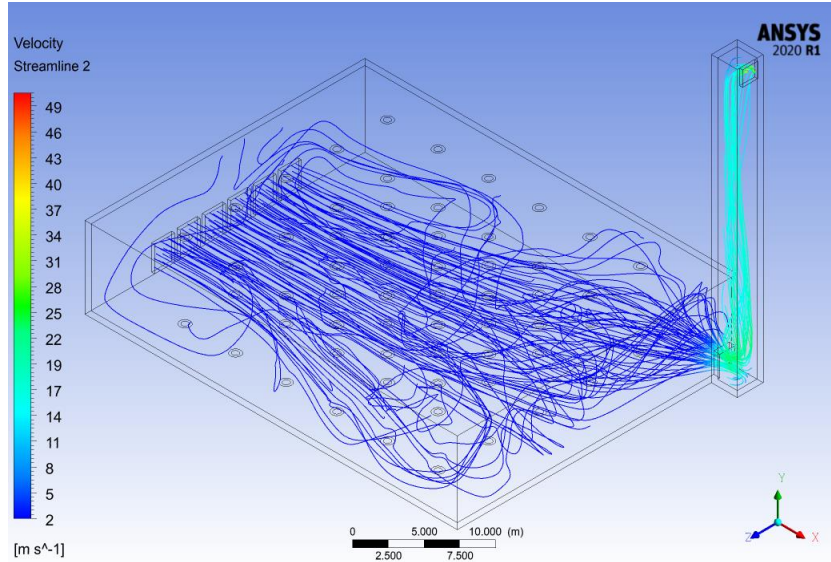
Figure 4. 1: Boundary conditions for two periods a) Summer, b) Winter.

The analysis of the figures in Figure 4. 1, The prayer hall's boundary conditions during the summer and winter seasons are depicted in the following figure 4.1: In the summer, the inlet air temperature is 30°C, while the temperature of the external walls reaches 45°C. This underscores the high risk of overheating, which necessitates the effective management of natural ventilation and solar protection, particularly due to the shade cast by the minaret. In the winter, the inlet air

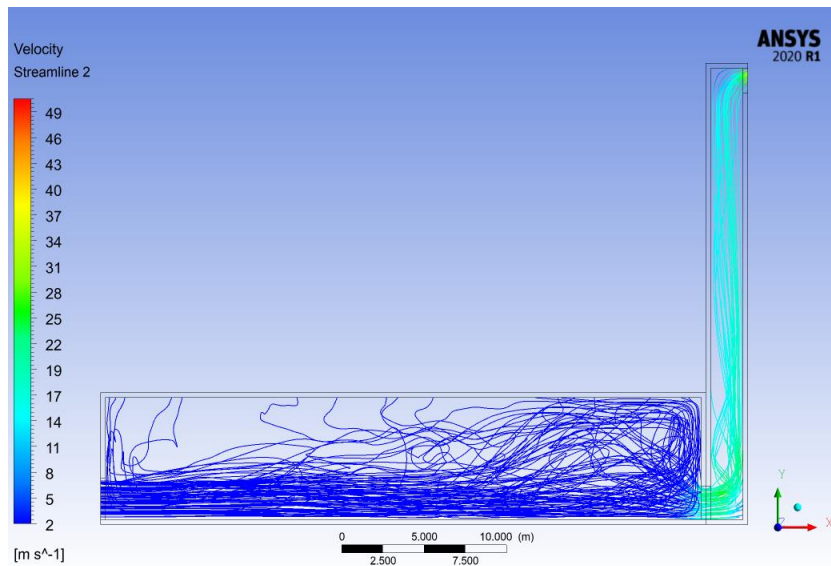
Chapter 4: Results and discussion

temperature is 17°C , and the temperature of the external walls is 23°C . These values are closer to the indoor temperature, which restricts heat loss. However, they underscore the significance of the thermal inertia of the materials and the insulation at the junction with the minaret in order to ensure optimal thermal comfort in the prayer hall.

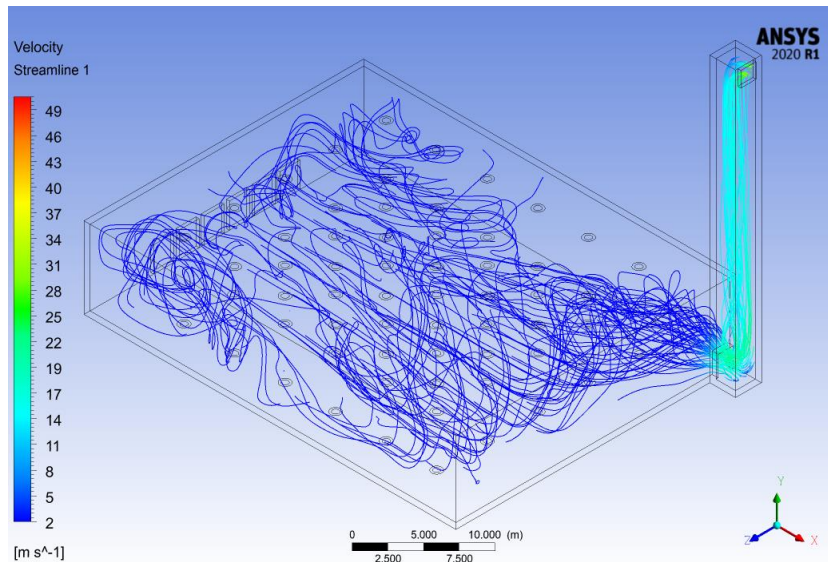
1.1.Streamlines evolution:



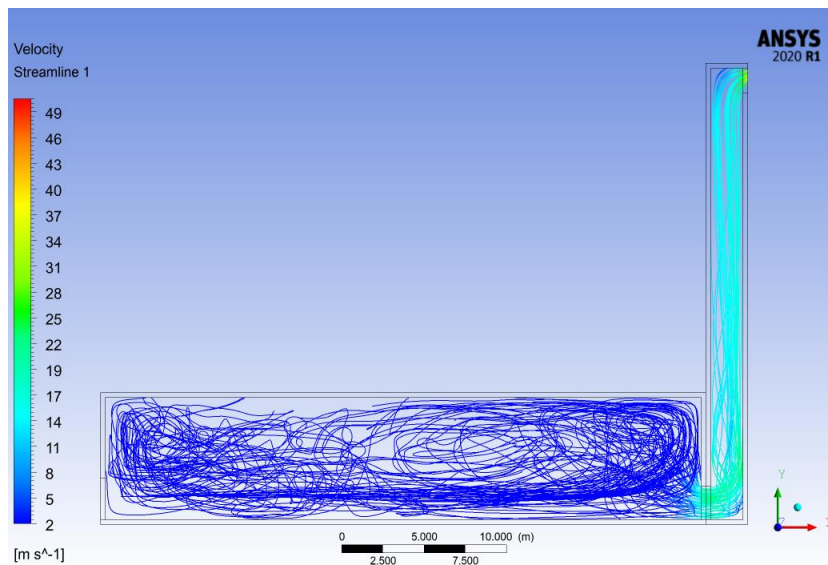
(a1)



(a2)



(b1)



(b2)

Figure 4. 2: Streamlines evolution during the period: a1) Summer 3D, a2) Summer 2D, b1) Winter 3D and b2) Winter 2D

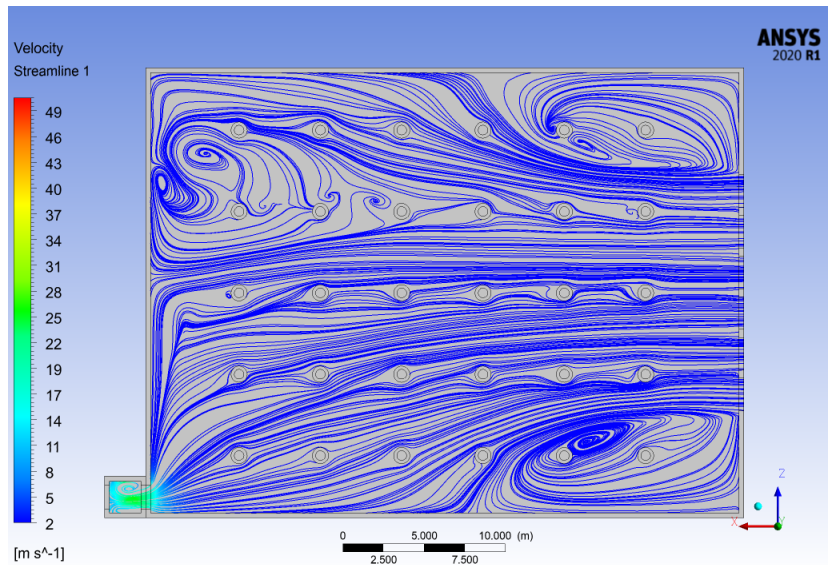
The analysis of the figures in Figure 4. 2, illustrates the progression of the streamlines throughout the prayer hall and minaret. The streamlines illustrate the path that fluid particles would

Chapter 4: Results and discussion

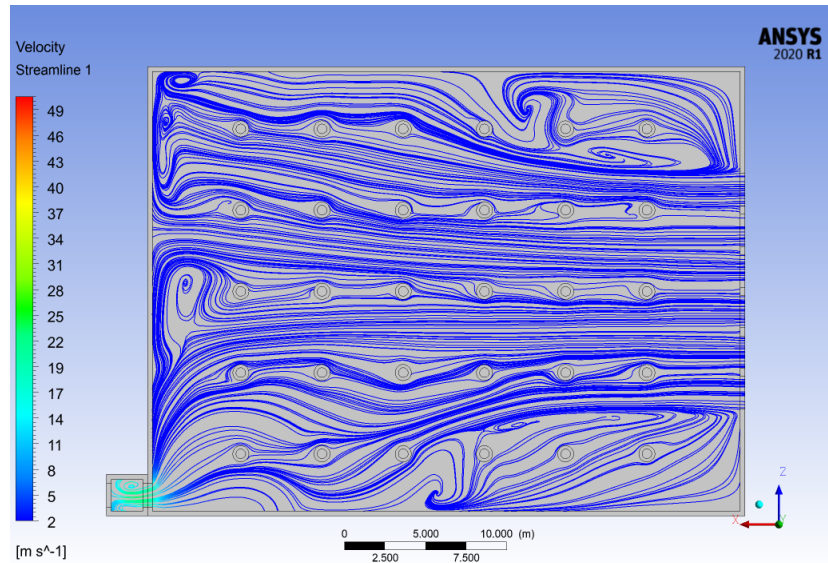
traverse in the wind at the mosque entrance under a certain velocity. The input velocity is 2 m/s, and it attains an outlet velocity of 20 m/s at the apex of the minaret. The airspeed inside the prayer hall remains constant at 2 m/s; however, the airflow is redirected due to the presence of the wall and beams. They enable us to visualize the ventilation influenced by the architectural geometry, especially the existence of the minaret. The acceleration of air towards the minaret's base generates a depression that aids in the expulsion of hot air during summer via the chimney effect. This contributes to reducing the felt warmth in the prayer space.

Velocity streamlines show air drawn from the prayer hall into the minaret base. This illustrates the minaret's potential to drive natural ventilation. Airflow patterns indicate upward movement within the minaret shaft.

Velocity streamlines (Winter) show air drawn into the minaret base. The flow pattern differs from the summer case, but the minaret still drives ventilation. Air is extracted from the prayer hall, influencing internal circulation.



(a)



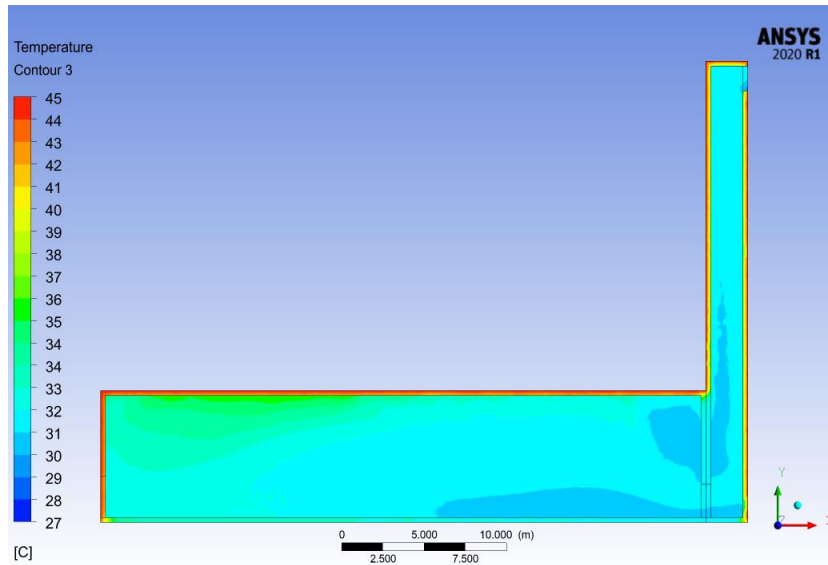
(b)

Figure 4. 3: 2D streamlines evolution during period: a) summer b) winter

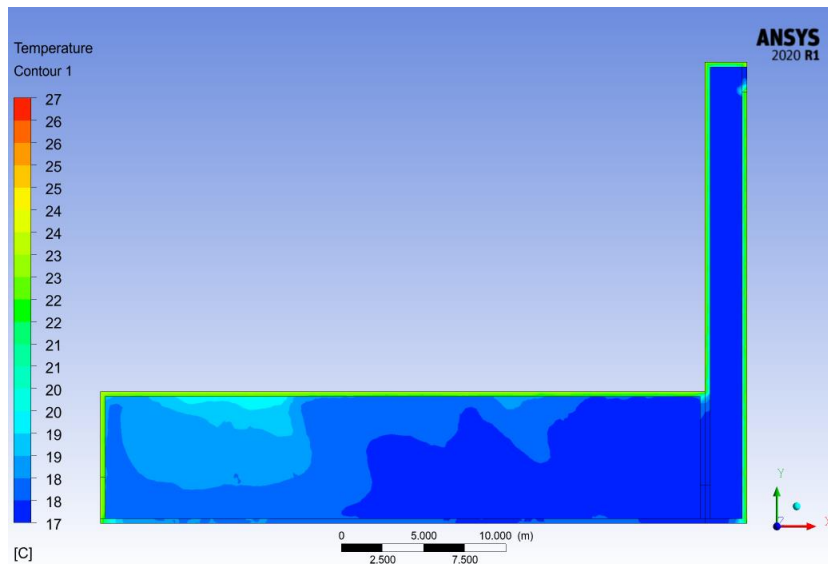
The analysis of the figures in Figure 4. 3, at a height of 1.5 m within the mosque and minaret during both summer and winter reveals that the density of flow lines is markedly greater in summer, signifying enhanced air circulation assisted by an entry velocity of 2 m/s. This phenomenon generates distinct turbulence zones, especially around obstructions and corners, where local velocity diminishes, and the air assumes swirling paths, resulting in characteristic recirculation that can locally affect thermal comfort. The structural beams significantly impact the direction of flow lines by deflecting, fragmenting, or accelerating air flows, depending on their positioning, thereby augmenting the complexity of trajectories and potentially intensifying the formation of turbulence zones downstream. The chimney effect produced by the architectural design results in a remarkable increase in airflow velocity at the minaret's entrance, achieving speeds of 17 to 19 m/s during summer, thereby validating the device's efficacy in swiftly expelling trapped hot air and enhancing natural ventilation. During winter, the circulation becomes milder, the density of the streamlines diminishes, and the turbulence zones are less broad, promoting heat retention.

1.2. Temperature evolution

Chapter 4: Results and discussion



(a)



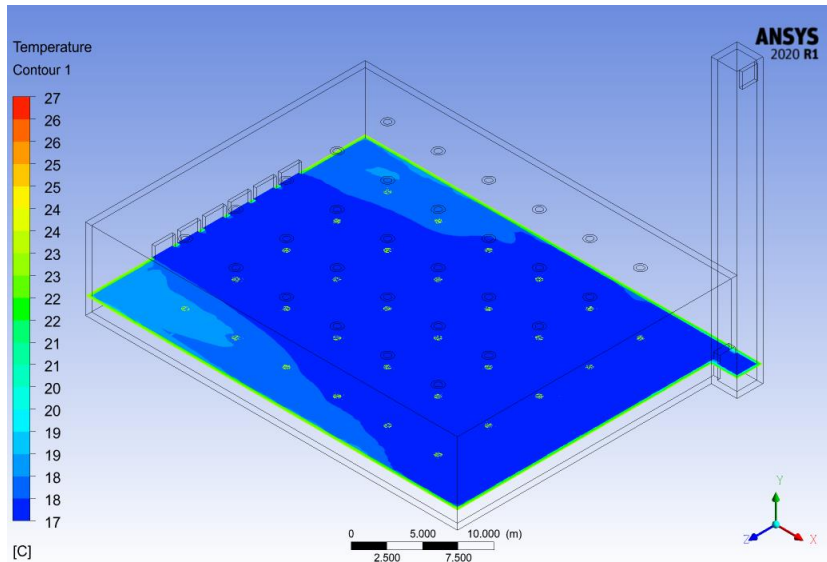
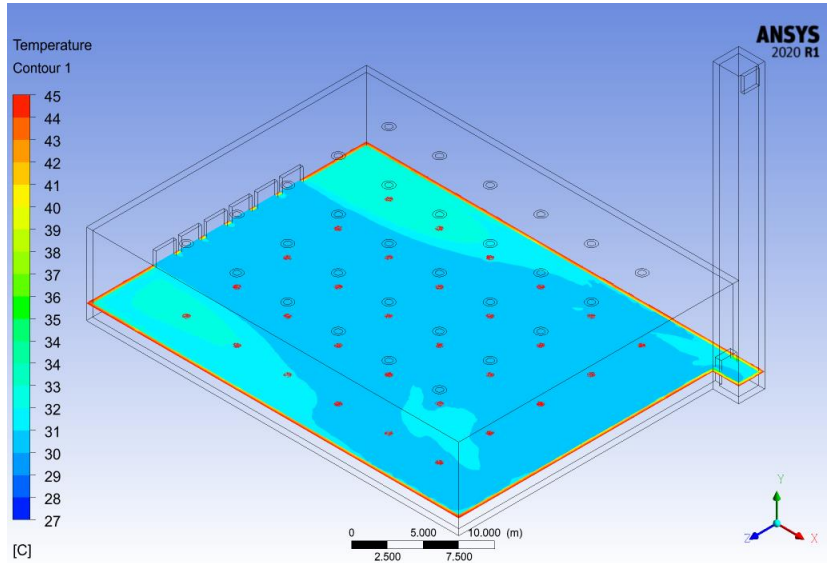
(b)

Figure 4. 4: Temperature Contour evolution during period: a) summer b) winter

The analysis of the figures in Figure 4. 4, in the center of the door between the prayer hall and the minaret reveals a significant disparity between the two seasons: During summer, with external walls at 45°C and an initial interior temperature of 30°C, warm air accumulates in the prayer hall, resulting in a pronounced thermal increase towards the door, facilitating heat transfer to the minaret and heightening the necessity for ventilation to alleviate this thermal surplus;

Chapter 4: Results and discussion

conversely, During winter, with exterior walls at 23°C and an initial interior temperature of 17°C, a markedly cooler environment is established. The temperature profile reveals a more gradual transition through the door, characterized by a diminished thermal gradient and decreased ventilation demand, which facilitates heat retention within the mosque and ensures thermal comfort suitable for the cold season.

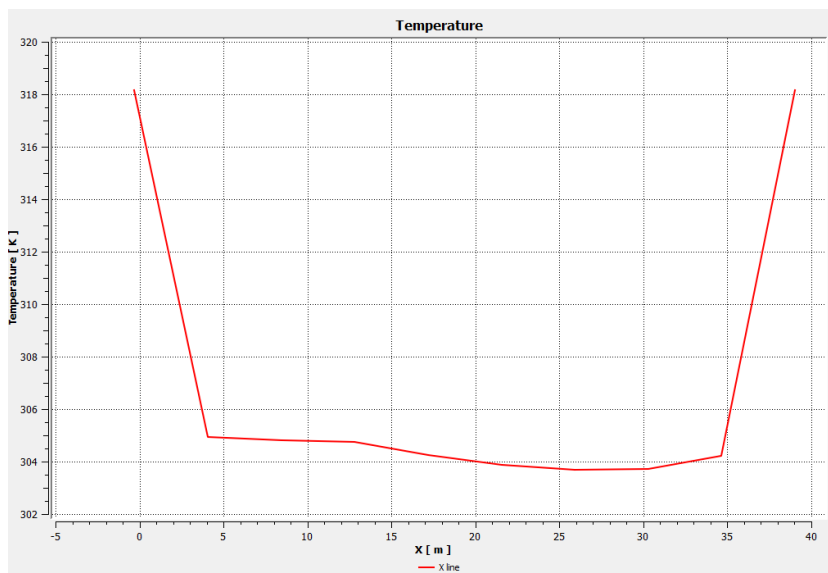


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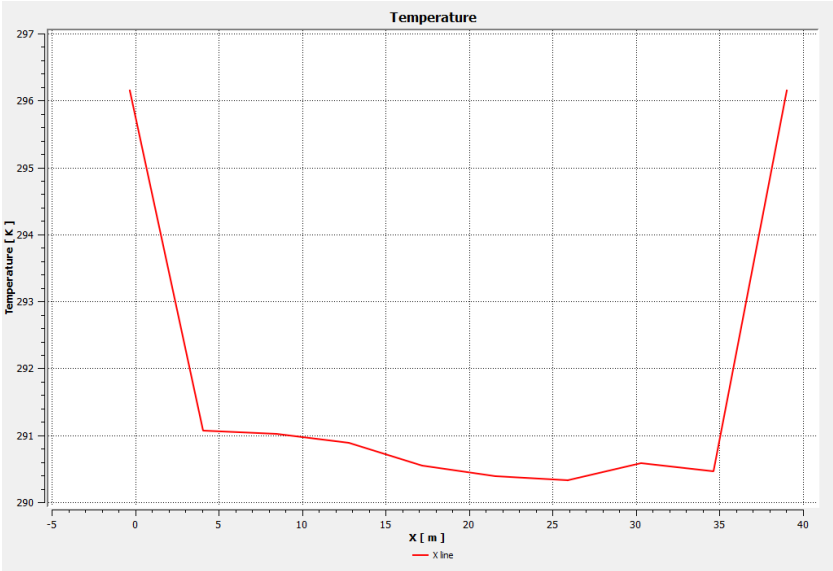
Figure 4. 5: ZX Plan Temperature Contour during period: a) summer b) winter

The analysis of the figures in Figure 4. 5, illustrates a top-down view of the temperature contour at an elevation of 1.5 m, corresponding to the average height of a human. A vast expanse of milder air (approximately 31-33°C) is discernible in summer conditions, extending from the inlet on the left to the front and central regions of the hall. This view illustrates that the natural ventilation system is effectively supplying cooled air to a substantial portion of the occupied space. The air progressively warms as it travels from left to right, absorbing heat from the building's structure and occupants. Towards the rear of the chamber, temperatures climb into the green range (34-36°C).

The plane at 1.5 meters demonstrates that the minaret-driven system generates distinct thermal zones, which directly affect the comfort of the occupants: The occupants of the front and middle portions of the mosque would experience the most agreeable conditions, as they would be exposed to a consistent flow of colder, fresher air. The area closest to the base of the minaret on the right is the warmest. This region is the point at which the heated interior air congregates before being drawn up and exhausted by the minaret. The individuals residing in this particular area would experience a higher level of warmth than those in the remainder of the hall.



(a)



(b)

Figure 4. 6: X line Temperature Chart during period: a) summer b) winter

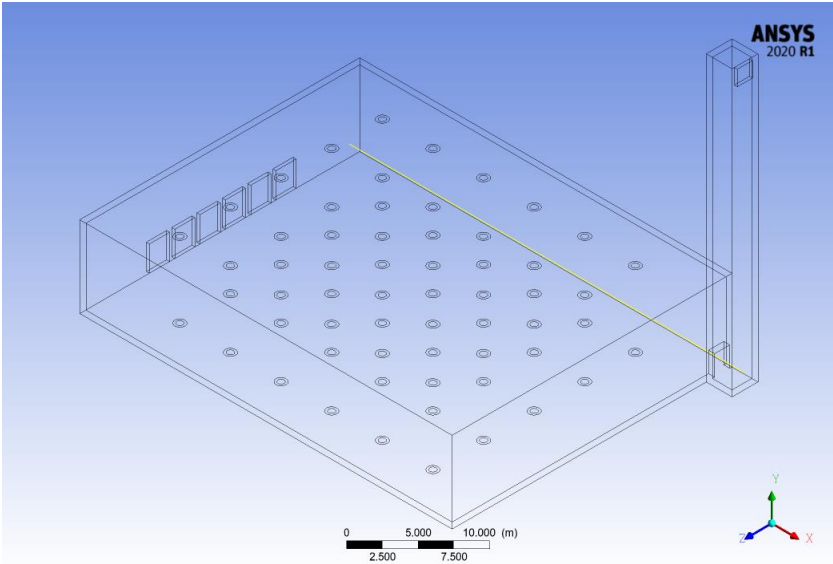


Figure 4. 7: Measure line demonstration (X line)

The analysis of the figures in Figure 4. 6, illustrates the temperature profile graph along a line (X-axis) within the prayer hall. The yellow line indicates the "X line" along which temperature data is plotted. This line traverses a significant portion of the prayer hall and extends into the area connecting to the minaret.

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Start of the X line ($x = -5\text{m}$ to $x = 4\text{m}$): High Temperature (around $318\text{ K} / 45^\circ\text{C}$). The temperature starts very high, peaking at approximately 318 K (around 45°C). This initial high temperature likely represents the temperature of an external wall or the immediate vicinity of a hot surface, consistent with the given wall temperature. This might be the external boundary or a wall section through which the line passes before entering the main occupied space.

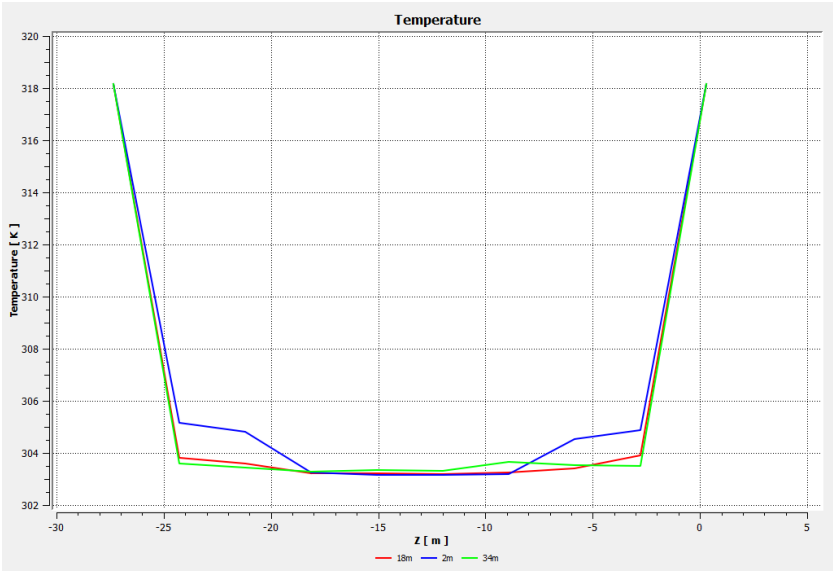
Transition and Initial Drop ($x = 4\text{m}$ to $x = 5\text{m}$): There is a sharp drop in temperature from 318 K to approximately 305 K (around 32°C). This indicates that the X line is moving away from the very hot external wall/boundary and into the main prayer hall, where cooler air (from the inlet) is present.

The main prayer hall ($x = 5\text{m}$ to $x = 34\text{m}$) is relatively Stable, with a gradual increase. In this long section, representing the core of the prayer hall, the temperature remains relatively stable, fluctuating between approximately 304 K and 305 K (around $31\text{-}32^\circ\text{C}$). Initially, it's around 305 K , then slightly drops to approximately 304 K (around 30.85°C) in the middle section (approximately $x = 20\text{m}$ to 30m). This suggests that the coolest air from the inlet has a more significant impact in the central-to-mid sections of the hall, or perhaps it's a zone of relatively good airflow. The values of 304 K to 305 K are very close to the inlet temperature of 30°C (303.15 K), indicating that the cooling effect from the inlet air is reasonably practical in this primary occupied zone.

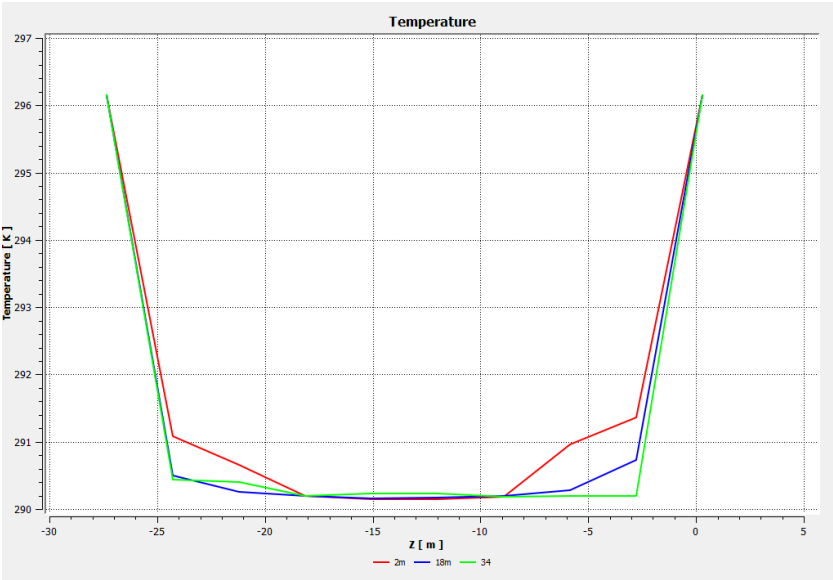
Approaching the minaret ($x = 34\text{m}$ to $x = 36\text{m}$), there is a gradual rise; as the X line approaches the connection point to the minaret, the temperature starts to rise again, from around 304 K to about 305 K . This indicates that the air is getting warmer as it moves towards the exhaust point.

The minaret connection/outlet zone ($x = 36\text{m}$ to $x = 39\text{m}$) experiences a sharp increase in temperature, mirroring the initial peak; the temperature rises from 305 K to over 318 K (approximately 45°C). This final sharp rise indicates that the X line has reached the area directly connected to the minaret, which effectively exhausts the hottest air from the prayer hall. The temperature reaches the maximum given wall temperature of 45°C (318.15 K).

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(a)



(b)

Figure 4. 8: Z Lines Temperature Chart during period: a) summer b) winter

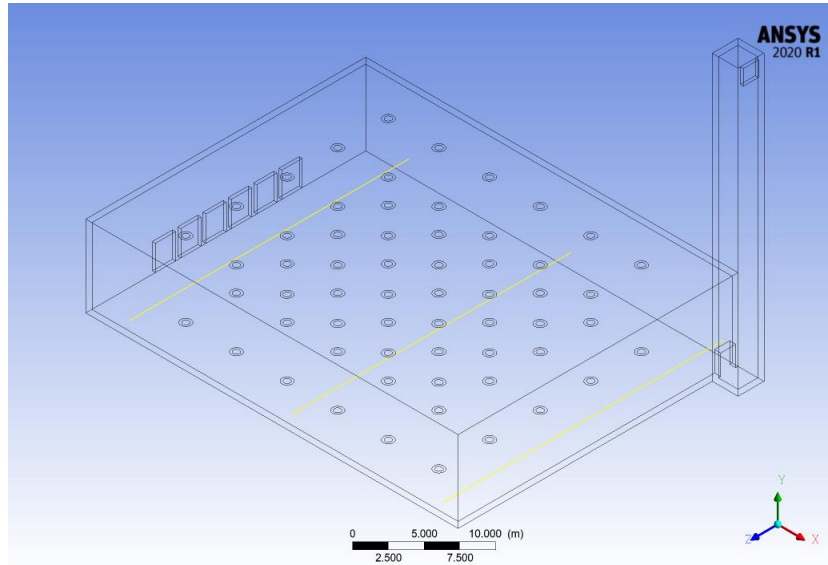


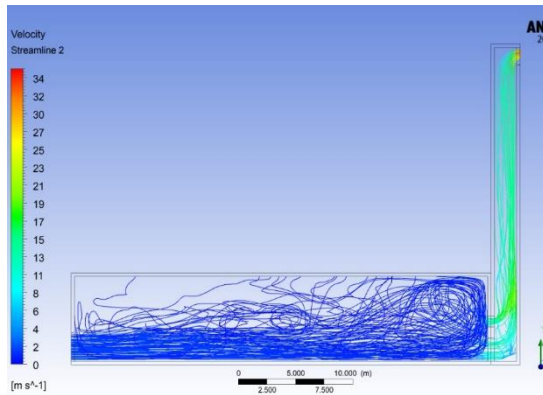
Figure 4. 9: Measure line demonstration (Z line)

The analysis of the figures in Figure 4. 8, Temperature comparison graph along Z-axis lines (18m, 2m, 34m). Shows cooler, stable temperatures ($\sim 303\text{-}304\text{ K}$) in the central region across different lines. This quantifies thermal uniformity influenced by ventilation patterns.

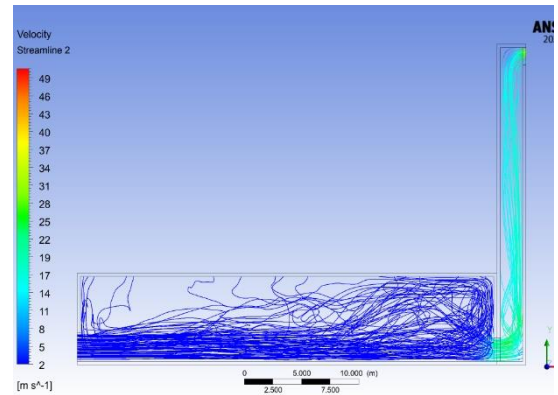
2. Simulation results for modified case (Door & Window Open):

2.1. Door & Window Open (1m apart)

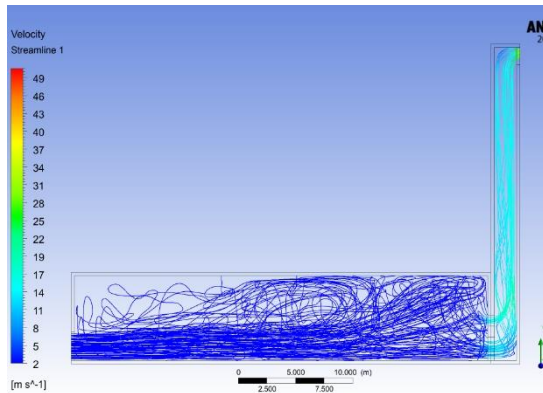
2.1.1. Streamlines evolution:



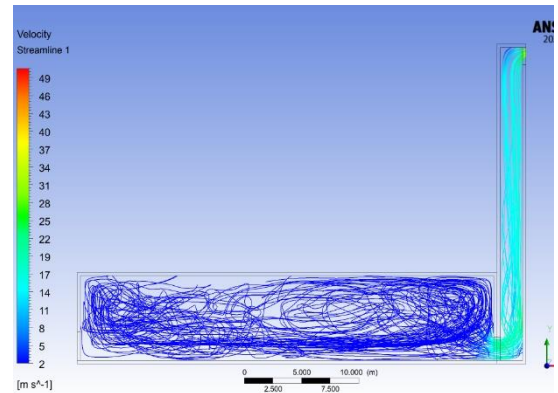
(a1)



(a2)



(b1)



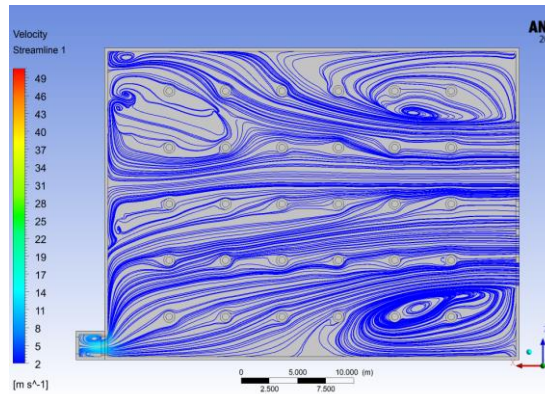
(b2)

Figure 4. 10: Streamlines evolution: a1) Summer case 1m, a2) Summer case, b1) Winter case 1m and b2) Winter case

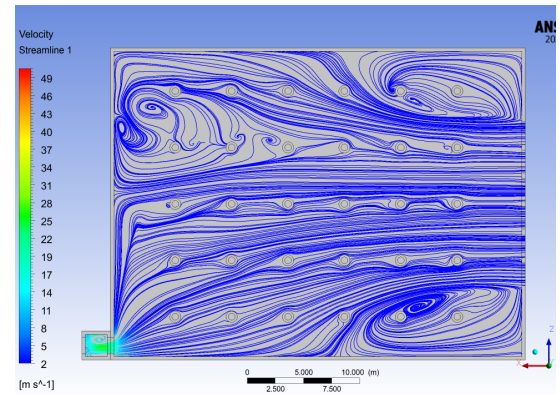
The analysis of the figures in Figure 4. 10, The density of the streamlines in the connection zone is significantly increased by the addition of an opening 1 meter above the door connecting the prayer room and the minaret, in combination with an air entry speed of 2 m/s. This results in a more dynamic air circulation and a markedly improved hot air suction rate. This configuration promotes the acceleration of the flow, ensuring that the airspeed at the entrance of the minaret reaches between 17 and 19 m/s, thereby optimizing the extraction. In addition, the orientation of the streamlines is influenced by the presence of this new opening and the arrangement of the beams, which guides and structures the air trajectories while reducing areas of stagnation and turbulence.

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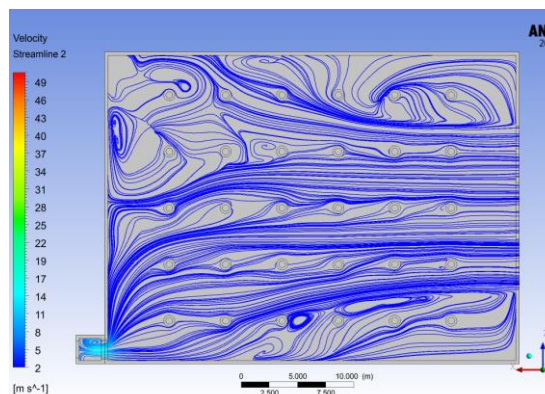
This results in improved thermal comfort and more effective natural ventilation in the prayer hall and the minaret. Velocity streamlines (Summer, Door & Window Open, 1m apart). Air enters through the door/window and exits via the minaret. The minaret drives ventilation, influencing airflow patterns across the hall.



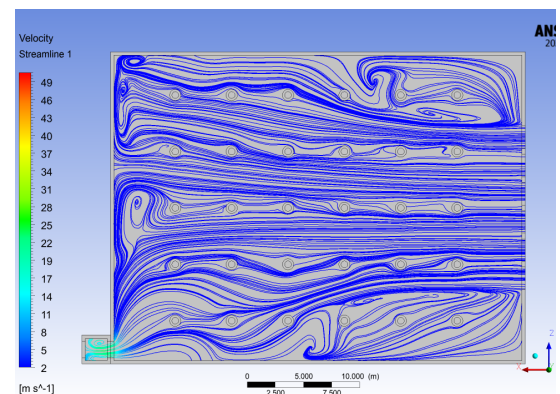
(a1)



(a2)



(b1)



(b2)

Figure 4. 11: 2D streamlines evolution: a1) New case summer, a2) Initial case summer, b1) New case winter and b2) Initial case winter.

The analysis of the figures in Figure 4. 11, The density of the streamlines (see fig2.1.2) in the connection zone is significantly increased by the addition of an opening 1 meter above the door connecting the prayer room and the minaret, in combination with an air entry speed of 2 m/s. This results in a more dynamic air circulation and a markedly improved hot air suction rate. This configuration promotes the acceleration of the flow, ensuring that the airspeed at the entrance of the minaret reaches between 17 and 19 m/s, thereby optimizing the extraction. In addition, the orientation of the streamlines is influenced by the presence of this new opening and the

Chapter 4: Results and discussion

arrangement of the beams, which guides and structures the air trajectories while reducing areas of stagnation and turbulence. This results in improved thermal comfort and more effective natural ventilation in the prayer hall and the minaret.

2.1.2. Temperature evolution:

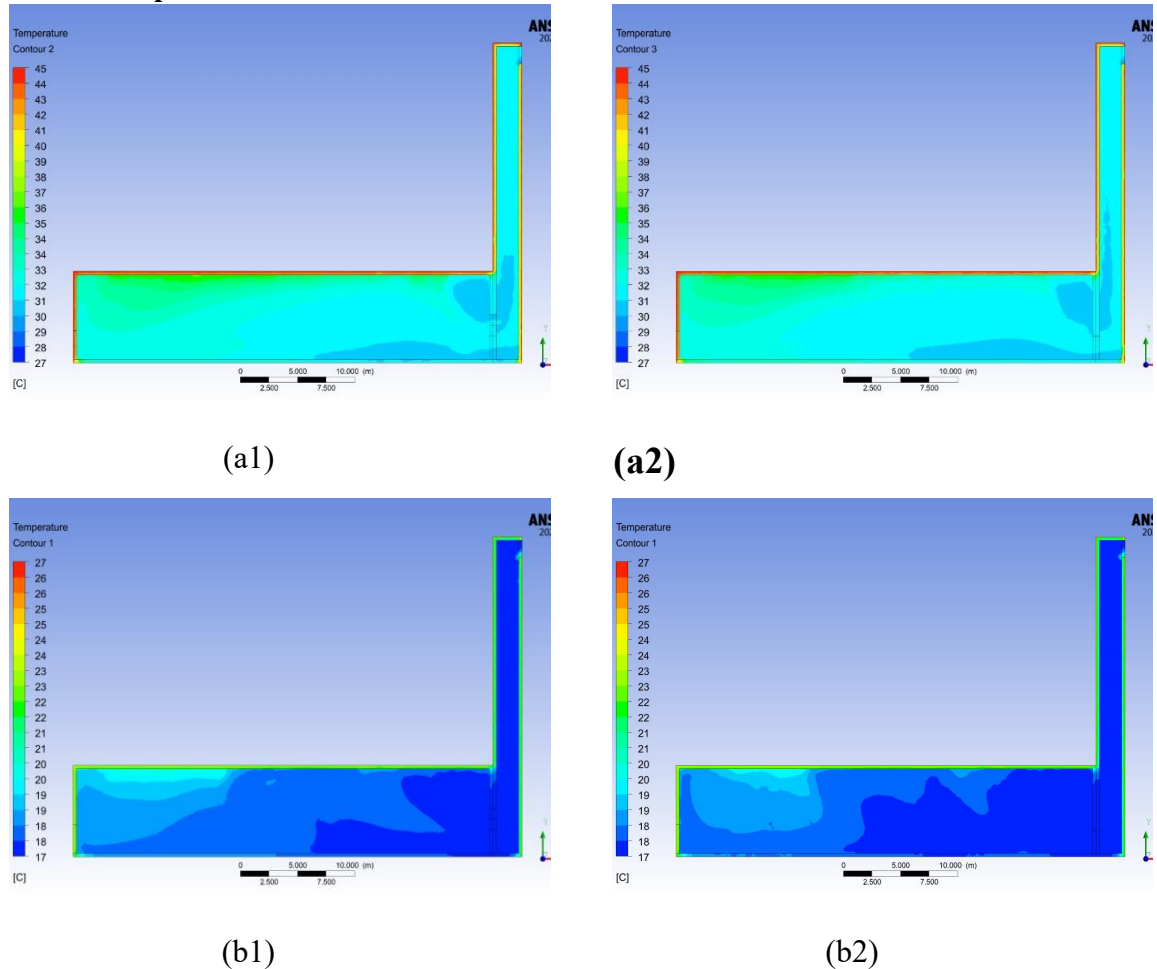
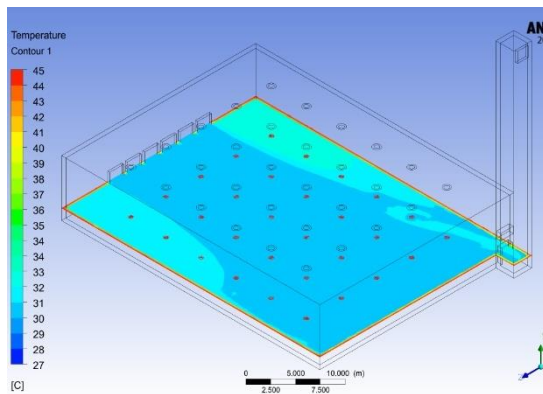


Figure 4. 12: Temperature Contour – Vertical plane: a1) New case summer, a2) Initial case summer, b1) New case winter and b2) Initial case winter

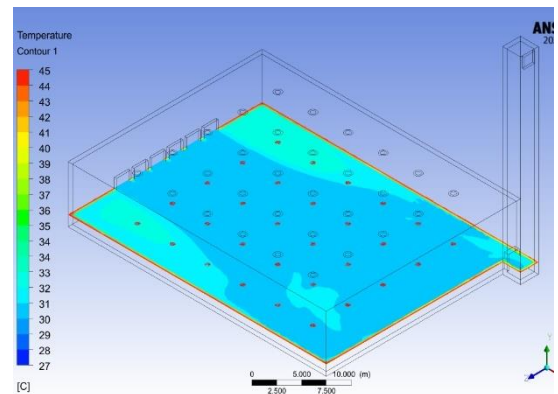
The analysis of the figures in Figure 4. 12, The seasonal impact and the effect of adding an opening 1 metre above the door connecting the prayer room to the minaret are highlighted in the comparative analysis of temperature profiles in the prayer room, as illustrated in **figure 4.3**: In the summer, the indoor temperature can reach as high as 37°C in the absence of an additional opening, resulting in a hot zone and significant thermal discomfort. However, the addition of the opening significantly reduces the maximum temperature in the prayer room, allowing it to hover around 32°C, thereby enhancing thermal comfort by facilitating the evacuation of hot air. In winter, the

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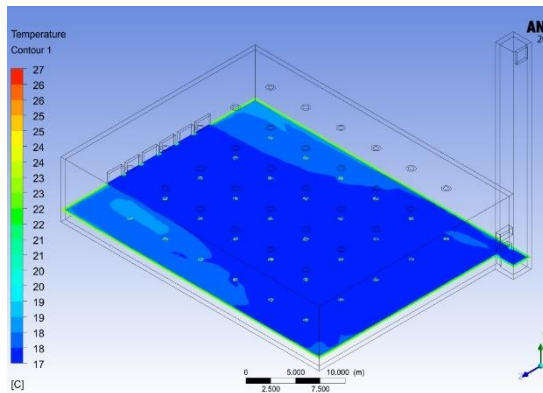
comparison reveals that the absence of an opening results in an indoor temperature of approximately 17°C, creating a cold zone and increasing the risk of discomfort. Conversely, the addition of an opening allows for a slight homogenization of the temperature profile without causing excessive cooling, ensuring that the indoor temperature remains at approximately 18°C. Consequently, the supplementary aperture enhances thermal distribution and ventilation, thereby reducing summer overheating and ensuring that the occupants experience a comfortable winter. This architectural solution is thus valuable for the thermal comfort of the occupants year-round. The stream from the door behaves as before, moving along the floor.



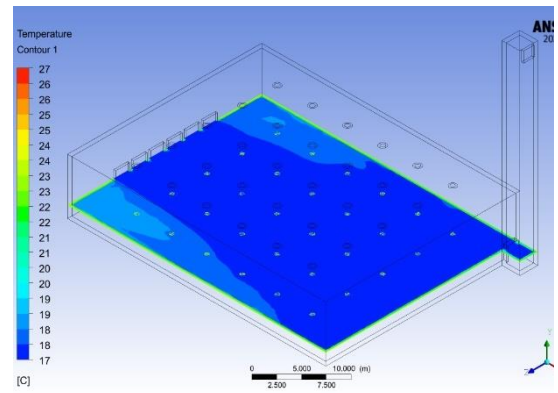
(a1)



(a2)



(b1)



(b2)

Figure 4. 13: Temperature Contour – Horizontal plane: a1) New case summer, a2) Initial case summer, b1) New case winter and b2) Initial case winter

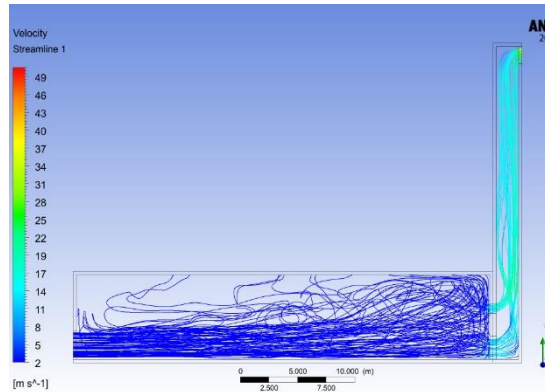
The analysis of the figures in Figure 4. 13, The beneficial impact of incorporating an opening on thermal comfort is underscored by the analysis of the temperature contour plan at a height of 1.5 meters in the prayer room during both summer and winter. In summer, the comparison

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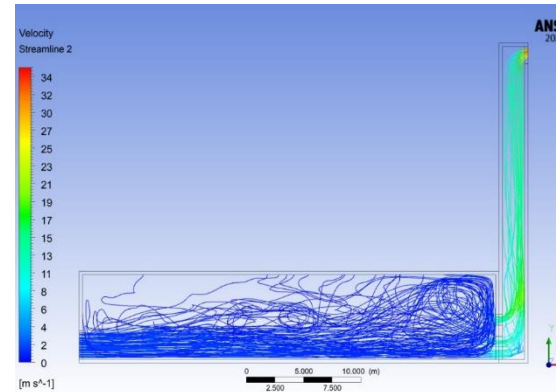
demonstrates that the average temperature in the prayer room decreases significantly with the addition of the opening, from 36.5°C in the initial case to 32.2°C. This reduction in temperature significantly reduces the hot zone and improves occupant comfort. In winter, the addition of the opening enables better homogenization of the thermal profile, resulting in a slight increase in average temperature from 17.2°C to 18.1°C, which limits cold zones and ensures a more comfortable environment. Thus, the opening is positioned one meter above the door, which optimizes natural ventilation and temperature distribution, thereby providing thermal comfort improvements in both summer and winter. In summer temperature distribution in the new design with the added window, the cooling effect at this 1.3m apart is visibly diminished.

2.2. Door & Window Open (2m apart)

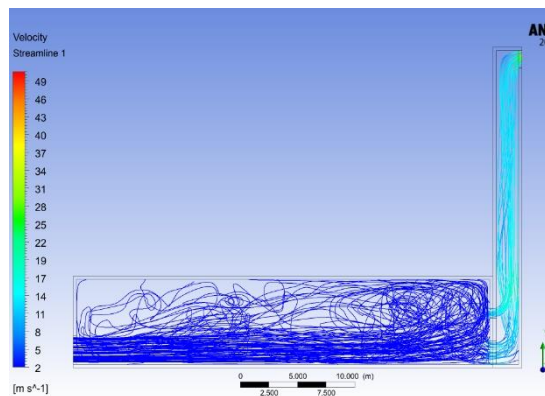
2.2.1. Streamline evolution:



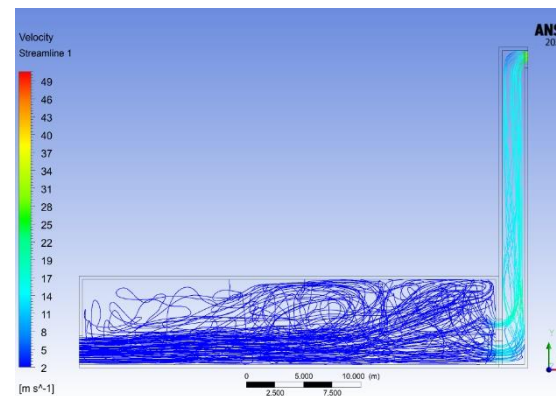
(a1)



(a2)



(b1)



(b2)

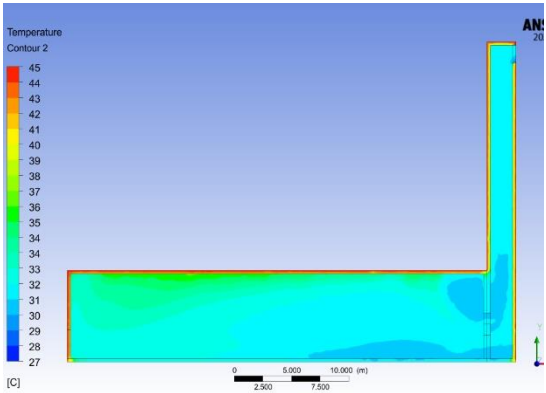
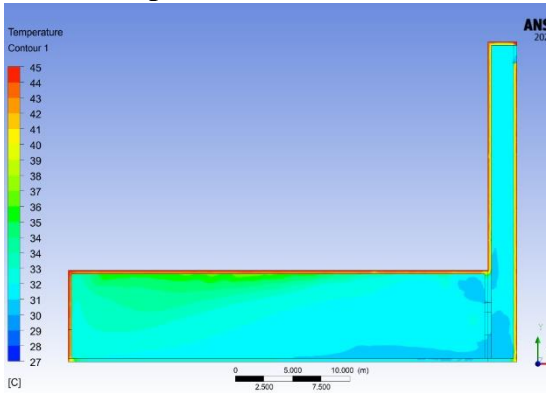
Figure 4. 14: Streamlines evolution: a1) Summer case 2m, a2) Summer case 1m, b1) Winter case 2m and b2) Winter case 1m.

The analysis of the figures in Figure 4. 14, the comparative analysis of the summer and winter configurations, illustrated in Fig. 4 .4, demonstrates that the density of the streamlines and the efficiency of the hot air suction are directly influenced by the choice of the opening height, which ranges from 1 m to 2 m above the door connecting the prayer hall to the minaret. In the summer, the opening at 2 m generates a more structured airflow and a higher density of streamlines, resulting in an air speed of 19 m/s at the entrance of the minaret, compared to 17 m/s for the 1-meter opening. In contrast, the air entry speed in the prayer room remains constant at 2 m/s. This reinforcement of the chimney effect enables the more efficient extraction of the accumulated heated

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air, thereby enhancing thermal comfort. Although the density of the airflow lines is generally lower in winter, the addition of these openings continues to promote better air distribution and limit stagnation zones, ensuring sufficient air renewal without causing excessive cooling. This process helps maintain a comfortable indoor environment in all seasons.

2.2.2. Temperature evolution:



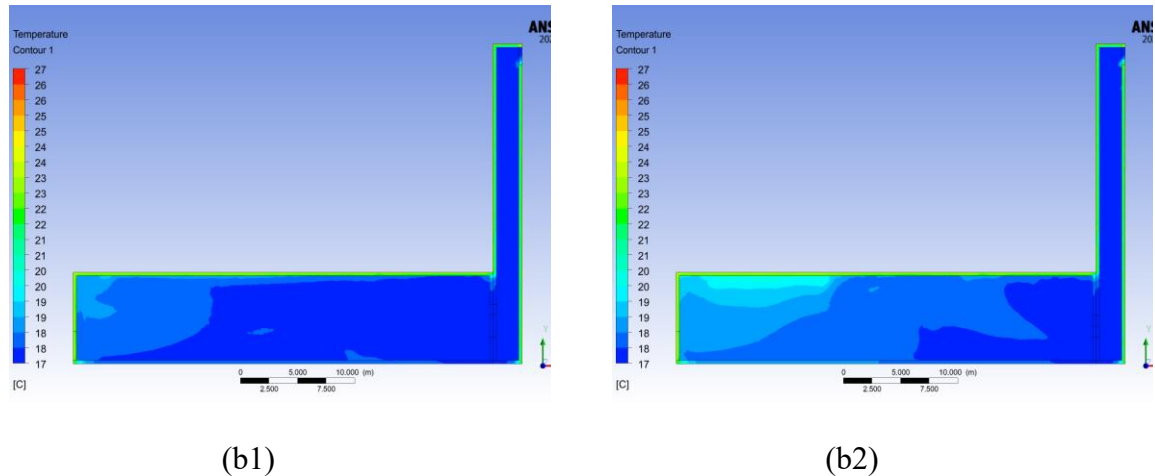
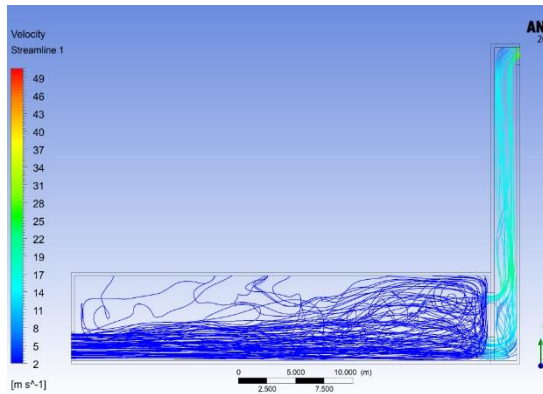


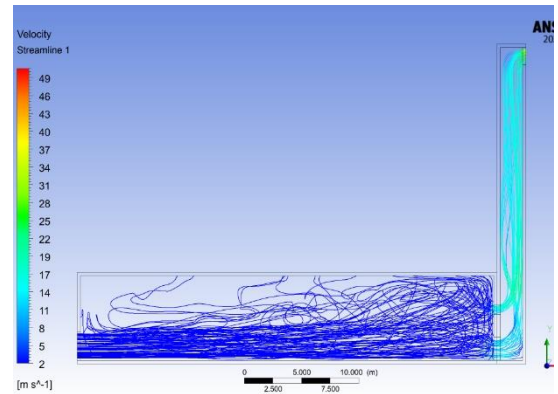
Figure 4. 15: Temperature Contour: a1) Summer case 2m, a2) Summer case 1m, b1) Winter case 2m and b2) Winter case 1m.

The analysis of the figures in Figure 4. 15, In summer, the temperature profiles recorded on a vertical plane located in the middle of the door connecting the prayer room and the minaret demonstrate that the average temperature in the prayer room decreases from 36.5°C to 32.2°C when an opening is added 1m or 2m above the door. This reduction in the extent of the hot zone and the significant improvement in thermal comfort is a result of the gentler thermal gradient and the improved evacuation of hot air towards the minaret. The temperature profile is homogenised by the additional opening in winter when the exterior walls are at 23°C and the initial interior temperature is 17°C. The average value increases from 17.2°C without the opening to 18.1°C with the opening, thereby limiting cold zones and ensuring a more equitable distribution of heat. These findings verify that the optimal placement of the apertures on the vertical plane at the door's centre optimises thermal distribution and natural ventilation, thereby enhancing comfort during both the summer and winter seasons.

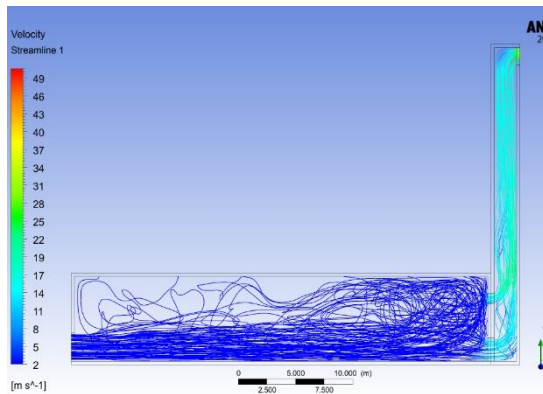
2.3. Door & Window Open (3m apart) 2.3.1. Streamline evolution:



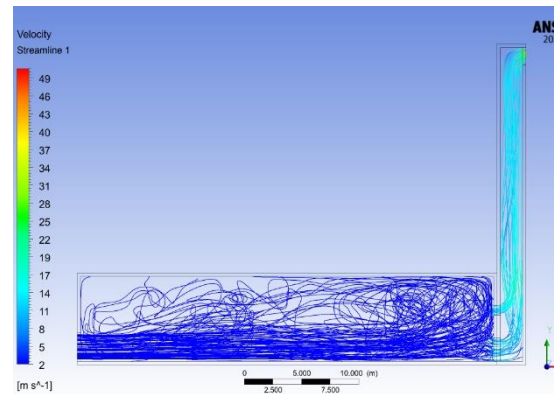
(a1)



(a2)



(b1)



(b2)

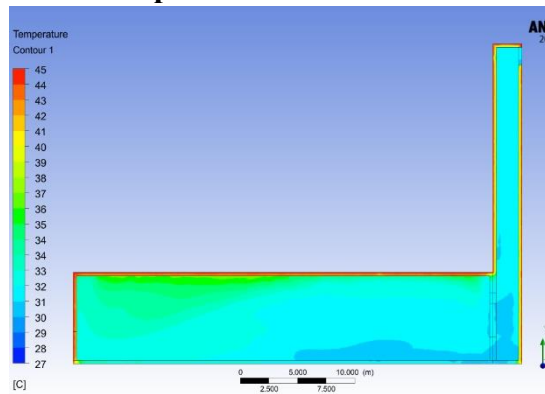
Figure 4. 16: Streamlines evolution: a1) Summer case 3m, a2) Summer case 2m, b1) Winter case 3m and b2) Winter case 2m.

The analysis of the figures in Figure 4. 16, the relocation of the aperture between the prayer hall and the minaret from 2m to 3m has a substantial effect on thermal comfort and air dynamics in both summer and winter: Positioning the opening at 3 meters increases the density of the streamlines and promotes a more structured air circulation, resulting in a speed of 16.8 m/s in the communicating opening and an exit speed of 17.4 m/s in the summer. This enables significantly more efficient aspiration and extraction of warm air, resulting in improved thermal comfort in the prayer room. At 2 meters, the speed of the opening is 15.1 m/s, and the exit speed is 15.9 m/s, with a slightly lower streamline density, indicating a reduced aspiration capacity. Moving the opening

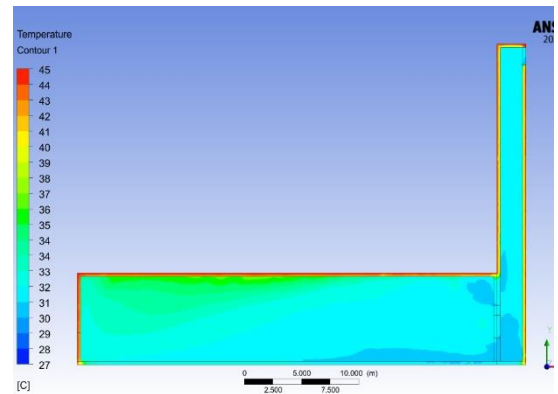
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to 3 m continues to optimise the flow structuring and aspiration while limiting heat loss and ensuring sufficient air renewal, even though the speeds are generally lower in winter (7.3 m/s at the opening and 7.8 m/s at the exit for 3 m; 6.2 m/s at the opening and 6.7 m/s at the exit for 2 m). Consequently, the vacuum effect, the density of the current lines, and thermal comfort are optimised in all seasons by the opening at 3 m. In contrast, the extraction of heated air and the administration of indoor comfort are less effective with an opening at 2 m.

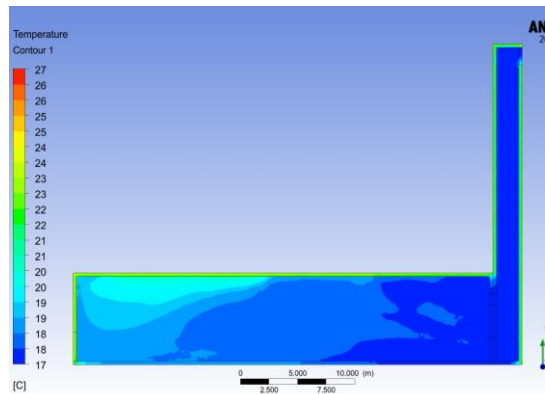
2.3.2. Temperature evolution:



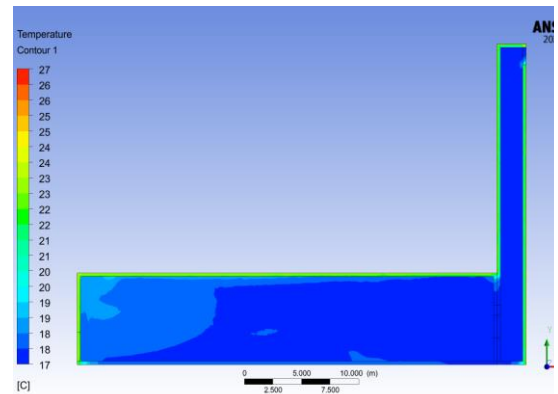
(a1)



(a2)



(b1)



(b2)

Figure 4. 17: Temperature Contour: a1) Summer case 3m, a2) Summer case 2m, b1) Winter case 3m and b2) Winter case 2m.

The analysis of the figures in Figure 4. 17, the simulation results indicate that the temperature profile and thermal comfort in both summer and winter are significantly impacted by relocating the communicating aperture between the prayer hall and the minaret from 2m to 3m in

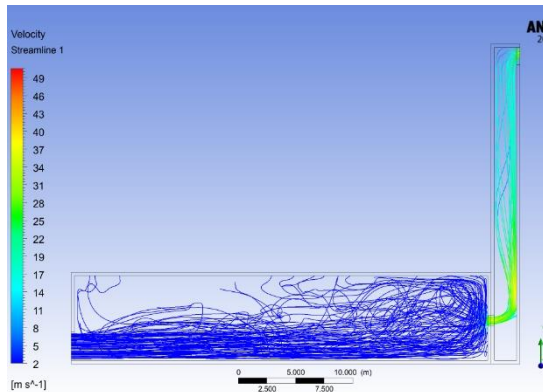
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height. In the summer, the 3m opening reduces the temperature gradient. It significantly enhances thermal comfort by limiting heat accumulation in the occupied area, resulting in an average indoor temperature of 18.1°C, compared to 17.2°C for the 2m opening, despite an external wall temperature of 45°C. This reduces the sensation of cold walls and optimises heat distribution. The relocation of the aperture enhances the retention of heat in winter and the inflow of warm air in summer, resulting in superior thermal comfort and more favourable temperature gradients in the prayer chamber, irrespective of the season.

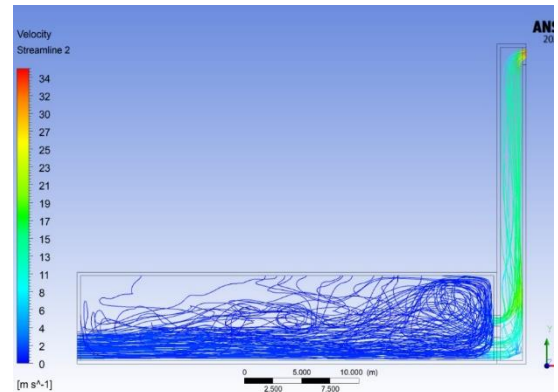
3. Window and closed communicating door:

3.1. Window and closed communicating door (1m apart):

3.1.1. Streamline evolution:



(a1)



(a2)

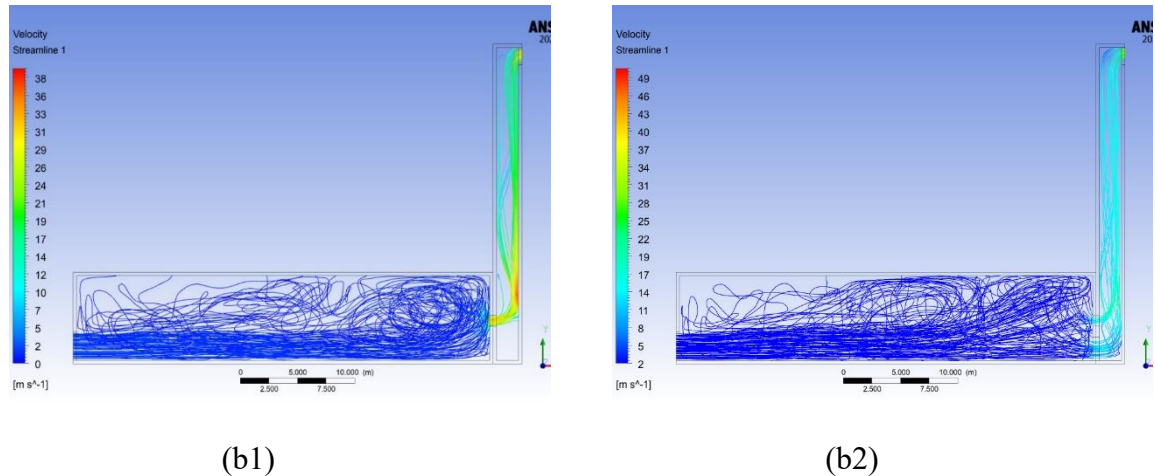


Figure 4. 18: streamlines evolution (1m apart case): a1) Summer- closed door, a2) Summer- open door, b1) Winter- Closed door and b2) Winter- open door.

The analysis of the figures in Figure 4. 18, the interpretation of the simulation results regarding the density of streamlines in summer and winter, with a permanent opening 1 metre above the door connecting the prayer room to the minaret, emphasises that this configuration promotes a more structured and dynamic air circulation. This is particularly evident in summer, when the density of streamlines increases significantly, leading to an enhanced aspiration of warm air and an improvement in thermal comfort in the prayer room. For an air entry speed of 2 m/s, the additional opening effectively directs the airflow towards the minaret, resulting in a significantly higher exit speed when the connecting door is open compared to when it is closed. The comparison of cases demonstrates that the open door enhances the chimney effect, increases the density of the streamlines, and improves the extraction of hot air. In contrast, a closed door limits circulation, reduces aspiration and can generate stagnation zones that are unfavourable to thermal comfort. The significance of positioning and managing openings to optimise natural ventilation and thermal comfort in all seasons is confirmed by the fact that the opening at 1 m continues to ensure sufficient air renewal without causing excessive cooling in winter despite the naturally lower density of the airflow. This maintains a balance between air quality and indoor heat retention.

3.1.2. Temperature evolution:

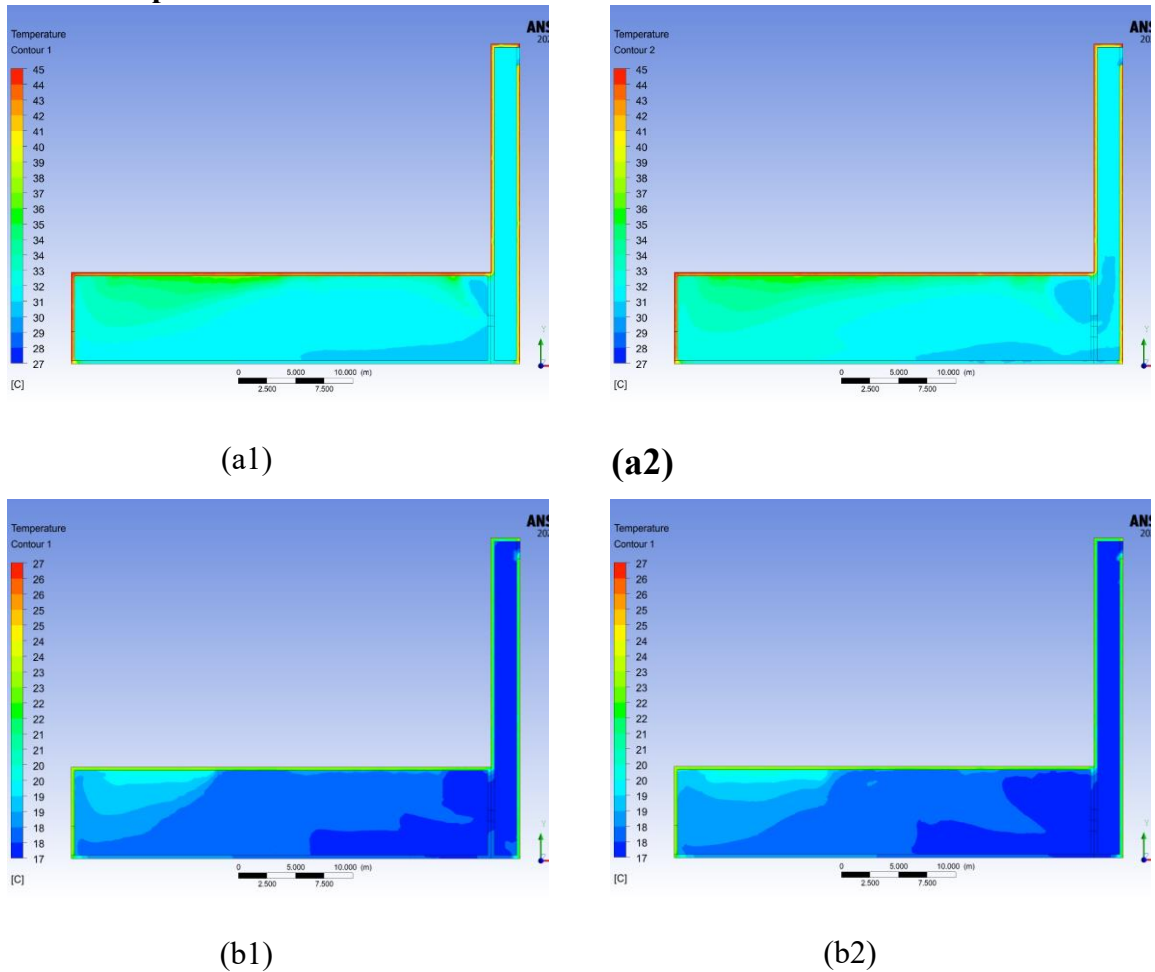


Figure 4. 19: Temperature Contour (1m apart case): a1) Summer- closed door, a2) Summer- open door, b1) Winter- Closed door and b2) Winter- open door.

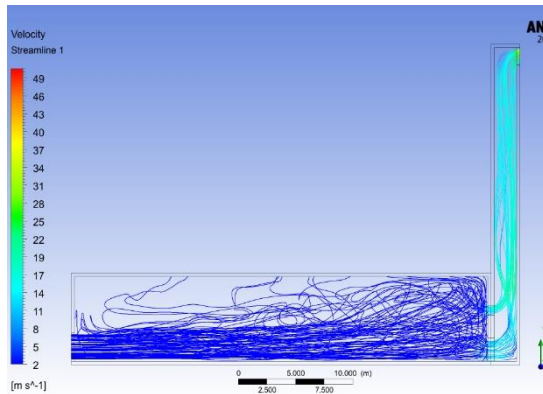
The analysis of the figures in Figure 4. 19, the thermal behaviour of the prayer room is significantly influenced by the configuration of the openings, as evidenced by the analysis of the simulation results. For example, the thermal comfort and temperature profile are directly impacted by the comparison between the open and closed communicating door when a permanent opening is located 1 metre above the door. In the summer, the exterior wall's temperature reaches 45°C, and the prayer room's average temperature rises to 36.5°C when the door is closed, resulting in a significant temperature gradient and a hot zone that is uncomfortable. However, the average indoor temperature drops to 32.2°C when the door is opened, which significantly improves the occupants' comfort by improving hot air evacuation and reducing the thermal gradient. In winter, the prayer room's average temperature is maintained at 17.2°C by sealing the door. Opening it allows the

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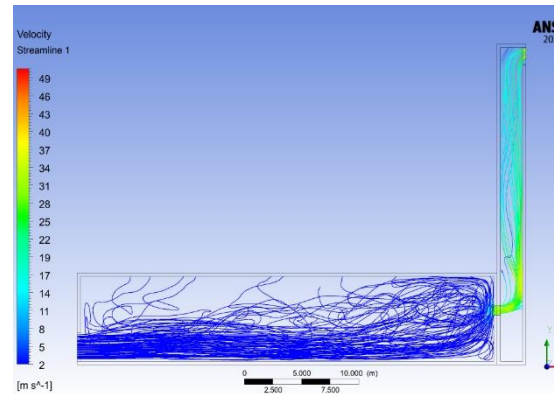
temperature to rise to 18°C, thereby homogenising the heat distribution and reducing frigid areas, even at an exterior wall temperature of 23°C. Consequently, the permanent aperture at 1 metre, in conjunction with the opening of the communicating door, enhances natural ventilation during the summer and enhances heat retention during the winter, resulting in a more favourable temperature gradient and superior thermal comfort in the prayer room.

3.2. Window and closed communicating door (2m apart)

3.2.1. Streamline evolution:



(a1)



(a2)

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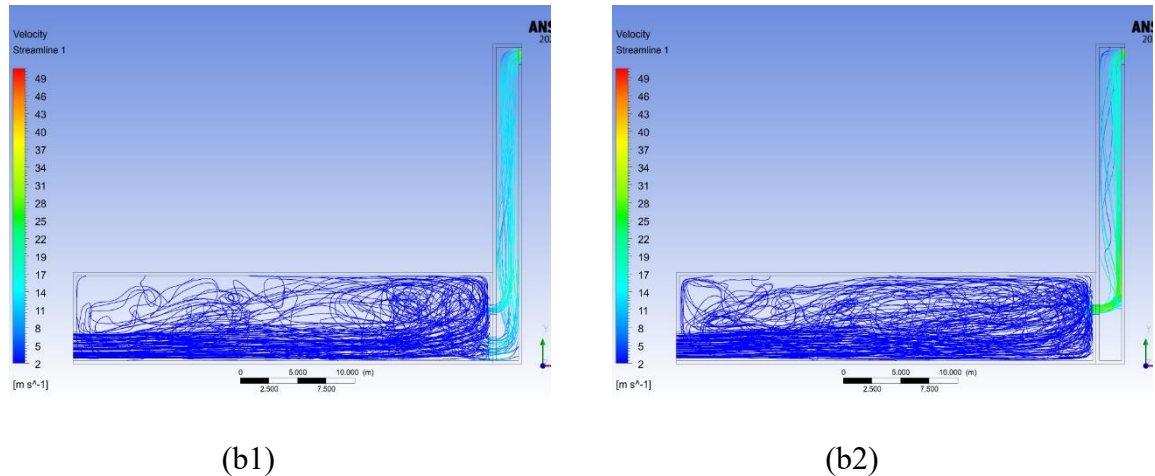


Figure 4. 20: Streamlines evolution (2m apart case): a1) Summer- closed door, a2) Summer- open door, b1) Winter- Closed door and b2) Winter- open door.

The analysis of the figures in Figure 4. 20, according to the analysis results for the summer and winter seasons, the density of the streamlines and the dynamics of the airflow are significantly influenced by the configuration of the connecting door, as evidenced by a persistent aperture 2 meters above the door connecting the prayer hall to the minaret. The air intake speed remains constant at 2 m/s, and the exit speed at the summit of the minaret reaches high values. At the same time, the density of the streamlines increases considerably when the door is open in the summer. This facilitates the rapid extraction of accumulated warm air and the efficient aspiration of warm air, thereby enhancing thermal comfort and reducing indoor temperature. On the contrary, the airflow is less structured, the density of the streamlines decreases, and the exit speed decreases. Additionally, stagnation zones may form when the door is closed, which can lead to thermal discomfort and a restriction in heat evacuation. Despite the more moderate overall dynamics, the perpetual aperture at 2 meters and the open door ensures sufficient air renewal without excessive chilling in winter.

In contrast, the closed door may lead to the accumulation of stagnant air or humidity. As a result, the optimisation of natural ventilation, the structuring of movements, and thermal comfort in all seasons is accomplished by combining a perpetual high aperture with an open connecting door. In contrast, the advantageous outcomes of these combinations are inhibited by a closed door, particularly during the overheated summer months.

3.2.2. Temperature evolution:

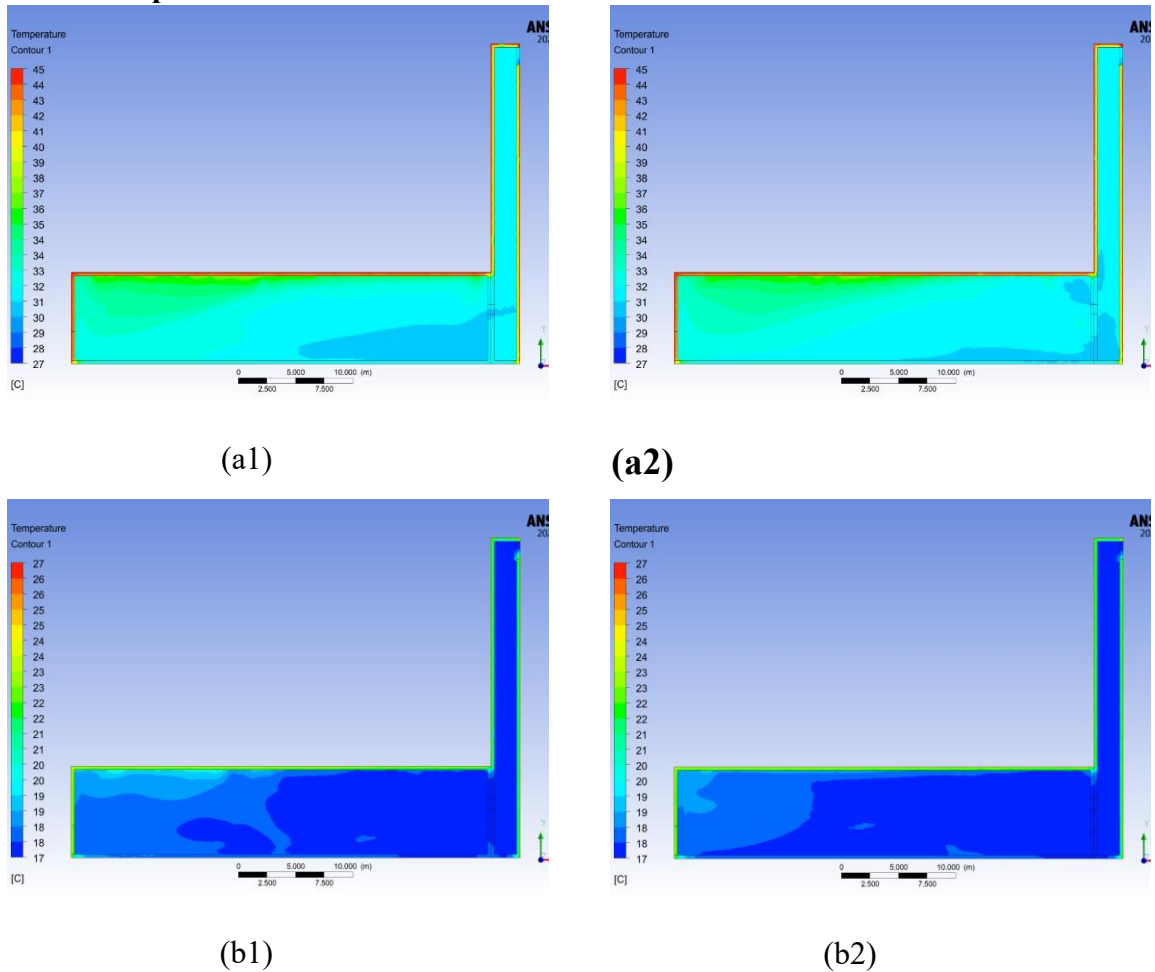


Figure 4. 21: Temperature Contour (2 m apart case): a1) Summer- closed door, a2) Summer- open door, b1) Winter- Closed door and b2) Winter- open door.

The analysis of the figures in Figure 4. 21, the comparison of the two temperature contour files, which correspond to the permanent opening at 2 m (Figure 2.3.3) and 1 m (Figure 2.3), underscores the impact of the opening height and the state of the communicating door on thermal comfort in the mosque during summer and winter. For the opening at 2 m (Figure 2.3.3), the average temperature in the prayer hall decreases from 36.5 °C with the door closed (a1) to 32.2 °C with the door open (a2) in summer and from 17.2 °C with the door closed (b1) to 18 °C with the door open (b2) in winter. This demonstrates a noticeable improvement in thermal comfort and a reduction in the temperature gradient when the door is opened. The 1 m opening (Figure 2.3) exhibits comparable tendencies; however, the values are marginally less advantageous.

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Specifically, the average temperature decreases from 37.0 °C (a1) to 33.0 °C (a2) during the summer and from 17.0 °C (b1) to 17.8 °C (b2) in the winter when the door is opened. Therefore, the optimal compromise for optimising natural ventilation, homogenising thermal distribution, and ensuring superior comfort for the faithful is the aperture at 2 m in conjunction with an open door. The opening at 1 m also remains beneficial, albeit with a diminished effect.

3.3. Window and closed communicating door (3m apart)

3.3.1. Streamline evolution:

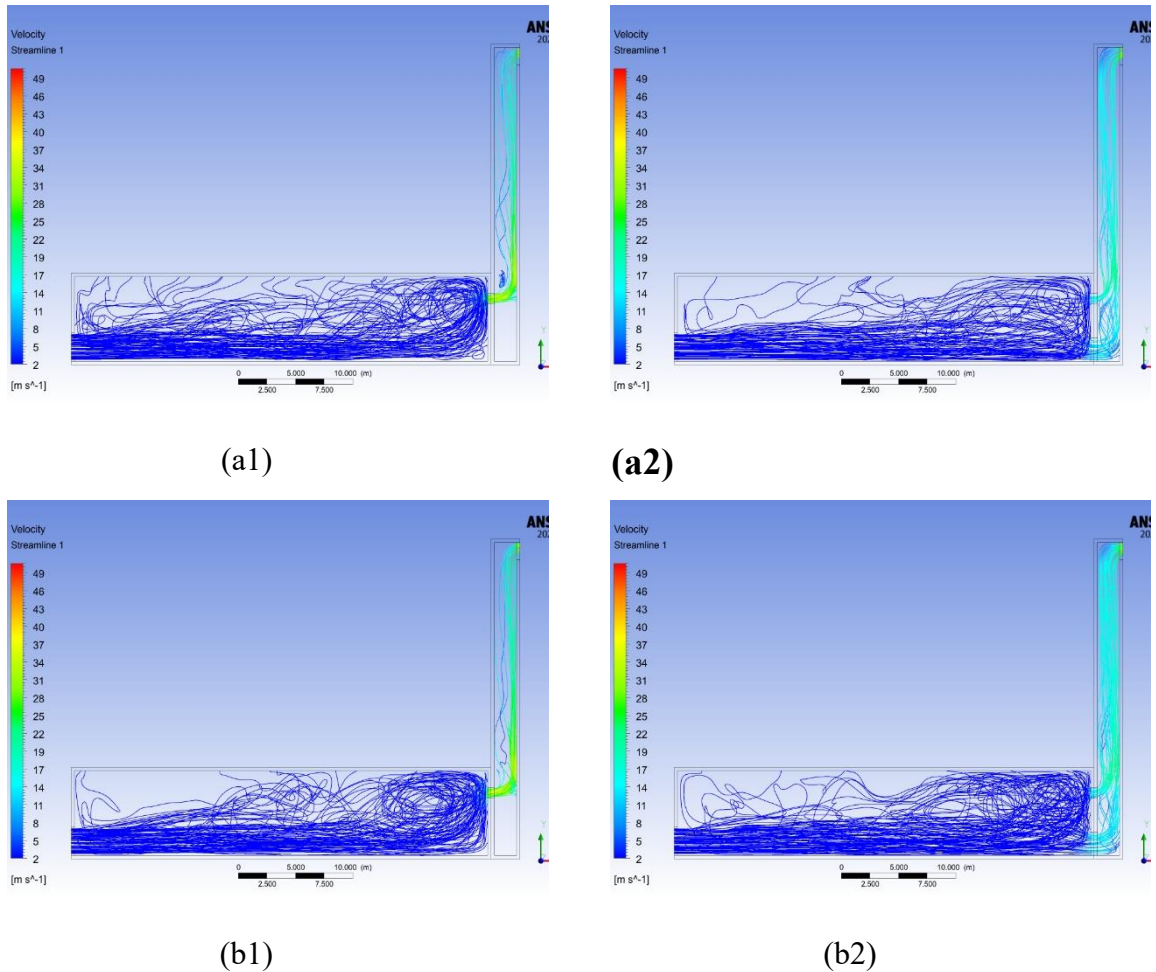


Figure 4. 22: Streamlines evolution (3m apart case): a1) Summer- closed door, a2) Summer- open door, b1) Winter- Closed door and b2) Winter- open door.

The analysis of the figures in Figure 4. 22, which depict the evolution of the streamlines in the case of an opening positioned 3 meters above the communicating door, underscores the impact of the summer and winter configurations, as well as the state of the door (open or closed), on the thermal comfort and air dynamics of the mosque: In the summer, the open door (a2) produces a significantly higher density of streamlines than the closed door (a1), which suggests a more intense and structured air circulation. The air entry speed is 2 m/s, and the exit speed can reach up to 17.4 m/s. This results in the effective suction of warm air, leading to a significant improvement in thermal comfort for the faithful. In winter, the streamlines' density remains lower; however, the opening of the door (b2) in comparison to the closed door (b1) still enables an increase in the structuring of the flows and the exit speed (up to 7.8 m/s compared to 7.3 m/s in the opening),

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thereby ensuring adequate air renewal without excessive cooling. Consequently, the densification of the current lines, the suction and extraction speeds, and the optimal thermal comfort in both summer and winter are optimised by the combination of a high opening at 3 meters and an open communicating door. Conversely, a closed door can limit these beneficial effects and create stagnation zones that are detrimental to indoor comfort.

3.3.2. Temperature evolution:

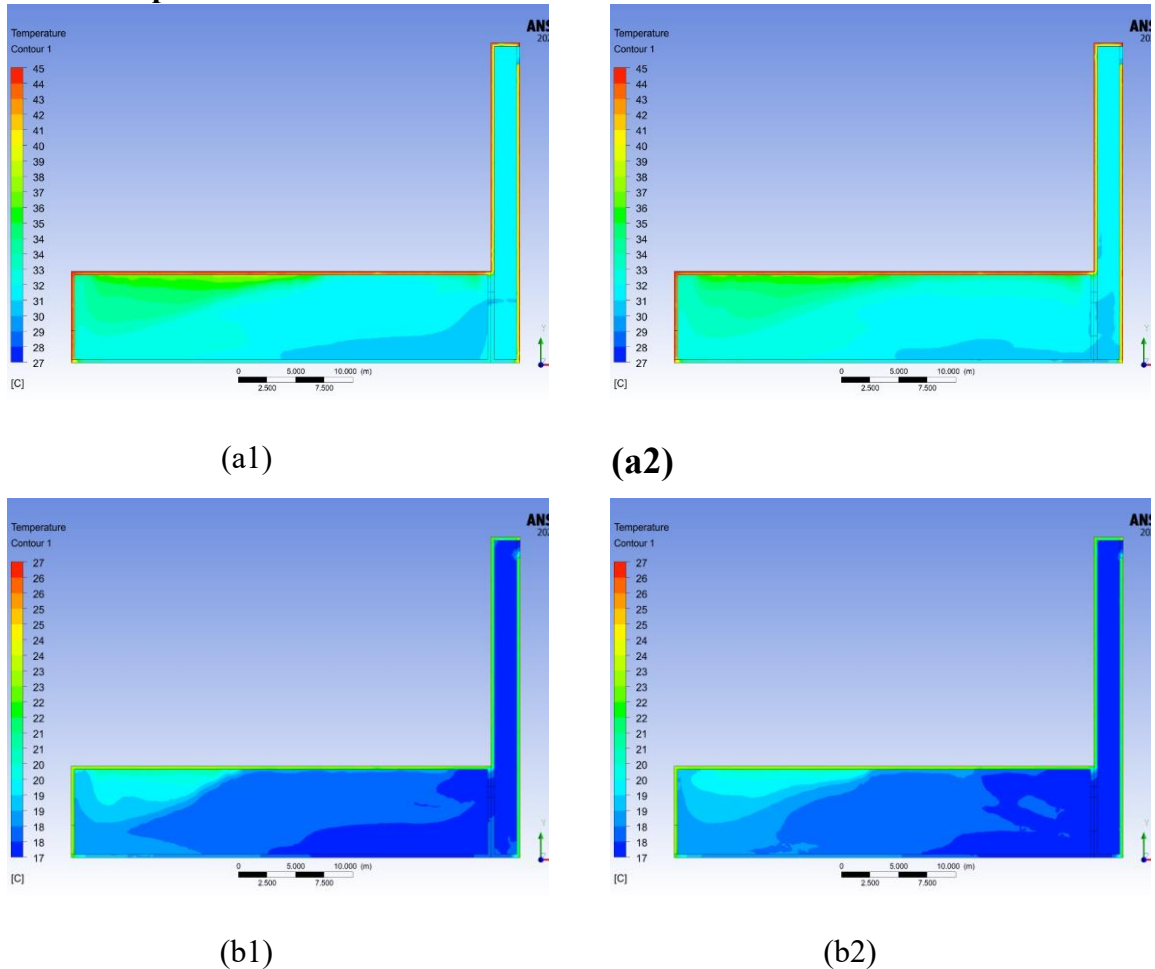


Figure 4. 23: Temperature Contour (3m apart case): a1) Summer- closed door, a2) Summer- open door, b1) Winter- Closed door and b2) Winter- open door.

The analysis of the figures in Figure 4. 23, the permanent opening at 3 meters provides a more substantial increase in thermal comfort than the 2-meter opening, particularly when the connecting door is wide open. This is because the average temperature is lower in the summer and

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more consistent in the winter. In both scenarios, the opening of the communicating door enhances natural ventilation, mitigates excessive thermal gradients, and guarantees a more comfortable interior environment for the devou

Conclusion

Conclusion:

This chapter illustrates the significant influence of the design and positioning of apertures between the prayer hall and the minaret on the thermal comfort of the faithful in both summer and winter through a comprehensive analysis of CFD simulation results conducted under ANSYS Fluent. In the initial configuration without modifications, the natural ventilation induced by the chimney effect of the minaret already enables the effective extraction of hot air, with inlet speeds of 2 m/s and outlet speeds reaching 17 to 20 m/s in summer. However, the temperature distribution remains heterogeneous, with persistent hot zones and significant thermal gradients, particularly when the exterior wall temperature reaches 45°C and that of the prayer hall 36.5°C. The results demonstrate this.

The density of the streamlines, the structuring of the air fluxes, and the efficiency of the vacuum are substantially enhanced by the addition of additional apertures above the communicating door at varying heights (1m, 2m, or 3m), particularly when the door is wide open. The occupants experience significantly improved thermal comfort as a result of the homogenization of the thermal distribution and the reduction of the extent of hot zones and the temperature gradient. In the summer, the average temperature of the prayer room is lowered to 32.2°C for openings at 2m or 3m. In the winter, these apertures also facilitate a more uniform thermal profile and a modest increase in the average indoor temperature (up to 18°C) while also limiting frigid zones and assuring adequate air renewal without excessive chilling.

In conclusion, this chapter emphasizes that the optimal placement of openings (particularly at 2m or 3m with the door open) is a viable architectural solution that optimizes natural ventilation, reduces extreme thermal gradients, and guarantees enduring thermal comfort in the prayer hall, all while reducing the reliance on active air conditioning or heating systems. Thus, these findings offer tangible suggestions for the bioclimatic design of mosques and the enhancement of the minaret's role in regulating indoor comfort.

General conclusion:

This thesis explores ways to make mosques more comfortable temperature-wise by integrating ideas from theory, architecture, and digital tools. We began by defining precisely what "thermal comfort" means, using the ASHRAE 55 standard as our guide. This involved looking at environmental things like air temperature and humidity, plus personal stuff like how active people are, their metabolism, and what they're wearing (clothing). Then, we dug into how traditional mosque architecture elements, such as openings, materials, large prayer halls, domes, and patios, naturally affect the thermal conditions inside.

The core of the research involved building a mathematical model to understand how heat transfers happen within mosques and then using ANSYS Fluent for numerical simulations. Our initial key findings showed that natural ventilation, primarily driven by the minaret's chimney effect, is quite adequate at pulling hot air out, with summer exhaust speeds hitting a good 17 to 20 m/s. However, without optimizing the openings, you still get significant temperature variations and hot zones, sometimes climbing up to 36.5°C.

The study demonstrated that strategically placing openings makes a significant difference in improving air circulation. For example, just adding an aperture about 2 or 3 meters above the door connecting spaces and keeping that door open helped reduce the average summer temperature in the prayer hall to 32.2°C. This made the whole environment feel much more uniform and comfortable. In winter, these same configurations helped maintain consistency, resulting in a slightly higher average temperature of 18°C. This reduces cold spots while ensuring proper air renewal.

In the future, research could investigate the integration of dynamic occupancy levels, validate our simulations with on-site experimental data, and examine other passive solutions, including solar shading, green roofs, and the systematic integration of evaporative cooling systems, such as fountains and water features. Further optimization of the design and positioning of fountains within mosque courtyards could be achieved by quantifying the cooling potential and humidity regulation afforded by various fountain configurations. In addition, the methodology we have established here can be fully implemented in other large-scale structures, including auditoriums and chapels, thereby establishing a strong scientific basis for energy-efficient architectural design that honors traditional heritage and integrates time-tested passive cooling strategies.