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Topic

Experimental Investigation of Natural Convection Heat Transfer in Building
Enclosures: A Metrological Approach to Thermal Comfort and Energy
Efficiency

Before the jury composed of :

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Dedication

Dedication

To those who stood by me when no one else could, who carried the weight of this journey with me despite the distance, and who turned absence into a constant presence in my
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To my dear mother, whose prayers, patience, and unconditional love accompanied me throughout these five years. This achievement is a reflection of your sacrifices and endless
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.express

.With all my love and gratitude

الملخص

تهدف هذه الدراسة إلى التحقيق التجريبي في ظاهرة انتقال الحرارة بالحمل الطبيعي داخل أغلفة المباني تحت الظروف المناخية الحارة والجافة، مع التركيز على تحسين الراحة الحرارية وتقليل استهلاك الطاقة. اعتمدت الدراسة على نموذج تجريبي مزود بأجهزة قياس مختلفة تشمل الترموكوبلات، حساسات الرطوبة، أجهزة قياس الإشعاع الشمسي، ومقاييس سرعة الرياح، مع تطبيق إجراءات معايرة وتحليل لاثقين القياس وفق المعايير الدولية. كما تم تقييم أداء نظام التظليل الخارجي ومقارنته بحالات مرجعية مختلفة لتحليل تأثيره على السلوك الحراري داخل الحيز المدروس. أظهرت النتائج Brise-Soleil أن أنظمة التظليل تساهم بشكل فعال في تقليل الحمل الحراري وتحسين الراحة الحرارية داخل المباني في المناخات الصحراوية

Résumé

Cette étude porte sur l'investigation expérimentale du transfert de chaleur par convection naturelle dans les enveloppes des bâtiments sous un climat chaud et aride, dans le but d'améliorer le confort thermique et de réduire la consommation énergétique. Un dispositif expérimental équipé de thermocouples, de capteurs d'humidité, de pyranomètres et d'anémomètres a été utilisé, avec une approche métrologique basée sur l'étalonnage et l'analyse des incertitudes de mesure conformément aux normes internationales. L'étude évalue également les performances d'un système de protection solaire de type Brise-Soleil et compare plusieurs configurations afin d'analyser leur influence sur le comportement thermique intérieur. Les résultats montrent que les systèmes de protection solaire permettent de réduire efficacement les charges thermiques et d'améliorer le confort thermique dans les bâtiments situés en climat désertique.

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List of abbreviations

ANSYS : Analysis System

AVG : Average

BIPV : Building-Integrated Photovoltaics

BREEAM : Building Research Establishment Environmental Assessment Method

CFD : Computational Fluid Dynamics

CFM : Cubic Feet per Minute

CMM : Cubic Meter per Minute

DGI : Daylight Glare Index

DHI : Diffuse Horizontal Irradiance

DHT11 : Digital Humidity and Temperature Sensor 11

DHT22 : Digital Humidity and Temperature Sensor 22

DIN : Deutsches Institut für Normung

DNI : Direct Normal Irradiance

EMF : Electromotive Force

FLOW : Air Flow Mode

GHI : Global Horizontal Irradiance

HVAC : Heating, Ventilation, and Air Conditioning

IEC : International Electrotechnical Commission

IEA : International Energy Agency

ISTA : Institute of Applied Sciences and Techniques

LCD : Liquid Crystal Display

LEED : Leadership in Energy and Environmental Design

LiDAR : Light Detection and Ranging

MAX6675 : Digital Thermocouple Converter Module

NIST : National Institute of Standards and Technology

PCM / PCMs : Phase Change Material(s)

PMV : Predicted Mean Vote

Liste des abréviations

PPD : Predicted Percentage of Dissatisfied

RH : Relative Humidity

RTD / RTDs : Resistance Temperature Detector(s)

TCR : Temperature Coefficient of Resistance

THMC : Thermal–Hydraulic–Mechanical–Chemical

VEL : Velocity

WRR : World Radiometric Referen

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General Introduction

Buildings constitute one of the most energy-intensive sectors worldwide, accounting for a significant share of global energy consumption. In Algeria, this issue is particularly important due to the hot and arid climate, which leads to high cooling demands in residential and public buildings. The residential sector represents a major portion of national energy use, making the improvement of building energy efficiency a crucial economic, environmental, and social challenge. Over the past decades, numerous studies have focused on enhancing thermal performance and reducing energy consumption in buildings. Various approaches have been investigated, including passive cooling strategies, building envelope optimization, solar protection systems, and natural ventilation techniques. These solutions aim to improve indoor thermal comfort while minimizing energy requirements. Among the physical phenomena governing indoor thermal conditions, natural convection plays a fundamental role in heat transfer and air movement within enclosed spaces. It directly influences temperature distribution, air circulation, and occupants' thermal comfort. A better understanding of these mechanisms is therefore essential for the design of energy-efficient and comfortable buildings, particularly in regions characterized by extreme climatic conditions. Despite significant progress in building thermal research, several challenges remain regarding the accurate assessment of indoor thermal behavior under real operating conditions. Experimental investigations and reliable measurement practices are essential for improving the understanding of heat transfer processes and validating thermal performance analyses. In this context, the present research focuses on the study of thermal behavior in building environments under hot and arid climatic conditions. Particular attention is given to natural convection phenomena, indoor thermal comfort, and the evaluation of passive strategies that can contribute to reducing thermal loads and improving building performance. The main objective of this work is to contribute to the understanding of thermal processes in buildings and to support the development of effective solutions for enhancing thermal comfort and energy efficiency in hot arid regions.

This dissertation is organized into three chapters. The first chapter presents the theoretical background and literature review. The second chapter describes the methodology adopted in this research. The third chapter presents the results obtained and discusses their implications in relation to the objectives of the study.

1. Chapter I: Literature Review and Contextual Framework

1.1 Introduction

The building sector represents one of the largest energy-consuming sectors worldwide, accounting for approximately 36% of global final energy consumption and nearly 55% of global electricity use[1]. This significant demand is primarily driven by the operation of residential and commercial buildings for heating, cooling, and lighting, with the residential sector alone accounting for nearly 70% of energy consumption within the building sector. This growing demand stems from several interconnected factors, including population growth, rapid urbanization, and rising living standards. Despite the progressive implementation of energy efficiency measures, the resulting improvements have been insufficient to achieve international emission reduction targets. In response, governments have introduced various policy instruments, including regulatory measures, voluntary certification schemes LEED, BREEAM, and economic incentives. Within this framework, improving the thermal performance of building envelopes emerges as a fundamental strategy, particularly in regions with harsh climatic conditions.

In the Algerian context, these challenges are even more pronounced, as the country experiences a hot and arid climate that imposes significant cooling demands, coupled with heavy reliance on natural gas for electricity generation and residential heating. Previous studies in Algeria have demonstrated the potential of passive strategies such as phase change materials (PCMs), envelope optimization, and natural ventilation. However, these investigations have predominantly relied on numerical simulations with limited experimental validation, and have largely neglected natural convection heat transfer within building enclosures despite its crucial role in thermal comfort. Moreover, metrological aspects such as measurement accuracy and uncertainty analysis are rarely addressed[2][3].

1.2 Energy consumption in Algeria

Algeria's energy system relies heavily on hydrocarbons, with natural gas playing a central strategic role. Domestic energy demand has more than doubled over the last two decades, driven by population growth, urbanization, and rising living standards IEA, 2023. Natural gas, supported by abundant reserves and developed infrastructure, constitutes the backbone of the country's

primary energy supply. Rising domestic consumption, particularly in residential, tertiary, and agricultural sectors, has reduced export volumes despite increasing national production. This dual pressure highlights the need for energy efficiency, rationalized consumption, and investment in low-carbon alternatives to ensure long-term energy security and support a sustainable transition [4][5].

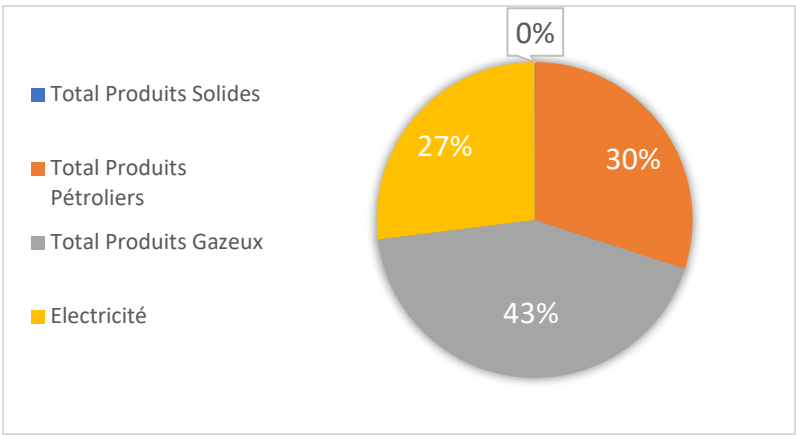


Figure 1-1 National Energy Demand in 2024 (billan energetique," 2024.)

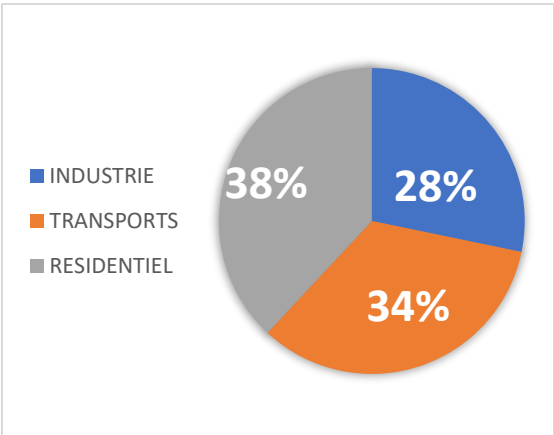


Figure 1-2 Sectoral Energy Consumption in 2024 (billan energetique," 2024.)

1.3 Analysis of National Energy Consumption in Algeria: Trends and Sectoral Distribution (2015–2024)

1.3.1 Sectoral Energy Consumption

Energy consumption in Algeria during the period from 2015 to 2024 reveals a clear upward trend. Total consumption increased from approximately 38,500 MTOE in 2015 to nearly 50,500 MTOE in 2024, representing an overall growth of about 31%. The residential sector consistently dominates as the largest energy consumer among the three sectors, reflecting the growing demand for heating and cooling in a harsh climate. It is followed by the transportation sector, which ranks second, while the industrial sector records the lowest consumption levels, although it shows gradual growth that reflects economic expansion.

A notable feature of the data is the significant decline observed in 2020 across all sectors, which was a direct consequence of the COVID-19 pandemic's impact on economic activity and mobility. However, energy consumption began to recover and increase gradually starting in 2021,

regaining its upward trajectory and surpassing pre-pandemic levels by 2024.[6], [7], [8], [9][10], [11], [12], [13][14]

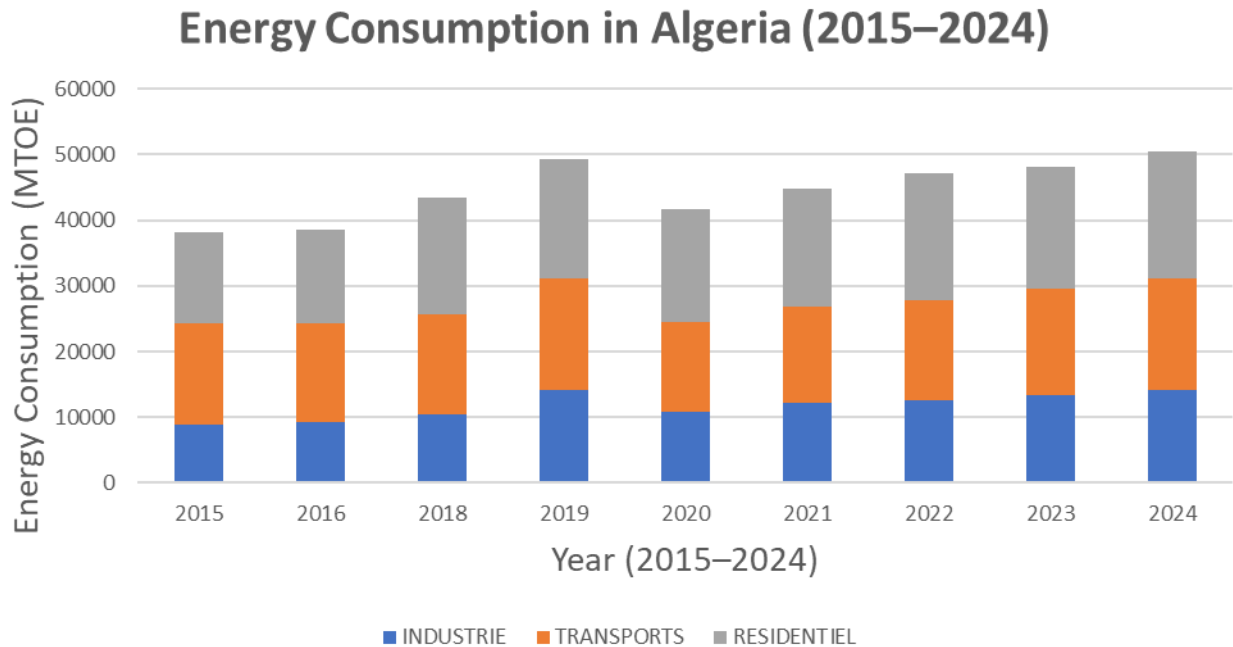


Figure 1-3 Energy Consumption in Algeria by sector industry, transport, and residential (2015–2024 (bilan energetique,” (2015–2024.)

1.3.2 Evolution of National Energy Demand (2015–2024)

These bar charts illustrate the evolution of national energy consumption in Algeria from 2015 to 2024, categorized by energy product type. The data clearly show the dominance of gaseous products (gray), which constitute the largest share of each annual bar, reflecting Algeria’s heavy reliance on natural gas as its primary domestic energy source. This is unsurprising given the country's vast natural gas reserves. Petroleum products (orange) rank second and maintain a relatively stable presence throughout the period, with consumption ranging between 13,000 and 15,000 MTOE and exhibiting only minor fluctuations. This stability indicates sustained demand, mainly driven by the transportation and industrial sectors. Electricity (yellow) appears as the third-largest component and shows noticeable growth, particularly since 2021, reflecting the expansion of distribution networks and increasing residential demand.

In contrast, solid fuels (light blue) are virtually absent throughout the entire period, confirming that Algeria has largely phased out coal and its derivatives as a source of energy. Similar to the previous figure, a slight decline can be observed in 2020 as a result of the COVID-19 pandemic. This was followed by a resumption of the upward trend, with total energy consumption reaching its peak at approximately 50,000 MTOE in 2024, highlighting the continued and accelerating growth of energy demand in Algeria.[6], [7], [8], [9][10], [11], [12], [13][14].

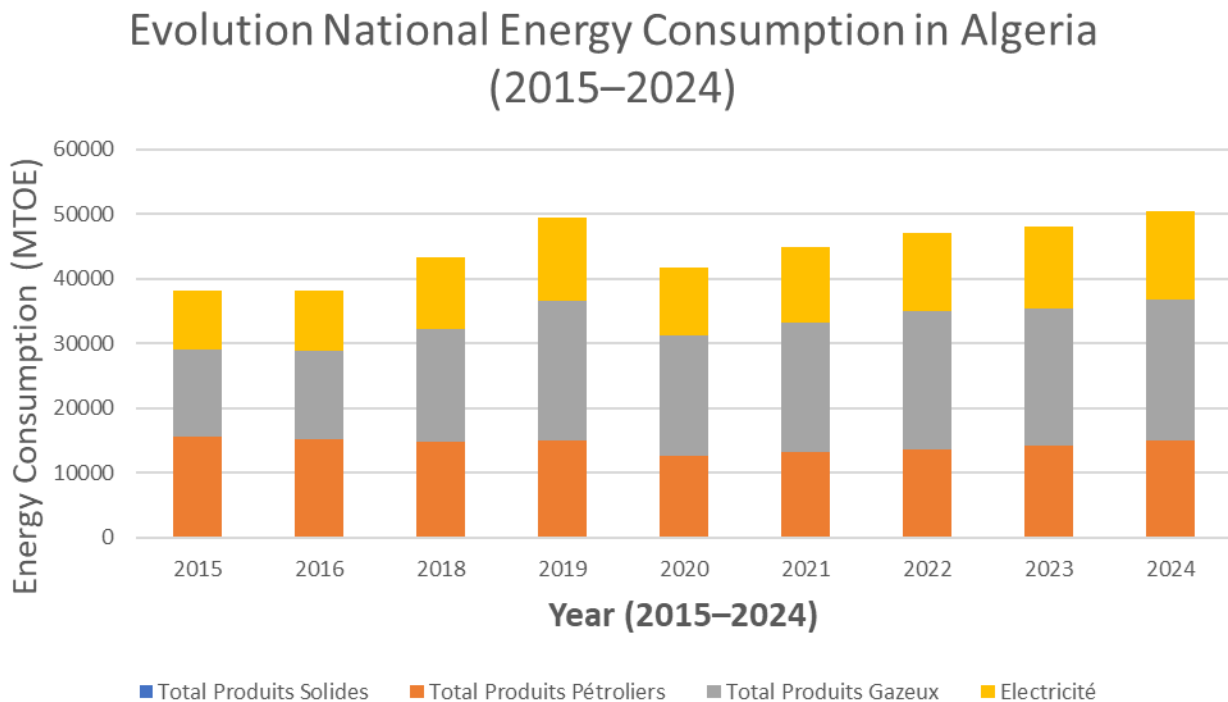


Figure 1-4 National Energy Consumption in Algeria (2015–2024) (*bilan energetique*,” (2015 –2024.)

1.4 The Role of Natural Gas in Electricity Generation and Residential Heating

Natural gas represents one of the main pillars of the energy system in Algeria, playing a crucial role in both electricity generation and the provision of residential heating and cooking needs. In the electricity sector, the national power system relies almost entirely on natural gas, which accounts for more than 90% of total electricity production. This strong dependence is attributed to the country’s abundant domestic reserves, economic efficiency, and relatively lower environmental impact compared to other fossil fuel sources. In recent years, natural gas–

based electricity generation capacity has experienced significant growth. The largest annual increase was recorded in 2019, with approximately 1,916 MW of new capacity added. This upward trend continued, reaching a total installed natural gas-fired capacity of about 25.1 GW in 2024, up from 24.19 GW in 2023. This growth highlights the strategic importance of natural gas in meeting rising electricity demand and ensuring grid stability. In the residential sector, natural gas is widely used for heating and cooking due to its low operating cost, high thermal efficiency, and ease of use, in addition to the extensive availability of distribution infrastructure in many urban areas. Moreover, advancements in modern technologies such as combined-cycle power plants, high-efficiency gas turbines, and distributed generation systems have enhanced the efficiency of natural gas utilization while reducing pollutant emissions. Consequently, natural gas plays a vital role in supporting energy security and achieving a balance between economic and environmental objectives, with future prospects for greater integration with renewable energy sources as part of the national energy transition strategy[15].

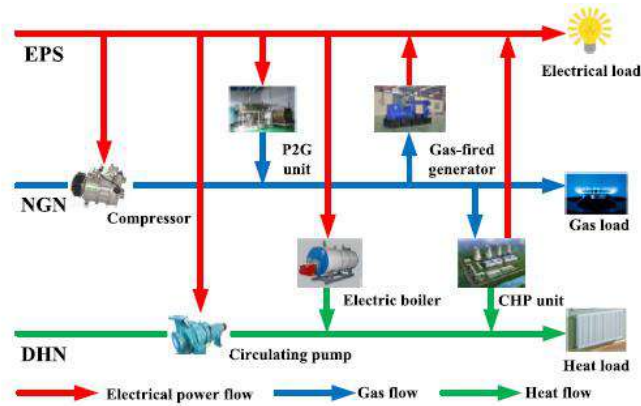


Fig. 1. Integrated electricity, natural gas and heating system.

Figure 1-5 Integrated electricity, natural gas and heating system (Guanxiong Wang,2024)

1.5 Major Research Directions in Thermal Comfort and Energy Efficiency Studies in Algerian Buildings

Research on thermal comfort and energy efficiency in buildings in the Algerian context has expanded significantly over the past decade, driven by the need to adapt buildings to hot and arid climates. The collected Scopus-indexed literature highlights several dominant research directions, including phase change materials (PCM), envelope and material optimization, passive solar systems, ventilation strategies, intelligent control, and thermal comfort assessment.

1.5.1 Phase Change Materials (PCM) for Thermal Regulation

Phase change materials (PCMs) represent one of the most investigated solutions for improving building thermal performance. Several studies demonstrated that PCM integration in walls and envelopes can reduce peak indoor temperatures and shift cooling loads by increasing thermal inertia Derradji, 2015[16]; M'ziane, 2021 [17]; Hamdani, 2021; [18] Xiong, 2022[19]; Hadjadj, 2024[20]; Zehouani, 2025[21]; Goudjil, 2025 [22]; Rahman, 2025 [23]; Rashid, 2025[24].

More recent works emphasize multi-layer PCM configurations and climate-adapted melting temperatures to maximize latent heat storage (Zehouani, 2025[21]; Goudjil, 2025)[22]. These studies collectively confirm PCM potential in hot climates.

However, most contributions remain simulation-based, with limited long-term experimental validation. Moreover, durability and economic feasibility are rarely addressed, indicating the need for metrologically controlled experimental investigations.

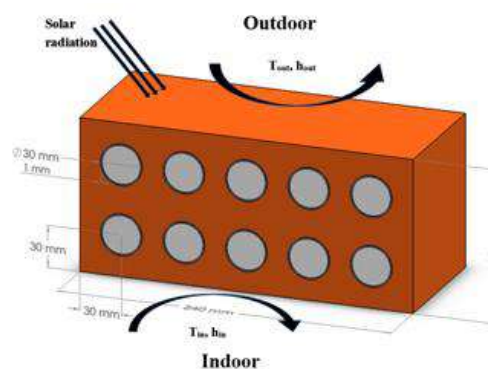


Fig. 1. Detailed dimensions of the physical model.

Figure 1-6 . Phase Change Materials (PCM) for Thermal Regulation (Zahra Assala Zehouani, 2025)

1.5.2 Building Materials and Envelope Optimization

Another major research direction concerns the thermal enhancement of building materials and envelope components. Studies on gypsum composites, modified bricks, and recycled-material composites show notable reductions in thermal conductivity and improvements in time lag Derradji, 2015[16]; Mnasri, 2020[25]; M'ziane, 2021[17]; Hamdani, 2021[18]; Xiong, 2022[19]; Belatrache, 2023[26]; Allam, 2023[27]; Dahmani, 2024[28]; Ziad, 2024[29]; Laoubi, 2026[30].

These works demonstrate that material composition and wall configuration strongly influence indoor thermal stability. The inclusion of recycled materials also supports sustainability objectives.

Nevertheless, several studies report mechanical strength reductions when thermal performance is enhanced, highlighting the trade-off between structural integrity and insulation capacity.

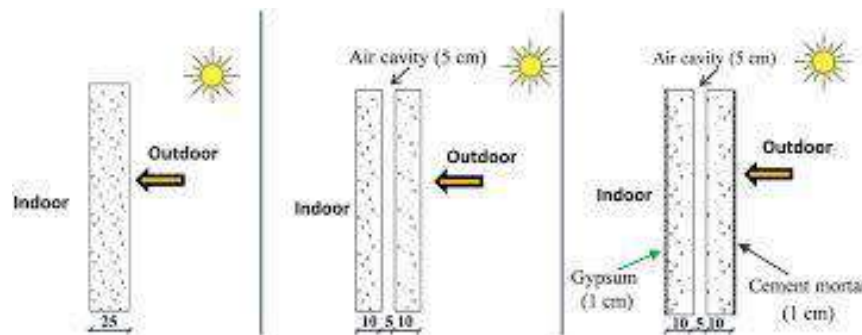


Figure 1-7 Building Materials and Envelope Optimization (Hamza Laoubi, 2026)

1.5.3 Passive Solar and Bioclimatic Systems

Passive solar systems constitute a well-established research axis in Algeria. Trombe walls, solar air heaters, and solar-based façade systems have been shown to improve indoor temperature stability and reduce heating demand Bensafi, 2023[31]; Xiong, 2022[19]; Khelifa, 2025[32]; Moumeni, 2025[33]; Ghriss, 2026[34].

These studies confirm the effectiveness of solar-based passive heating under desert and semi-arid climates. However, performance is highly dependent on solar availability, orientation, and seasonal variation, which limits generalization

1.5.4 Natural Ventilation and Airflow Management

Natural ventilation and airflow optimization are frequently explored using CFD modeling. Research shows that airflow management can significantly improve thermal comfort and reduce cooling demand Khelil, 2019[35]; Morsli, 2019[36]; Tarek, 2023[37]; Rashid, 2025[24]; Ameen, 2025[38]. Despite promising results, many studies rely on simplified models or controlled environments. Full-scale experimental validation of natural convection phenomena in real enclosures remains limited.

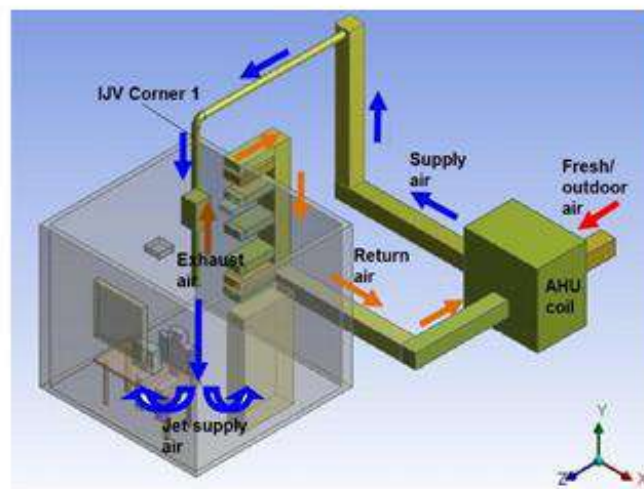


Figure 1-8 Natural Ventilation and Airflow Management

Arman Ameen , 2025

1.5.5 Smart Control and AI-Based Optimization

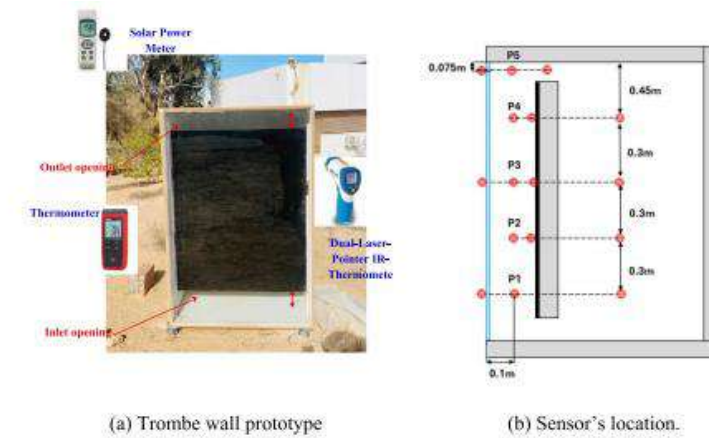
Intelligent control systems are increasingly investigated for building energy optimization. Neural networks, predictive models, and adaptive HVAC control strategies have demonstrated their potential to reduce energy consumption while maintaining comfort levels (Djebbar, 2018[39]; Benslimane, 2019[40]; Lakhdari, 2021[41]; Allam, 2023[27]; Bensafi, 2023[31]; Magraoui, 2025[42]; Ouaret, 2025 [43]; Ameen, 2025[38]; Zehouani, 2025[21]).

While these approaches are promising, they depend on reliable sensors, data quality, and system complexity, which may hinder practical implementation.

1.5.6 Thermal Comfort and Occupant-Centered Studies

Thermal comfort assessment is another significant research stream. Field measurements and model-based evaluations using PMV/PPD and adaptive comfort models have been widely applied in Algerian buildings Benslimane, 2019[40]; Khledj, 2021[44]; Belatrache, 2023[26]; Kadi, 2023[45]; Sakhri, 2023[46]; Bensafi, 2023[31]; Ouanes, 2024[47]; Alshenaifi, 2024[48]; Ben Bacha, 2025[49]; Khelifa, 2025 [32]; Magraoui, 2025[42]; Ouaret, 2025[43]).

These studies highlight discrepancies between predicted and perceived comfort, especially in hot climates. However, many rely on short monitoring campaigns that may not capture long-term behavioral adaptation



©<https://doi.org/10.1016/j.applthermaleng.2025.127619>

Figure 1-9 trombe wall with fins (Khaoula Friji , 2025)

1.6 Classification Framework for Proposed Solutions in Building

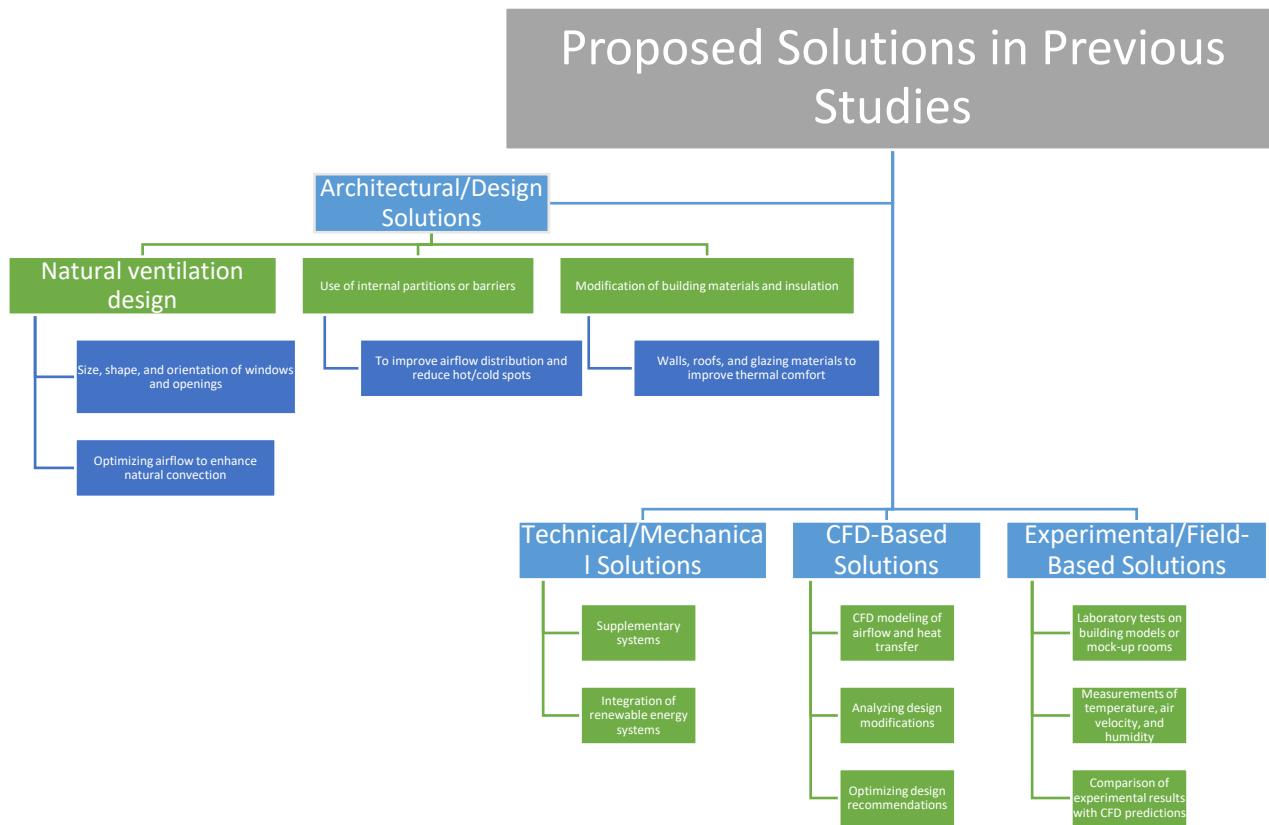


Figure 1-10 Structural Diagram of the Classification Framework for Proposed Solutions in Building Performance Studies

Following the review of prevailing research themes in studies addressing thermal comfort and energy efficiency in buildings within the Algerian climatic context, it is evident that these themes—despite their specificity stemming from the constraints of the hot and arid climate—constitute part of a broader global research framework. The main trends identified, such as improving building materials, enhancing envelope thermal performance, natural ventilation strategies, computational modeling, intelligent control, and thermal comfort assessment, can be systematically understood and organized within more comprehensive classifications based on the nature of the proposed solution and its implementation tools. To systematically categorize these diverse approaches, solutions from previous studies can be classified into four main categories based on their methodology and technology:

Chapter 1

1.6.1 Architectural/Design Solutions

These encompass passive strategies including natural ventilation design through optimization of window size, shape, and orientation; use of internal partitions to improve airflow distribution; and modification of building materials and insulation for enhanced thermal performance [43 44].

1.6.2 Technical/Mechanical Solutions

This category involves active systems such as supplementary ventilation equipment (fans, hybrid systems), localized heat exchangers, and integration of renewable energy systems like solar panels to reduce thermal loads[52].

1.6.3 CFD-Based Solutions

Computational approaches utilizing CFD modeling to simulate airflow and heat transfer, analyze design modifications, and optimize building performance through predictive simulations[53].

1.6.4 Experimental/Field-Based Solutions

Empirical methods involving laboratory testing of building models, field measurements of environmental parameters, and validation of computational models through experimental comparison.

This classification framework connects various methodological approaches and situates local research trends within a comparative analytical perspective. By categorizing interventions as design, technical, analytical, or experimental, it provides a conceptual structure that facilitates the systematic analysis and understanding of the full spectrum of solutions proposed in the field of building performance improvement[54].

1.7 Advances in Building Envelope Technologies for Thermal Control and Energy Efficiency

Thermal Control optimizing thermal insulation strategies within building enclosures, particularly under the pressures of climate change and decarbonization goals. The evolution of

these studies reflects a transition from material-based insulation strategies to integrated intelligent and simulation-driven optimization frameworks.

In 2024, Chen and You [55] introduced a machine learning-based robust predictive control framework for multi-zone buildings integrating solar and geothermal systems. Their work emphasized maintaining indoor thermal comfort under weather uncertainties while minimizing electricity costs. Although the study demonstrated improved system stability and cost reduction, its reliance on advanced predictive control algorithms limits applicability in conventional buildings without sophisticated management systems. Similarly, Wang et al. (2024)[56] developed a multi-objective optimization tool for early-stage urban design, balancing thermal loads and daylight performance. While effective in passive design planning, the simplified thermal prediction approach reduces detailed heat transfer accuracy compared to CFD-based analyses.

Material-based passive cooling strategies were also explored in 2024. Kumar [57] investigated double-skin bio-thermal insulation integrated with radiation-reflective cool roofs, demonstrating significant reductions in indoor temperature under extreme climates. However, long-term durability and scalability remain uncertain. Aboudh (2024)[58] studied photovoltaic-integrated shading devices, reporting reduced solar heat gains and improved indoor environment quality, though experimental validation was limited.

By 2025, research expanded toward advanced envelope technologies and dynamic insulation systems. Jalghaf and Kovács[59] optimized phase change materials (PCM) and thermal insulation thickness using transient heat transfer simulations, achieving substantial annual energy savings. However, the findings were predominantly simulation-based. Qiao et al. (2025)[60] further enhanced PCM applications through a twin-stage ceiling-floor cooling system, improving thermal storage performance but introducing system complexity.

Window technologies became a focal point in 2026. Zhang et al.[61]. proposed a nano-enhanced PCM window with reversible ventilation design, achieving notable seasonal adaptability and energy savings. Krelling et al. examined high-performance windows for thermal resilience during extreme cold events, demonstrating extended indoor survivability during power

outages. While these studies confirm envelope enhancement potential, cost-effectiveness and climate-specific limitations require further investigation.

Insulation-based renovation strategies also received considerable attention. Arbulu et al (2025) [62].identified overheating risks associated with excessive insulation in Spanish climates, highlighting the delicate balance between energy efficiency and indoor thermal comfort. Alpízar-Castillo and Ramírez-Elizondo (2025) [63]found diminishing energy returns beyond certain insulation levels in Dutch housing, emphasizing economic feasibility. Teichmann et al (2025) [64]. reported that façade insulation alone in high-rise buildings yields suboptimal savings without holistic system upgrades.

Green and bio-based solutions were examined by Evangelisti et al (2025)[65], who experimentally validated an ultra-lightweight soil-free green roof in Mediterranean climates, demonstrating cooling demand reduction. Uyanga et al (2025)[66]. reviewed hydrogel-based passive radiative cooling technologies, identifying strong potential but highlighting durability challenges. He et al. (2025)[67] introduced dual-responsive smart windows capable of regulating solar transmittance and infrared emissivity, significantly reducing indoor temperatures in simulations, though long-term environmental performance remains underexplored.

In 2026, research increasingly adopted integrated simulation approaches. Morakinyo et al (2026) [68] . used co-simulation tools to analyze nature-based façade compositions, demonstrating substantial heating demand reductions but also identifying seasonal performance variability. Li et al (2026)[69] developed a reversible heat pipe-embedded wall capable of dynamically switching between insulation and heat transfer modes, enhancing seasonal adaptability while increasing system complexity. Tezeri et al. (2026) [70]applied machine learning and multi-objective algorithms to design climate-resilient residential buildings, achieving reductions in energy use intensity and overheating hours, yet real-world validation remains limited.

Overall, the reviewed literature demonstrates significant progress in enhancing building thermal performance through innovative insulation materials, smart envelopes, renewable integration, and computational optimization techniques. However, several research gaps remain evident. Many studies rely heavily on building performance simulation without detailed fluid

dynamics analysis. The majority focus on material optimization rather than investigating the underlying natural convection mechanisms within building enclosures, which critically influence indoor temperature distribution and thermal comfort. Furthermore, limited experimental–CFD integrated studies have comprehensively analyzed convective heat transfer behavior inside confined building spaces.

Therefore, an integrated experimental and CFD investigation of natural convection heat transfer in building enclosures, combined with a metrological assessment of thermal comfort and energy efficiency, is essential to bridge this gap. Such an approach enables deeper understanding of airflow patterns, temperature stratification, and insulation performance, providing more accurate predictive capability for sustainable building design.

1.8 Limitations in Modeling Natural Convection and Experimental Uncertainty

A critical review of previous studies reveals several fundamental weaknesses, particularly regarding the treatment of natural convection and measurement uncertainty. Most existing research prioritizes macro-scale indicators such as annual energy consumption, U-values, or overall thermal comfort indices, while simplifying or entirely neglecting buoyancy-driven natural convection within building enclosures. In many simulation-based investigations, airflow patterns are either approximated using simplified zonal models or excluded from detailed analysis, leading to limited understanding of temperature stratification, localized overheating, and vertical thermal gradients that directly affect occupant comfort. Furthermore, numerous studies rely heavily on Building Performance Simulation tools without rigorous CFD validation capable of resolving transient convective heat transfer mechanisms. In addition, experimental works often report surface temperatures or energy savings without addressing measurement uncertainty, sensor calibration accuracy, spatial resolution limitations, or error propagation in thermal comfort indices such as PMV and PPD. The absence of comprehensive metrological analysis—considering uncertainty quantification, repeatability, and instrument precision—reduces the reliability of reported performance improvements. Consequently, the combined neglect of natural convection physics and insufficient treatment of experimental uncertainty limits the accuracy, reproducibility, and physical interpretability of many previous investigations in the field of thermal comfort and energy efficiency in building enclosures.

1.9 Brise-Soleil Systems for Solar Shading and Thermal Performance Enhancement in Buildings

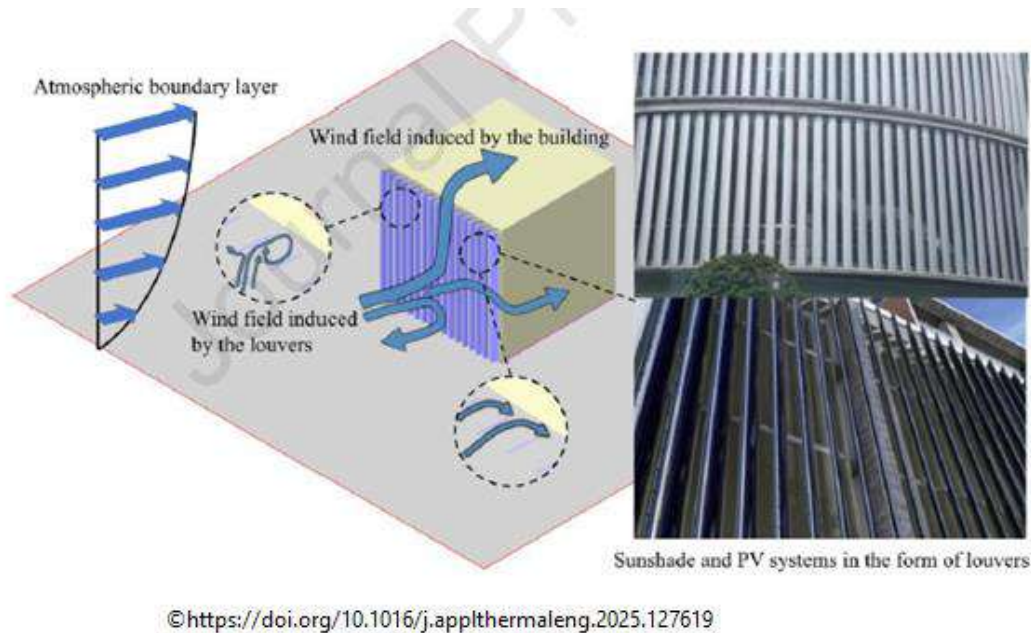


Figure 1-11 Physical view and flow field diagrams of the louver-façade system (Zelang Guo 2026)

Brise-soleil and louver systems represent advanced architectural solutions for sustainable building envelopes, serving a dual role in enhancing both thermal and visual performance. From an energy perspective, these systems contribute to reducing total energy demand by up to 37.2% in hot climates by mitigating solar heat gain and eliminating glare, while simultaneously preserving the quality of outdoor views. From an advanced technical standpoint, their function extends beyond conventional shading to influence the aerodynamics around the building façade; vertical louvers, in particular, alter wind flow patterns and create semi-enclosed cavities that directly impact the Convective Heat Transfer Coefficient (CHTC). Furthermore, these systems emerge in modern architecture as an ideal platform for integrating Building-Integrated Photovoltaics (BIPV), transforming passive shading elements into active units for clean energy generation, thereby enhancing the building's overall efficiency and its status as an eco-friendly structure[71].

1.10 Reasons for Choosing Brise-Soleil and Louvers / Shading Louvers Technology

The Brise-Soleil Louvers (or Shading Louvers) thermal insulation strategy is used in buildings for multiple reasons related to energy efficiency and environmental comfort. These movable or fixed slats act as solar shading devices, blocking direct solar radiation while still allowing natural daylight to enter the interior[72].

1.10.1 Reducing thermal load

These panels provide effective protection from direct sunlight, reducing heat gain indoors by up to 80% in some cases, especially in hot regions such as the Middle East. This significantly lowers cooling energy consumption, as studies in cities like Cairo and Lisbon have shown savings of up to 60%[72].

1.10.2 Visual Comfort and Lighting

The brise-soleil reduced visual glare by up to 100% in offices with fully glazed facades, while maintaining a good external view through carefully studied gaps between the panels. In hot climates such as Qatar, it prevents the Daylight Glare Index (DGI) from exceeding 22, ensuring year-round visual comfort without the need for lighting control on southern and eastern/western orientations[73]

1.10.3 Overall Energy Efficiency

The non-reflective brise-soleil achieves energy savings of up to 37.2% in total energy demand for east/west-facing offices, 36.3% for south-facing offices, and 11.6% for north-facing offices when combined with transparent panels and dimmable lighting control. In bifacial PV louver designs, it balances electricity generation (5795–6046 kWh annually) with a 5.5% reduction in air conditioning consumption, at a cost of electricity nearly equivalent to that of the grid[74].

1.10.4 Architectural Design

The design relies on optical properties (reflectance/transmittance) and panel dimensions (21.5 cm width, 45° tilt, 22 cm distance from the facade) to achieve a balance between aesthetics and functionality. In hot climates, non-reflective opaque panels are preferred for south, east, and west orientations, while transparent panels with lighting control are justified for north-facing facades, enhancing both sustainability and visual appeal[73], [74].

1.11 Conclusion

In conclusion, this chapter examined the issue of high energy consumption in buildings, particularly in hot and arid climates such as Algeria. It reviewed key strategies including phase change materials (PCMs), building envelope optimization, passive solar systems, and natural ventilation. However, several research gaps were identified, especially the overreliance on simulation tools and the lack of consideration of natural convection and experimental validation. Accordingly, shading systems such as brise-soleil were identified as effective solutions to enhance thermal comfort and energy efficiency. This chapter highlights the need for an integrated approach combining experimental and numerical methods, which will be further developed in the next chapter.

2 Chapter II:Experimental Design, Instrumentation, and Metrological Methodology

2.1.1 Introduction

This chapter presents the research methodology adopted in this study to investigate heat transfer phenomena within building enclosures. The study is based on an experimental approach aimed at analyzing natural convection and its influence on the thermal behavior of indoor environments. Particular attention is given to the interaction between environmental parameters and the thermal performance of the enclosure.

The experimental investigation involves the measurement of several environmental variables, including air temperature, relative humidity, solar radiation, and wind speed. These parameters are essential for understanding the thermal conditions affecting the building envelope and the indoor thermal environment.

To ensure the reliability and accuracy of the collected data, a metrological approach is adopted throughout the experimental process. This includes the calibration of measurement instruments and the application of appropriate procedures to minimize measurement uncertainties. By combining accurate environmental measurements with a controlled experimental setup, this methodology allows for a comprehensive analysis of natural convection heat transfer and its impact on thermal comfort and energy efficiency in buildings.

2.2 Conceptual and Methodological Framework of the Study

Based on the scientific rationale for selecting "Brise-Soleil" and shading louver systems as effective solutions for improving building thermal efficiency, this study adopts a comprehensive and systematic research framework. The proposed methodology integrates experimental investigation, numerical simulation using ANSYS Fluent software, and metrological analysis in order to provide a detailed assessment of the thermal and aerodynamic behavior of these systems.

This integrated approach allows for the analysis of heat transfer mechanisms under both natural and forced convection conditions within enclosed spaces, while minimizing uncertainties associated with experimental measurements and numerical predictions. By combining experimental observations with computational modeling, the methodology ensures a more accurate and reliable interpretation of the thermal performance of solar shading devices.

Furthermore, this methodological framework establishes a conceptual bridge between the introductory context presented in Chapter One and the theoretical foundations discussed in Chapter Two. It provides the necessary basis for understanding the physical principles, heat transfer mechanisms, and analytical methods that underpin the evaluation of building envelope shading systems and their contribution to improving thermal comfort and energy efficiency in buildings.

2.3 Description of the Experimental Setup

2.3.1 Building Enclosure Model

The studied cell has a surface area of 1 m^2 and a height of 80 cm . Its dimensions were determined based on those of a typical room within a building. The cell was constructed using cement-based materials, representative of conventional building construction. The cell includes a small window measuring $39.5 \times 24.5 \text{ cm}^2$ and a small door measuring $47.5 \times 29 \text{ cm}^2$ [75].

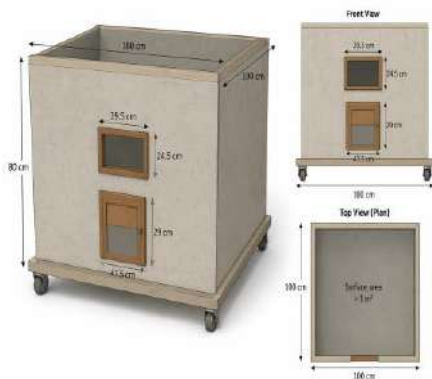


Figure 2-2 Experimental Setup and Its Dimensions case 1



Figure 2-1 Experimental Setup case 2

2.3.2 Measurement Locations

2.3.2.1 Sensor locations in cells and in Case 2 (Wind catcher)

For the two experimental cases, thermocouples were arranged at different positions inside the prototype according to the configuration of each scenario, as illustrated in the corresponding figures(Figure 2-6) and (Figure 2-5). The selected measurement points were chosen to represent the main areas where thermal variations are expected, allowing continuous monitoring of temperature evolution over time and providing a clearer understanding of heat transfer and temperature distribution within the system.

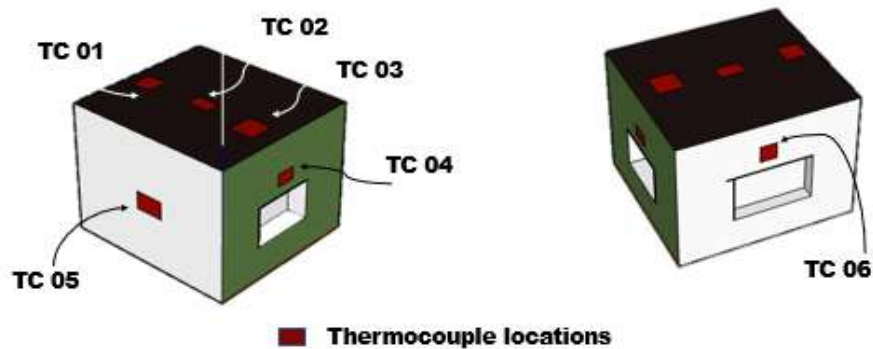


Figure 2-4 Sensor locations in cells

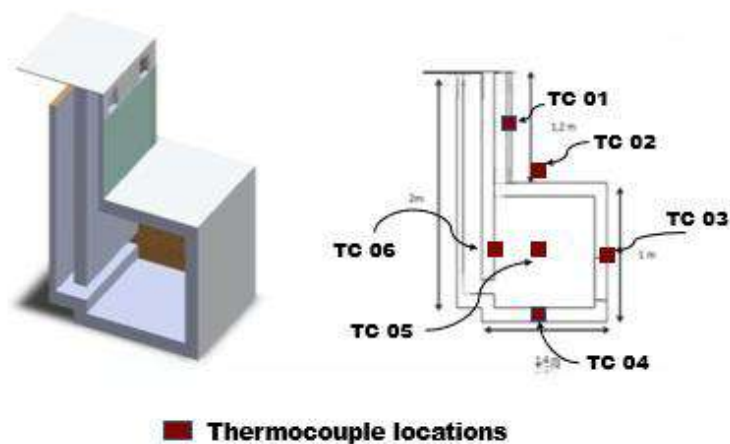


Figure 2-3 Sensor locations in Case 2

2.4 Integration of the Brise-Soleil Shading System

2.4.1 Description of the Brise-Soleil shading device installed on the façade.

This study investigates an external solar shading system inspired by the Brise-Soleil concept applied to the opaque façades of a residential building. Horizontal and vertical shading panels with different dimensions, inclination angles, and spacing configurations were modeled in EnergyPlus to evaluate their effect on solar gains, indoor thermal comfort, and cooling energy consumption while maintaining daylight and visual comfort..[76].

2.4.1.1 *Type of louvers (horizontal or vertical).*

The proposed shading strategy includes horizontal and vertical external panels applied to west-facing opaque residential façades to reduce direct solar radiation. Different panel configurations and spacing were analyzed separately using EnergyPlus to evaluate their thermal performance and impact on solar gains and cooling efficiency, with results indicating that horizontal shading is generally more effective.[76]

2.4.1.2 *Spacing between louvers.*

The spacing between shading panels varies according to the number of installed elements and façade configuration, ranging from 0.92 m to 0.12 m. Several spacing scenarios were evaluated to determine the optimal balance between solar protection, thermal performance, and energy efficiency.[76].

2.4.1.3 *Orientation and inclination angle.*

The shading panels are oriented toward solar exposure on west-facing façades, with different tilt angles (30°–150°) investigated to assess their effect on shading efficiency and building thermal performance. Previous studies show that lower tilt angles, especially around 30°, provide better solar control and higher cooling energy savings compared to larger angles.[76].

2.4.1.4 *Position of the shading system relative to the building opening*

The proposed shading system is externally installed on opaque façade surfaces, away from window openings, to ensure solar protection while preserving natural daylight and outdoor

visibility. Panel lengths range from 0.1 m to 0.7 m in compliance with building regulations, and the system is independently integrated into the façade without affecting occupant visual comfort.[76].

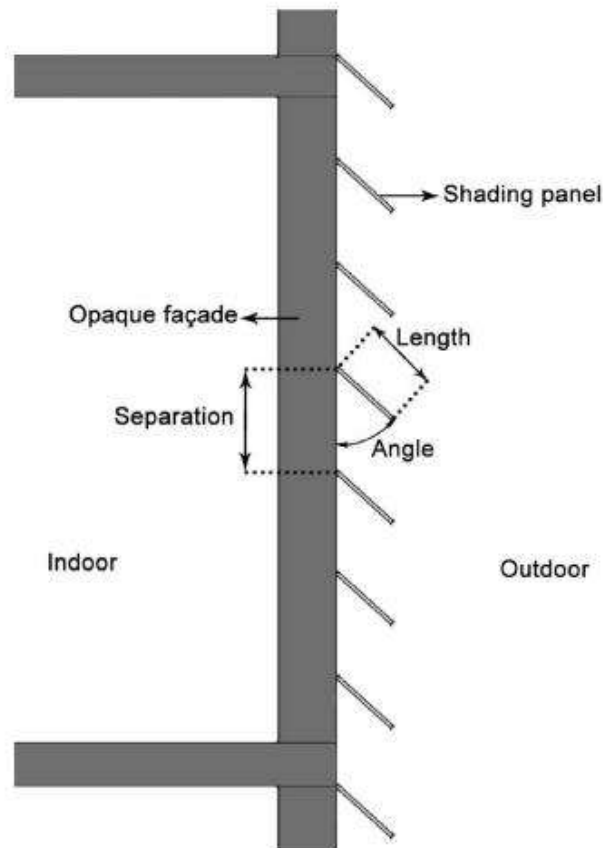


Figure 2-5 Input parameters of shading panels for the simulation.

2.5 Solar Geometry and Shadow Calculations

2.5.1 Solar Angles

Solar declination is the angle formed between the Sun's rays and the plane of the equator, as illustrated in Figure 3. This angle varies only with the day of the year. It is also equal to the latitude at which the Sun is directly overhead at solar noon on that day.

The solar declination is positive when the Sun is directly overhead at locations north of the equator (from December 21 to June 21), and negative when it is directly overhead south of the equator (from June 21 to December 21)[77].

The value of the solar declination (δ) can be calculated using the following equation:

$$\delta = (23.45^\circ)\sin[360^\circ(284 + n)/365]$$

Where **n** is the day number in the year, with January 1 as 1.

Our study was on May 17 and 18 .So n=137

$$\delta = (23.45^\circ)\sin[360^\circ(284 + 137)/365]$$

$$\delta = 12.10^\circ$$

Solar Angles[78]

$$\alpha = 90 - |\varphi - \delta|$$

φ : Latitude of Ouargla Algeria Province [78]

$$\alpha = 90 - |31.9527 - 12.10|$$

$$\alpha = 70.143^\circ$$

2.5.2 overhang and shading depth

The basic formula for calculating the overhang/shading depth of architectural windows facing the sun is a simple triangular formula based on the angle of the sun's elevation and the vertical height of the window.

$$D = \frac{H}{\tan \alpha}$$

Where:

D: Shading depth (the length of the overhang

H: The vertical height from the window

α : The solar elevation angle

So:

$$H = 24.5 \text{ cm}$$

$$\alpha = 73.5623^\circ$$

$$D = \frac{24.5 \times 10^{-2}}{\tan 73.5623}$$

$$D = 0.0722m$$

Shading efficiency

$$\text{Shading efficiency} = \frac{\text{blocked area}}{\text{total window area}}$$

$$\text{Shading efficiency} = \frac{0.0722}{(39.5 \times 10^{-2}) \times (24.5 \times 10^{-2})}$$

$$\text{shading efficiency} = 74.60\%$$

2.6 Shading System Configuration for the Experimental Cell

The proposed shading configuration for the experimental cell consists of externally mounted horizontal and vertical louvers applied on the opaque west-facing façade. Due to the reduced dimensions of the test cell (1 m² surface area and 80 cm height), the louver geometry and spacing were proportionally scaled to suit the façade dimensions. The separation distance between louvers was estimated between 0.08 m and 0.12 m to achieve effective solar protection while maintaining adequate daylight penetration. The shading panels were oriented primarily toward the west façade and installed with tilt angles ranging from 30° to 90°, with 30° considered the optimal configuration for improving thermal performance and reducing solar heat gains.



Figure 2-7 AI-assisted 3D render of the test cell setup showing the specifications of the external shading system.



Figure 2-6 Shading system configuration for the thermal test cell setup

2.6.1 Fabrication and Assembly of the Experimental Prototype

Figure 2_82 presente the different stages of the experimental setup fabrication and structural assembly of the test cell and its integrated shading system. Initially, the required materials and tools, including metal profiles and shading panels, were prepared. The metal elements were then measured and cut according to the predefined geometric dimensions. After that, rivets and fastening tools were used to ensure strong and durable mechanical connections during assembly. Finally, the main structure and shading system were assembled, incorporating an adjustable mechanism that allows manual variation of the panel inclination angle for the experimental investigation of its effect on thermal performance and natural ventilation inside

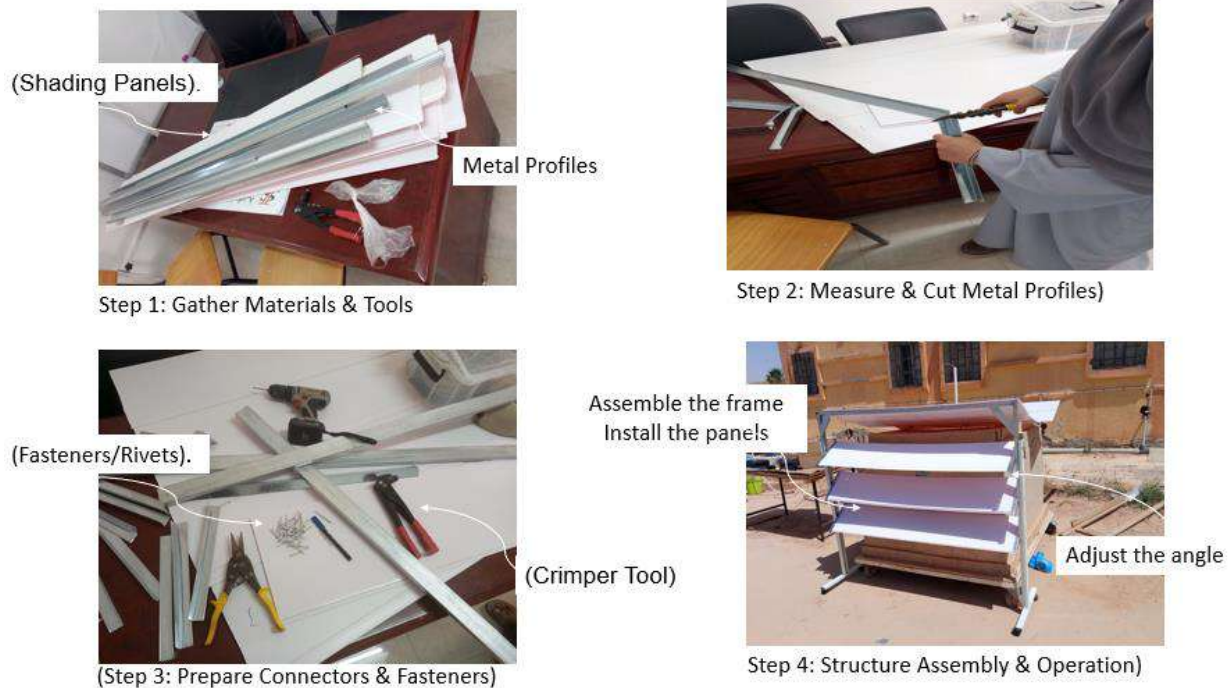


Figure 2-8 Step-by-step manufacturing and assembly process of the external shading louver system for the experimental cell.

the test cell.

2.7 Measurement Instruments

2.7.1 Temperature Measurement Devices

2.7.1.1 *Importance of Temperature Measurement*

Temperature is a key parameter in THMC (Thermal–Hydraulic–Mechanical–Chemical) models used in repository systems. It is essential for monitoring the behavior of engineered and natural barriers, making accurate measurements critical [79].

2.7.1.2 *Measurement Techniques and Signal Characteristics*

Temperature is measured using sensors that detect changes in physical properties. The main techniques are thermocouples, Resistance Temperature Detectors (RTDs), and thermistors[79].

2.7.1.3 *Thermocouples*

generate a voltage (emf) between two dissimilar metals when temperature changes, with a nonlinear increase in output.[79].

2.7.1.4 *Resistance Temperature Detectors (RTDs)*

measure temperature through changes in electrical resistance, usually using platinum. They are highly accurate, stable, and nearly linear over a wide temperature range.[79].

2.7.1.5 *Thermistors*

Thermistors are temperature-sensitive resistors that measure temperature by changes in electrical resistance. They are highly suitable for detecting small temperature variations and provide greater sensitivity and faster response than RTDs.

2.7.2 Humidity Measurement

Humidity refers to the amount of water vapor present in air, which can be expressed as absolute or relative humidity. It is commonly measured using instruments such as hygrometers, which operate based on different physical principles including temperature differences, condensation (dew point), mass variation, or electrical property changes. Relative humidity (RH) represents the ratio between the actual water vapor content and the maximum possible at a given temperature. It is widely measured using electrical sensors that detect changes in

capacitance or resistance, although other techniques such as optical, mechanical, and infrared methods are also used. Humidity sensors are classified into electrical, mechanical, optical, and integrated types, each with specific operating principles and limitations depending on the sensing material and environmental conditions.[81].

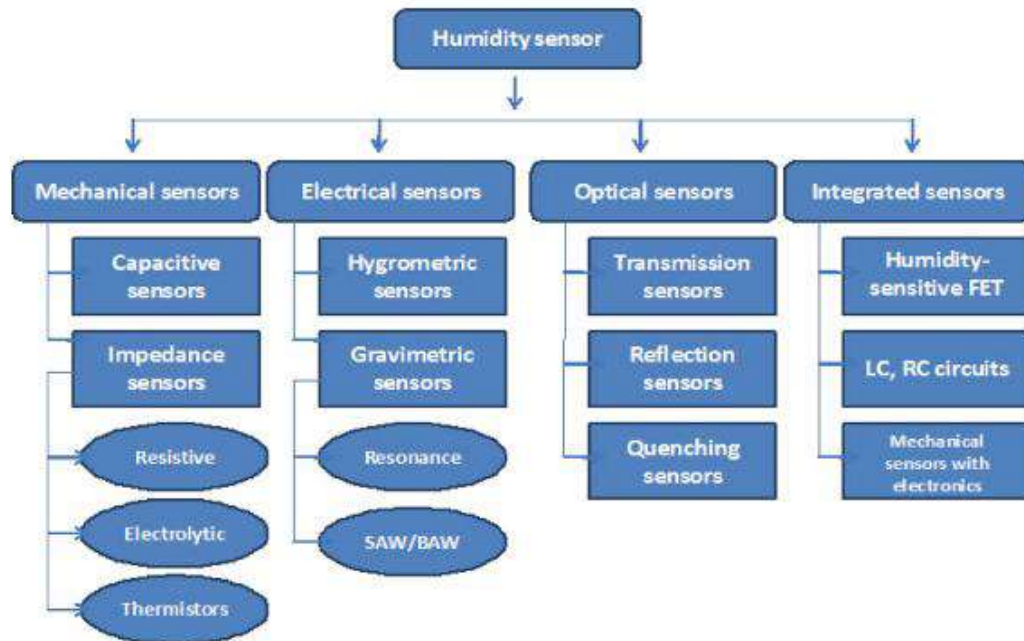


Figure 2-9 classification of humidity sensor

2.7.3 Solar Radiation Measurement

Terrestrial solar radiation is measured using instruments such as pyranometers and pyr heliometers. Pyranometers capture radiation over a hemispherical field of view, while pyr heliometers measure direct solar radiation coming from the narrow solar disk. Sky radiation can also be measured by shading a pyranometer to block direct sunlight. The total radiation received on a horizontal surface is the sum of direct beam radiation adjusted by the cosine of the incidence angle and the diffuse radiation from the sky, expressed as:

$$G = B \cos(i) + D$$

Where:

G : Total (global)

B: Direct beam

i: incidence angle

D: Diffuse Sky (scattered)



Figure 2-10 The experimental Solar Radiation device (Pyranometers)

This relationship allows the calculation of any one component if the other two are known and forms the basis for calibrating radiometers. Calibration is typically performed using precise reference instruments. The global standard for solar radiation measurements is the World Radiometric Reference (WRR), maintained by the World Meteorological Organization at the Physical Meteorological Observatory Davos. This standard is established using absolute cavity pyrhemometers, which determine radiation by equating absorbed solar energy with electrically generated heat[82].

Table 1 Characteristics of Solar Radiation Measurement Instruments

Instrument	Measures	Key Features	Accuracy
Pyranometer	Global (GHI), diffuse (DHI)	180° field, thermopile sensor, ISO 9060 standards	±1-5% [82]

Pyrheliometer	Direct beam (DNI)	Narrow aperture, sun tracker required	$\pm 1\text{-}2\%$ [83]
Spectroradiometer	Spectral irradiance	Full wavelength scan, filter radiometers for bands	Varies by band[84]

2.7.4 Wind Speed Measurement

Wind energy is a vital and rapidly growing renewable energy source, whose efficiency depends mainly on factors[85] .such as wind speed, air density, pressure, temperature, and turbulence . Since the power generated by a wind turbine is proportional to the cube of wind speed, selecting suitable installation locations largely depends on accurate wind measurements[86]. Devices called anemometers, first introduced by Leone Battista Alberti, are essential for measuring wind speed, improving energy efficiency, reducing costs, and enabling the expansion of wind power systems, including their integration into small-scale turbines and smart grids. These devices come in various types based on their operating principles, such as mechanical, hot-wire, ultrasonic, lidar, and fiber optic anemometers. However, each type has certain limitations; for instance, mechanical sensors can be affected by electrical environments, ultrasonic sensors are sensitive to electromagnetic interference, and hot-wire sensors may suffer from calibration issues due to temperature variations and limited operating ranges[87].

Table 2 Comparison of Wind Speed Measurement Instruments and Their Operating Principles

Type	Principle	Range	Strengths
Cup	Rotational frequency	0.5-60 m/s	Robust, cost effective[88]
Ultrasonic/Sonic	Acoustic Doppler shift	0-65 m/s	No moving parts, 3D data [89]
Hot-Wire	Forced convection cooling	0-250 m/s	High resolution [90]
LiDAR/Fiber Optic	Doppler/light reflection	Remote profiling	Non-intrusive [91]

2.7.5 Temperature Sensor Calibration

The thermal calibration in this work is based on the International Temperature Scale of 1990 (ITS-90), which serves as the primary reference for high-accuracy temperature measurements in scientific applications. The calibration procedure was performed using 17 reference points covering a wide temperature range, carefully selected to ensure traceability and minimize measurement uncertainty. This approach enables the development of an accurate calibration relationship between sensor readings and true reference values, thereby improving the reliability and precision of the experimental results [92].

Temperature measurement is a fundamental parameter in industrial and scientific applications, where accurate control is essential for quality and compliance. It is traditionally based on standardized scales such as Celsius and Fahrenheit, defined using fixed reference points like the ice point (0°C) and boiling point (100°C) of water under standard atmospheric pressure. The ITS-90 extends this concept by introducing a series of highly precise fixed points across a wide temperature range, enabling accurate and repeatable calibration of thermometers. These fixed points correspond to equilibrium states of pure substances such as oxygen, water, sulfur, silver, and gold, covering temperatures from cryogenic levels to extremely high values [93].

In practice, temperature calibration is carried out by placing the sensor in a stable environment, such as a dry-well calibrator or micro-bath, and comparing its output with a calibrated reference thermometer. Corrections are then applied depending on the device type: electrical sensors are adjusted using calibration coefficients, while mechanical instruments may be corrected through physical adjustment or offset application. Thermocouple calibration is governed by international standards such as IEC 60584[94], which defines electromotive force (EMF) tolerances and reference tables based on fixed points like ice and steam points, while additional standards such as DIN 43710 [95] provide additional data for specific thermocouple types and industrial applications [96].



Bangladesh BEST Programme
Defining Fixed Points of ITS -90



Material	Equilibrium State	Temperature (K)	Temperature (°C)
Hydrogen	Triple point	13.8033	-259.3467
Hydrogen (or He)	Vapour pressure	20.3	-252.85
Neon	Triple point	24.5561	-248.5939
Oxygen	Triple point	54.3584	-218.7916
Argon	Triple point	83.8058	-189.3442
Mercury (Hg)	Triple point	234.3156	-38.8344
Water (H ₂ O)	Triple point	273.16	0.01
Gallium (Ga)	Melting point	302.9146	29.7646
Indium (In)	Freezing point	429.7485	156.5985
Tin (Sn)	Freezing point	505.078	231.928
Zinc (Zn)	Freezing point	692.677	419.527
Aluminum (Al)	Freezing point	933.473	660.323
Silver (Ag)	Freezing point	1234.93	961.78
Gold (Au)	Freezing point	1337.33	1064.18
Copper (Cu)	Freezing point	1357.77	1084.62

17

Figure 2-11 Fixed Points of the International Temperature Scale of 1990 (ITS-90)

2.7.5.1 Calibration Procedure

The calibration of Type K thermocouples connected to the MAX6675 module was carried out to evaluate measurement accuracy and enhance the reliability of the acquired data. Initially, twelve thermocouples were connected to an Arduino board via the MAX6675 module, and a data logging system was configured to record temperature readings over time. The thermocouples were placed in a test setup as shown in the figure, and an ice bath was prepared by adding ice to establish a stable reference temperature of 0°C. The sensors were left until the readings stabilized, after which the values were recorded. Subsequently, the setup was transferred to an electric hot plate set at 50°C, where measurements were monitored until thermal stability was achieved and then recorded. The temperature was then gradually increased up to 80°C, with continuous data logging throughout the process. At the same time, temperature readings were

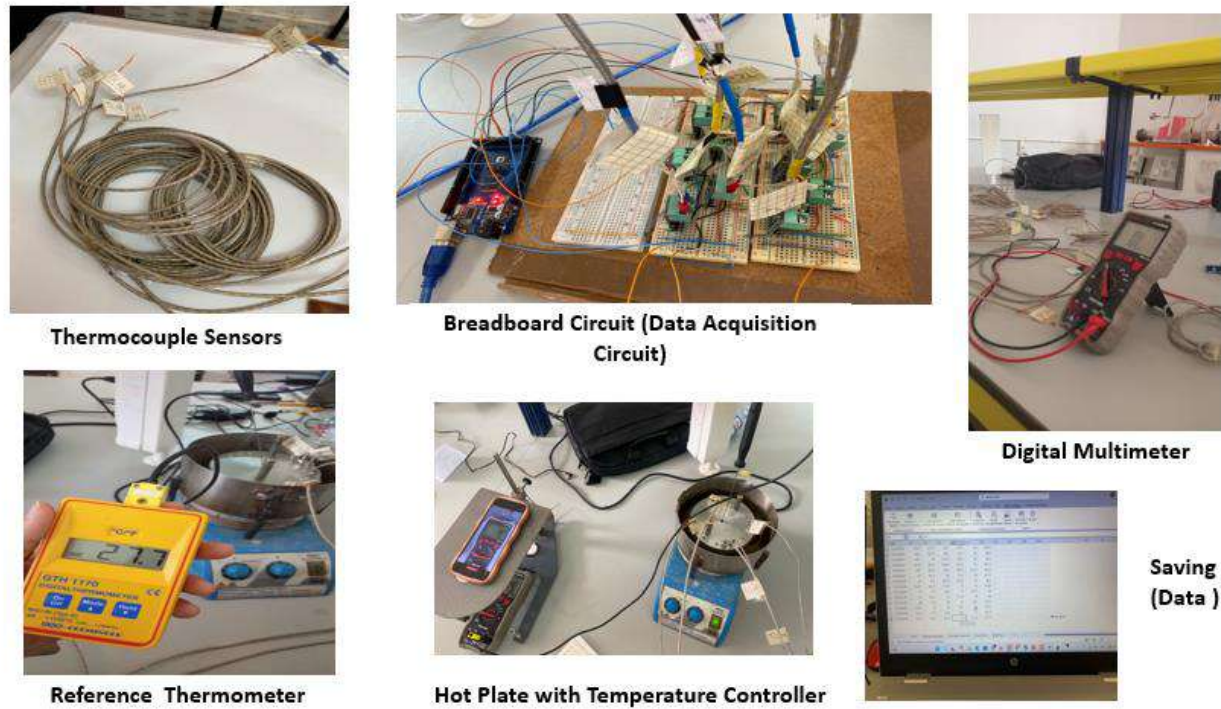


Figure 2-12 calibration of temperature sensor protocol

manually measured using a reliable reference digital thermocouple for validation purposes. A systematic comparison between the recorded data and the reference measurements at different calibration points enabled the identification of deviations and the calculation of correction factors for each thermocouple, thereby improving the overall performance and accuracy of the measurement system.

2.7.5.2 Data Processing and Statistical Analysis

The experimental data were processed using Microsoft Excel software. For each thermocouple, the measured values were paired with the corresponding reference values to form datasets for analysis. For each measurement channel, the following procedures were carried out:

- calculating the mean value to minimize the influence of random errors
- plotting the measured values against the reference values
- applying linear regression to determine the calibration parameters.

The quality of the fit was assessed using the coefficient of determination R^2 , which provides an estimate of the correlation between the experimental data and the adopted model.

2.7.5.3 Thermocouple uncertainty

A thermocouple measurement has a combined standard uncertainty that comes from several contributions, such as the reference thermometer, readout electronics, junction temperature, bath or furnace stability, non-uniformity, inhomogeneity, drift, and extraneous emf. For calibration by comparison, the individual components are converted to the same unit, then combined in quadrature[97]

$$U_c = \sqrt{\sum U_i^2}$$

and the expanded uncertainty is usually taken as

$$U = KU_c$$

With

$$K = 2$$

for about 95% confidence. For converting voltage uncertainty to temperature uncertainty, the relation is

$$U(t) = \frac{U(E)}{S_n(t)}$$

where

$S_n(t)$ is the Seebeck coefficient of the thermocouple type at temperature t . In practice, the final uncertainty budget is built from the specific terms of the setup, and each term is expressed either directly in temperature or converted from emf before combination[97].

2.7.6 Humidity Temperature Sensor Calibration

In the context of the calibration (étalonnage) of humidity and temperature sensors, the study combined both reference-based and experimental approaches to ensure high measurement reliability. For humidity calibration, Reference humidity generators (salt chambers) were used to define stable and well-controlled relative humidity points, providing accurate reference conditions for the calibration procedure.

Based on these predefined reference points, an experimental setup was implemented using DHT11 and DHT22 sensors in addition to thermocouples. The sensors were connected to an Arduino Uno board, which converted the signals from analog to digital form and enabled automatic data logging and export in an analyzable format such as Excel. A controlled test

environment was created using a sealed transparent plastic enclosure, where water vapor was gradually introduced to vary relative humidity from approximately 29% to 93%.

A reference humidity measuring device was placed inside the enclosure alongside the sensors to ensure accurate comparison. Over a period of 20 to 30 minutes, simultaneous measurements were recorded and compared with the reference values. This allowed the determination of deviations and the calculation of correction factors for each sensor, thereby improving their accuracy and overall performance under

Saturated Salt Solutions - Controlling Air Humidity											
Saturated Salt Solution	Temperature (°C) (deg F)										
	0	5	10	15	20	25	30	35	40	50	60
	Relative Humidity over the Salt Solution (%)										
Ammonium nitrate - NH_4NO_3			75	70	67	64	60	53			
Ammonium sulphate - $(\text{NH}_4)_2\text{SO}_4$	82	82	82	82	81	81	81	80	80	79	
Lithium chloride - $\text{LiCl}^{1)}$					11.31	11.35	11.28	11.25	11.21	11.10	10.95
Magnesium chloride - MgCl_2	34	34	33	33	33	33	32	32	32	31	29
Magnesium nitrate - $\text{Mg}(\text{NO}_3)_2$	60	59	57	56	54	53	51	50	48	45	
Sodium Chloride - $\text{NaCl}^{1)}$	75.51	75.65	75.67	75.61	75.47	75.29	75.09	74.87			
Potassium sulphate - K_2SO_4	99	98	98	98	98	97	97	97	96	96	
Potassium nitrate - KNO_3	96	96	96	95	95	94	92	91	89	85	
Potassium chloride - KCl	89	88	87	86	85	84	84	83	82	81	80
Potassium acetate - $\text{CH}_3\text{CO}_2\text{K}$			23	23	23	23	22				
Potassium hydroxide - KOH		14	12	11	9	8	7	7	6	6	5
Sodium chloride - NaCl	76	76	76	76	75	75	75	75	75	74	75
Sodium nitrite - NaNO_2					65	64	63	62	61		
Sodium dichromate - $\text{Na}_2\text{Cr}_2\text{O}_7$	61	59	57	57	55	54	53	51	50	49	47

Figure 2-13 Salt Solutions Humidity Table

2.7.6.1 Calibration Procedure

Before starting the calibration process, the program code was uploaded to the Arduino board to activate the sensors, continuously acquire temperature and humidity data, and transmit the measurements to a computer for recording and subsequent analysis. The implemented code was also used to control the acquisition interval during the experiments.

For the experimental setup, a transparent airtight chamber was designed and sealed using silicone in order to ensure environmental stability and prevent air or vapor leakage, which is essential for maintaining traceability conditions and ensuring reliable comparison results. Inside the chamber, the tested sensors (DHT11 and DHT22), the reference instrument (Kimo AMI 300), and the vapor generation device were installed. To manage data acquisition, an integrated data logger system was developed using the Arduino IDE environment, where the programmed code automatically synchronized, recorded, and stored sensor readings with accurate time intervals.

The experiment began after verifying the stability of all devices, then the humidity level was gradually increased while sensor data were continuously recorded through the data logger system, in parallel with manual recording of the reference instrument readings every 15 seconds. After completing the measurements, all recorded data were exported to Microsoft Excel for processing and statistical analysis.

The relationship between the sensor readings and the reference values provided by the Kimo AMI 300 was then analyzed. To improve calibration accuracy, the data were divided into several measurement ranges, and an independent correction equation was established for each range instead of applying a single global equation to all values. This approach significantly reduced deviations between measured and reference values and improved the overall calibration accuracy. Finally, the calibration curves generated in Excel were used to derive the final correction equations implemented in the measurement system.

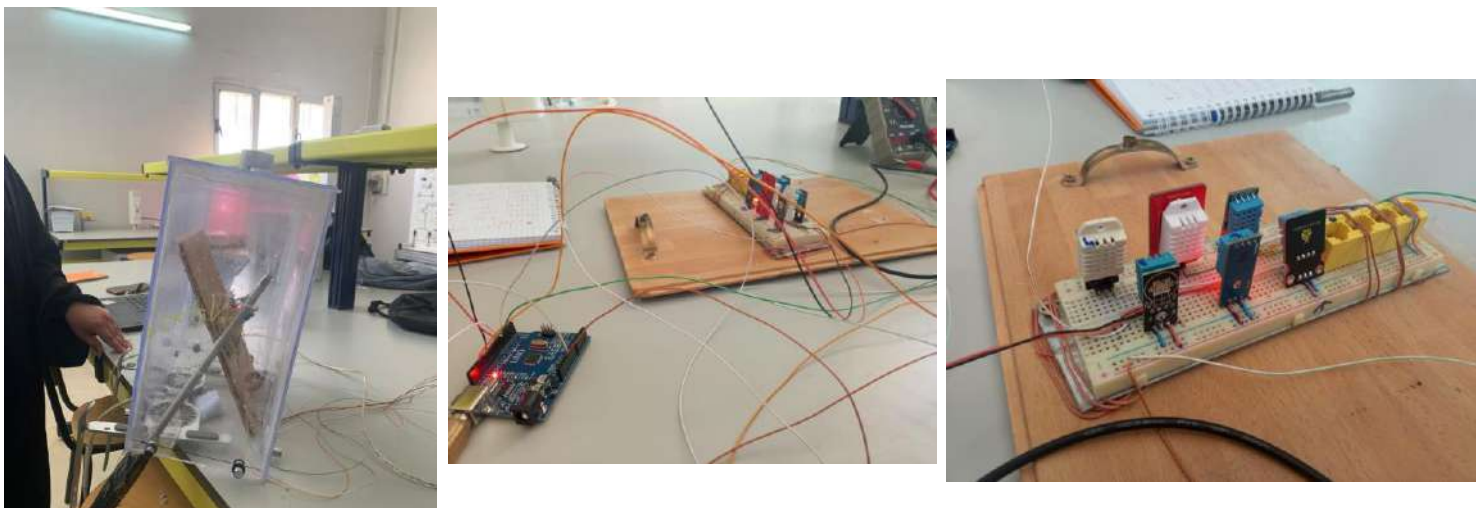


Figure 2-14 calibration of humidity sensor protocol

2.7.6.2 Humidity uncertainty

For relative humidity, the NIST humidity-generator model gives [97]

$$RH = \frac{f(p_s, t_s)e_w(T_s)}{f(p_c, t_c)e_w(T_c)} \times 100$$

Where

f is the enhancement factor

e_w is the saturation water vapor pressure

The combined standard uncertainty is then written as

$$U_c(RH) = \sqrt{U_r^2[f(p_s, t_s)] + U_r^2[f(p_c, t_c)] + U_r^2[e_w(T_s)] + U_r^2[e_w(T_c)] + U_r^2(P_s) + U_r^2(P_c)}$$

and the expanded uncertainty is

$$U = 2U_c(RH)$$

For dew/frost-point temperature, the key relation is

$$e_w(T_d)f(p_c, t_c) = e_w(T_s)f(p_s, t_s) \left(\frac{P_c}{P_s} \right)$$

and the uncertainty is obtained by propagating the input terms through the derivative of saturation vapor pressure with respect to temperature[97].

2.7.6.3 DHT11 sensor VS DHT22

From a metrological perspective, both DHT11 and DHT22 sensors are used to validate data and improve measurement reliability through direct comparison. The DHT22 is treated as a reference due to its higher accuracy, wider range, and better stability. In contrast, the DHT11 shows limitations such as poor stability and occasional freezing, reducing its reliability for continuous monitoring. Using both sensors together improves data robustness, reduces uncertainty, and increases confidence in the results.

DHT22	CARACTÉRISTIQUES	DHT11
 -40 à 125°C (±0,5°C)	 Plage de mesure de température	 0 à 50°C (±2°C)
 0 à 100% RH (±0,5% RH)	 Plage de mesure d'humidité	 20 à 80% RH (±5% RH)
 0,1°C	 Résolution de température	 1°C
 0,1% RH	 Résolution d'humidité	 1% RH
 ±0,2°C	 Répétabilité de température	 ±1°C
 ±1% RH	 Répétabilité d'humidité	 ±1% RH
 2 s	 Temps de réponse (secondes)	 1 s
 3,3 – 6 V	 Tension de fonctionnement	 3 – 5 V
 2,5 mA	 Courant maximum	 2,5 mA

Figure 2-15 Metrological comparison between DHT11 and DHT22 sensors

2.8 Experimental Procedure

The experimental campaign began with the measurement of outdoor environmental conditions, namely solar radiation and wind speed, using appropriate measuring instruments.

These parameters were considered as the external boundary conditions influencing the thermal behavior of the two experimental models during the testing period.

The experimental system consisted of two test rooms:

- A conventional experimental room.
- A second experimental room equipped with a Solar chimney (Chiminée solar) in order to investigate its influence on indoor thermal behavior and heat transfer.

A total of twelve (12) thermocouples and one relative humidity sensor were installed within the experimental setup. In addition, an extra thermocouple was used to measure the ambient temperature. All sensors were connected to an Arduino-based data acquisition system interfaced with a personal computer for continuous monitoring, data recording, and subsequent analysis.

The thermocouples were distributed as follows:

- Thermocouples installed on the external surfaces of both rooms exposed to solar radiation in order to evaluate the influence of climatic conditions on surface temperature.
- Thermocouples positioned inside both rooms to measure the indoor air temperature distribution and thermal stratification.
- One thermocouple installed inside the chimney of the second room to analyze temperature variation and heat transfer within the chimney system.
- An additional thermocouple used to measure ambient temperature as a reference value for comparison with the different measurement locations.

The relative humidity sensor was placed inside the experimental room to monitor the evolution of indoor humidity during the experimental period.

All measurements were recorded continuously and synchronously throughout the experiment. The collected data were automatically stored on a computer for further processing and analysis in order to evaluate the thermal performance and compare the thermal behavior of both rooms

under identical environmental conditions.

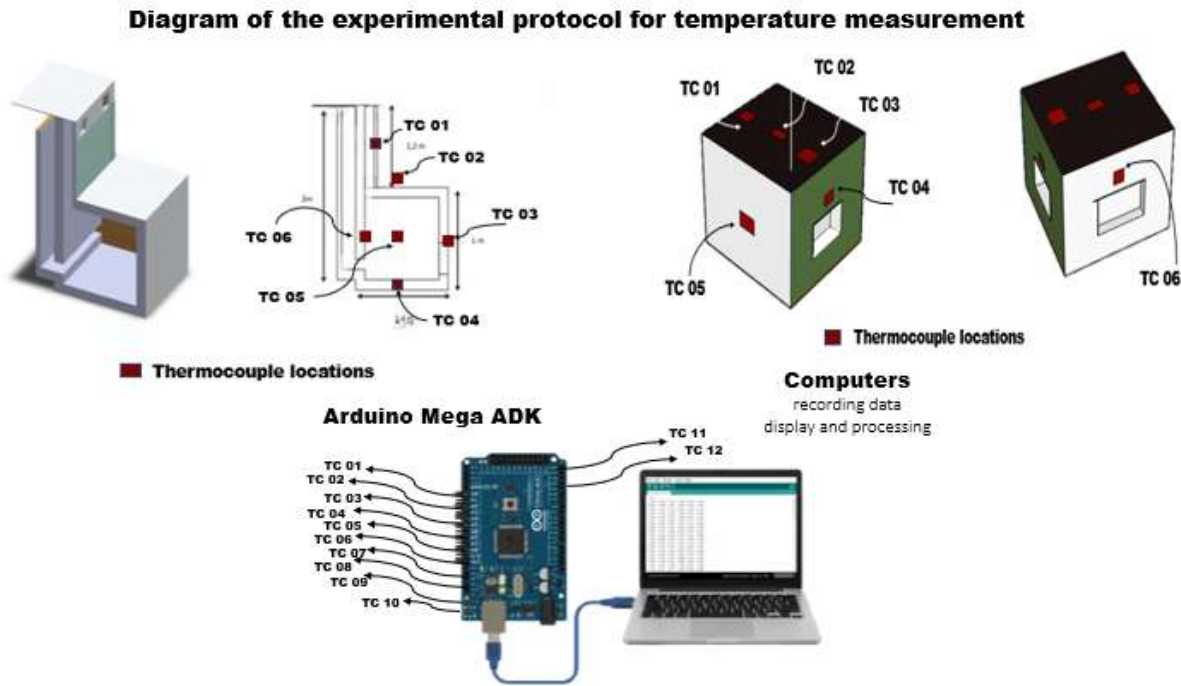


Figure 2-16 Diagram of the experimental protocol for temperature measurement

2.9 Data Processing and Statistical Analysis

After completing the calibration and experimental measurements, the recorded data were extracted from the Arduino-based data logger and transferred to Microsoft Excel and OriginLab for processing and statistical analysis. The collected measurements were organized according to the different experimental conditions and sensor locations, followed by data cleaning to eliminate abnormal or inconsistent values and ensure the reliability of the dataset. Several graphical representations were generated, including temperature–time curves, humidity–time curves, and calibration curves used to derive the final correction equations implemented in the measurement system.

In addition, several statistical parameters were calculated in order to evaluate the accuracy and reliability of the measurement system, including the mean value ($\bar{X}$), standard deviation (σ), Type A uncertainty U Type B uncertainty related to the measurement range, combined global uncertainty U_c relative uncertainty (%), and the coefficient of determination (R^2) used to assess the correlation between the measured and reference values. These statistical analyses were

employed to quantify measurement precision, evaluate sensor performance, and validate the calibration procedure. Comparative analyses were also carried out to assess the thermal behavior and performance of the experimental system under different operating conditions. The detailed results obtained from these analyses are presented and discussed in Chapter 3.

2.10 Conclusion

This chapter presented the experimental methodology adopted to investigate natural convection heat transfer and thermal comfort in a building enclosure under hot and arid climatic conditions. A reduced-scale building model equipped with a Brise-Soleil shading system was designed and installed on the west façade, with its geometry optimized based on solar analysis for the study site of Ouargla.

The experimental setup integrated calibrated measurement instruments, including thermocouples, humidity sensors, a pyranometer, and an anemometer, all connected to a data acquisition system. Comprehensive calibration procedures were performed for temperature and humidity sensors, ensuring high accuracy and reliability of the measurements. In addition, a full metrological uncertainty analysis was conducted to quantify measurement reliability and improve data traceability.

Data were collected continuously under three configurations—unshaded, white-coated, and Brise-Soleil shaded—under identical climatic conditions. The acquired datasets were then processed using statistical and graphical tools to enable comparative thermal performance analysis in the following chapter.

3 Chapter **III**: Results and Discussion

3.1 Introduction

This chapter represents the main experimental stage of this work, marking the transition from the theoretical framework to practical application. Its primary objective is to evaluate the performance of the solar shading system in the region of Ouargla. Initially, the climatic characteristics of the study area were presented including the calculation of important environmental parameters such as wind speed and solar radiation relevant to the study model. To ensure the reliability of the experimental data, the sensors used (based by arduino) particularly temperature and humidity sensors were carefully calibrated before conducting any measurements. Subsequently, a series of dynamic measurements of temperature and humidity were carried out at different locations inside the Building Enclosure Model. In parallel, the distribution of temperature and humidity within the studied space was presented, providing a comprehensive understanding of the thermal behavior of the system and its impact on achieving thermal comfort. The accuracy of the measurements was also verified through a comparison of the values obtained before and after the calibration process. Finally, this chapter presents the study site, the experimental model, the measurement instruments, the calibration methodology, and the procedure followed to perform the experimental measurements.

3.2 Research Methodology

This study adopted an experimental methodology to analyze natural convection inside a building enclosure and evaluate the effect of a solar shading system (brise-soleil) on indoor thermal conditions. The methodology began with the analysis of the climatic characteristics of Ouargla, including solar radiation and wind speed, to ensure realistic experimental conditions.

Temperature and humidity sensors were then selected and carefully calibrated to improve measurement accuracy and data reliability. Afterward, the sensors were installed at different locations inside the experimental model to monitor thermal variations within the enclosure. The solar shading system was subsequently installed, and new thermal measurements were compared with reference data collected before its implementation to evaluate its effectiveness in reducing heat gain and improving indoor conditions. Finally, the results were analyzed and

compared with previous studies on passive cooling techniques in semi-arid climates to assess the performance of the proposed shading system.

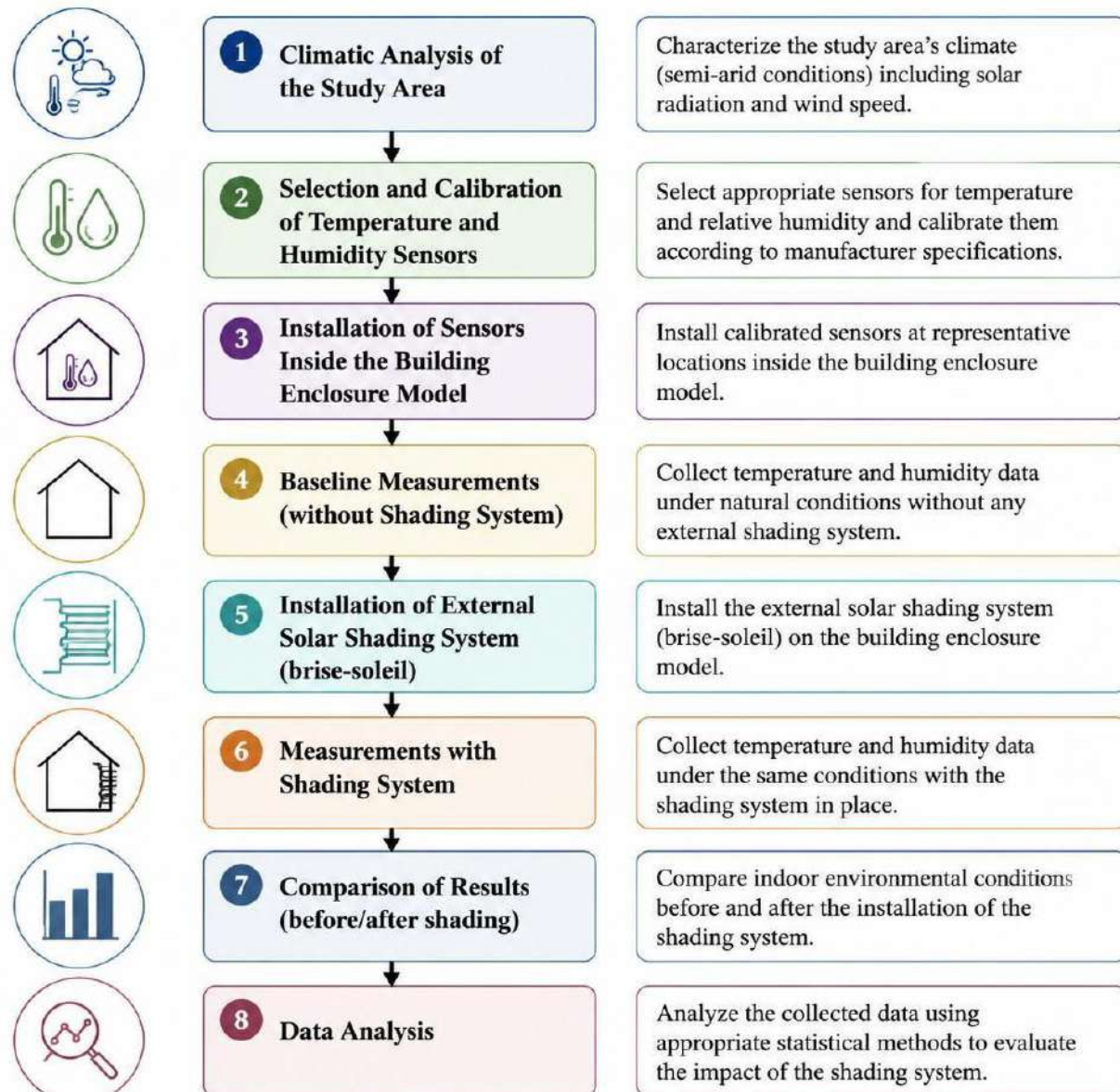


Figure 3-1 Flowchart of the experimental research methodology

3.3 Solar Radiation Characteristics in the Study Area

The figure 3_ 2 highlights Algeria's strong solar potential and the climatic conditions of Ouargla in southeastern Algeria. The region has an extremely arid desert climate with low rainfall, clear skies, and intense solar exposure, making it one of the most irradiated areas in North Africa. Annual global solar irradiation exceeds 2,340 kWh/m²·year in the southern Sahara, while Ouargla receives around 3,300 sunshine hours annually.

Due to the almost complete absence of clouds, direct solar radiation is dominant. Hourly measurements show solar irradiance reaching 1,000–1,100 W/m² between 11:00 a.m. and 2:00 p.m., while temperatures can rise to 35–50 °C during the afternoon. These conditions make Ouargla a key region in Algeria for photovoltaic and solar thermal energy development, as well as research on solar panel optimization under Saharan climate conditions.[98], [99].

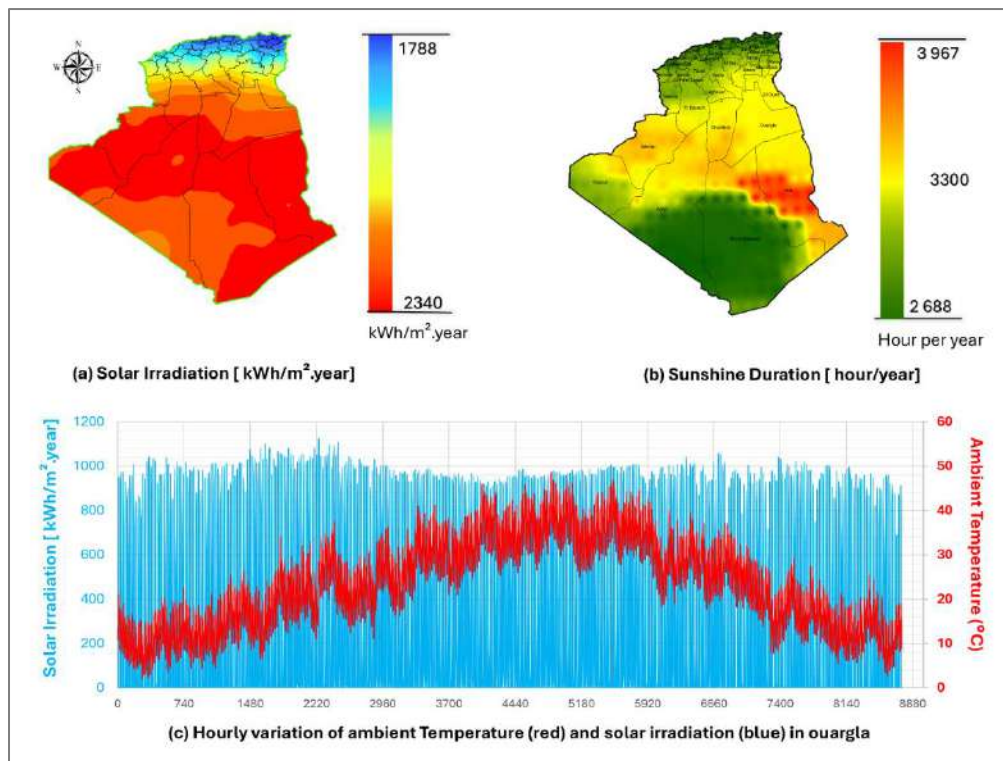


Figure 3-2 Thermal Resources in Algeria

3.4 Thermocouple calibration curves

Based on the methodology adopted in the previous chapter, this chapter presents the experimental results obtained, along with their analysis and comparison with the corresponding reference values.

A calibration curve represents the relationship between an instrument's indication and the corresponding measured value. It expresses a one-to-one (bijective) relationship; however, it does not constitute a complete measurement result, as it does not include any information about measurement uncertainty. The experimental data points obtained are therefore modeled using a linear relationship of the form:

$$y = ax + b$$

Temperature readings were recorded at regular intervals of 30 seconds, a duration sufficient to ensure thermal stability of the system. The collected data were then analyzed to determine the differences between the readings of the sensor under test and the corresponding reference values. These results enabled the construction of a correction curve illustrating the relationship between the two datasets, and consequently, the derivation of a calibration equation that can be integrated into the data processing program for improved measurement accuracy

3.4.1 Thermocouple Calibration and Performance Analysis

The figure 3 _3 illustrates the methodology used for calibrating and statistically evaluating the performance of ten temperature sensors based on thermocouples. In the first stage, individual calibration curves were derived for each sensor by directly comparing their readings with those of a certified reference instrument. These experimental data were then fitted using a linear regression model described by the general equation

$$y = ax + b$$

, where **a** represents the slope of the calibration line and reflects the sensor sensitivity, while **b** denotes the intercept, corresponding to the systematic offset or constant measurement error specific to each device. In parallel, the goodness of fit of the linear model was assessed

through the coefficient of determination R^2 , which revealed noticeable variations in sensor accuracy. Some sensors, such as T_{03} and T_1 , demonstrated near-ideal performance with R^2

values exceeding 0.997, indicating excellent agreement with the reference measurements, whereas other sensors, like T_{07} , showed significantly lower performance, with R^2

dropping to approximately 0.921. Finally, all derived statistical parameters were consolidated into a unified table linking each sensor to its corresponding correction equation and R^2 value, thereby forming a comprehensive database that can be used to implement calibration corrections and improve measurement accuracy while minimizing thermal uncertainty during experimental procedures.

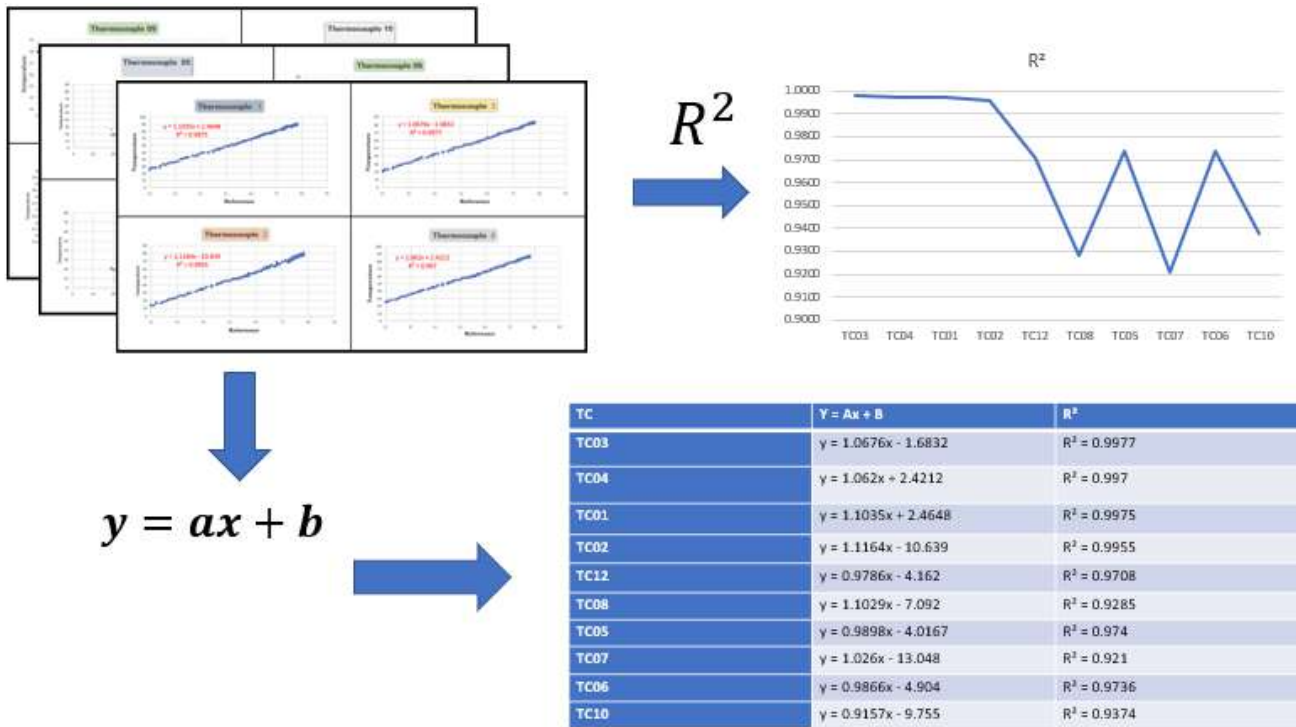


Figure 3-3 Calibration curves, regression equations, and R^2 values for the experimental thermocouples.

Table 3 Statistical parameters and metrological uncertainty analysis (Type A and Type B) for the first group of thermocouples compared to the reference.

Statistical Parameter	Reference	t_{05}	t_{06}	t_{07}	t_{08}	t_{10}	t_{12}
Mean ($\bar{X}$)	51.66	46.86	45.81	39.69	49.60	37.32	46.14
Standard Deviation (σ)	19.47	19.48	19.42	20.76	22.23	18.37	19.29
Type A Uncertainty	2.05	2.06	2.06	2.20	2.36	1.95	2.04
Type B Measure Range ($\pm$)	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Type B Uncertainty ($\pm/\sqrt{3}$)	1.15	1.15	1.15	1.1	1.15	1.15	1.15
Global Uncertainty	2.35	2.37	2.36	2.49	2.62	2.26	2.35
Relative Uncertainty (%)	4.56%	5.05%	5.15%	6.26%	5.29%	6.07%	5.09%

Within the context of evaluating the performance of the thermocouples used in this experimental work, the statistical results extracted from the calibration tables reveal a noticeable variability among the different sensors, both in terms of measurement accuracy and associated uncertainty. This clearly highlights the essential need for calibration prior to conducting any reliable thermal measurement. In the first group, consisting of seven thermocouples (T_{05} to T_{12}), comparisons between each sensor's readings and the reference value of 51.66 show non-negligible deviations. The T_{10} thermocouple recorded the lowest mean value in the group at 37.32, corresponding to a deviation of 14.34 units from the reference, while T_{07} also exhibited a significant deviation of 11.97 units. These statistically meaningful differences cannot be ignored in precision measurement contexts. Moreover, T_{08} presented the highest standard deviation in the group at 22.23, indicating not only a bias from the reference value but also strong instability in its readings. This is directly reflected in its Type A uncertainty, which reached 2.36, and its total uncertainty, which increased to 2.62—the highest in the group. Regarding relative uncertainty, values ranged from 4.56% for the reference to 6.26% for T_{07} , implying that in worst-case scenarios the measurement error exceeds one-sixth of the acceptable uncertainty in high-

precision thermal applications. This clearly indicates the necessity of applying correction factors derived from calibration curves.

Table 4 Statistical parameters and metrological uncertainty analysis (Type A and Type B) for the second group of thermocouples compared to the reference.

Statistical Parameter	Reference	T_1	T_2	T_3	T_4	T_9	T_{11}
Mean ($\bar{X}$)	58.67	67.21	54.85	60.95	64.72	26.70	27.62
Standard Deviation	17.57	19.42	19.66	18.78	18.69	1.17	1.14
Type A Uncertainty	1.69	1.87	1.89	1.81	1.80	0.11	0.11
Type B Measure Range	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Type B Uncertainty	1.15	1.15	1.15	1.15	1.15	1.15	1.15
Global Uncertainty	2.05	2.20	2.22	2.14	2.14	1.16	1.16
Relative Uncertainty (%)	3.49%	3.27%	4.04%	3.52%	3.30%	4.34%	4.20%

The second group, composed of six thermocouples (T_1 to T_{11}), exhibits two distinctly different performance levels, making it the most analytically insightful dataset. On one hand, thermocouples T_1 , T_2 , T_3 , and T_4 show relatively moderate deviations from the reference value of 58.67. T_1 recorded the highest mean within this subgroup at 67.21, corresponding to a deviation of 8.54 units above the reference. Their relative uncertainties remained within acceptable limits, ranging between 3.27% and 4.04%, with consistent standard deviations between 18.69 and 19.66, indicating relatively stable thermal responses. On the other hand, the situation changes drastically for T_9 and T_{11} , which represent the most critical cases in the entire study. Their mean values dropped significantly to 26.70 and 27.62, respectively, compared to the reference of 58.67, resulting in deviations exceeding 31 units. This level of error clearly renders these sensors unreliable for any meaningful measurement. More importantly, their very low standard deviations (1.17 and 1.14) indicate that the readings were not random or noisy, but rather consistently biased around incorrect values. This is characteristic of systematic drift, where the sensor loses its original calibration due to aging or repeated thermal stress, producing stable

but fundamentally inaccurate outputs a particularly deceptive type of error since it does not manifest as visible fluctuations.

In conclusion, the comparison between the two groups strongly reinforces a fundamental scientific principle: calibration is not an optional step but a core requirement for measurement validity. A sensor such as T_9 may initially appear reliable due to its stable readings, yet it actually contains a hidden systematic error exceeding 31 thermal units. In contrast, a sensor like T_8 clearly signals its malfunction through fluctuating outputs. Both cases demonstrate that only regular calibration can effectively detect and correct both random and systematic deviations before they accumulate and irreversibly distort experimental results.

3.4.2 Metrological Validation (Accuracy, Precision, and Linearity)

The performance of the measurement system was rigorously assessed using standard metrological criteria, namely accuracy, precision, and linearity.

3.4.2.1 Accuracy (*Trueness*)

The calibrated measurements exhibit strong agreement with the reference values. This confirms a substantial reduction in systematic errors and demonstrates the effectiveness of the calibration procedure in improving measurement accuracy.

3.4.2.2 Precision (*Repeatability*)

Experimental results show a high level of repeatability, characterized by a low standard deviation across repeated measurements. This indicates strong measurement stability under identical operating conditions.

3.4.2.3 Linearity

The coefficient of determination R^2 , consistently approaching unity, confirms a highly linear response of the system across the entire measurement range. This validates the suitability of the linear calibration model adopted in this study.

3.4.3 Embedded Implementation of Calibration Coefficients

The calibration parameters a_i and b_i were embedded directly into the Arduino firmware, enabling real-time correction of sensor outputs.

This embedded approach ensures:

- Real-time generation of calibrated measurements without external processing
- Reliable and consistent data acquisition
- Elimination of post-processing dependencies, improving system efficiency

3.4.4 Discussion of Results

The experimental findings clearly demonstrate that the calibration procedure significantly enhances the overall performance of the measurement system. A marked reduction in systematic deviations is observed, while the stability and repeatability of the measurements remain unaffected. Moreover, the use of a thermal imaging system to verify the homogeneity of the thermal field provides additional experimental validation. It confirms that residual discrepancies are primarily attributable to inherent sensor characteristics rather than environmental inconsistencies.

Overall, the developed system exhibits:

- High accuracy after calibration
- Excellent temporal stability
- Suitability for low-cost multipoint measurement applications

3.5 Calibration Results of Humidity Sensors

This section presents the experimental calibration results of the relative humidity and air temperature sensors (DHT11 and DHT22) compared with the reference measurements of the Kimo AMI 300. The calibration was performed inside a sealed environmental chamber to maintain stable climatic conditions and minimize the influence of external air currents, following the protocol described in Chapter 2.

The sensors were placed next to the reference device, while humidity inside the chamber was gradually increased through controlled vapor injection to evaluate sensor performance over a wide measurement range. Humidity and temperature data were recorded at 30-second intervals and compared with the reference readings to ensure environmental stability.

The collected data were then statistically analyzed to determine deviations between sensor and reference measurements. Unlike temperature calibration, relative humidity covers a wide

range (0–100%), making it difficult to represent accurately with a single linear correction equation :

$$y = ax + b$$

For this reason, the humidity range was divided into several smaller intervals (0–33%, 33–44%, 44–56%, and 56–65%), where each interval was modeled independently using its own linear correction equation. These segmented calibration models were subsequently combined into a global correction approach in order to improve calibration accuracy over the entire measurement range and reduce systematic deviations between the sensor readings and the reference values.

$$\sum (a_i X + b_i)$$

Through this methodology, individual correction curves and precise calibration equations were established for each sensor. The resulting equations were directly integrated into the Arduino IDE program code, ensuring optimized digital processing and significantly improving the accuracy and reliability of humidity measurements during experimental operation.

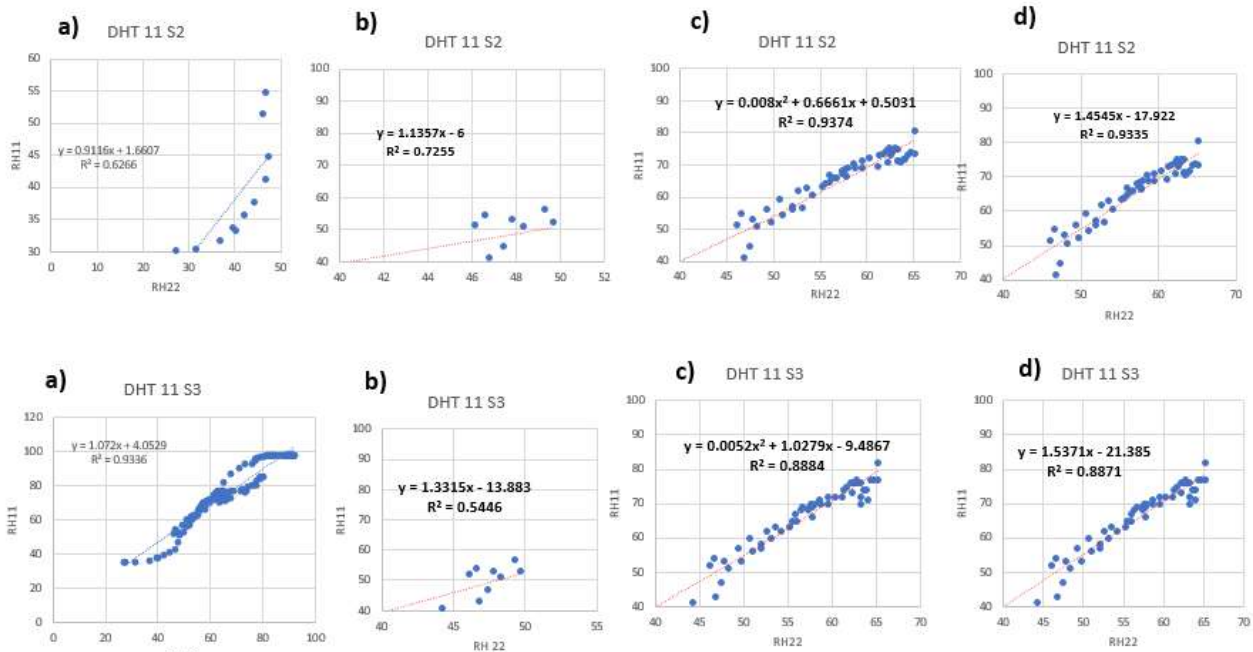


Figure 3-4 Metrological comparison and calibration of DHT11 S2 and DHT11 S3 sensors using DHT22 as a reference at different humidity ranges.

(a, b, c, and d represent different humidity intervals)

Statistical Parameter	DHT 22 S5	DHT 11 S2	DHT 11 S3	<i>Table 5 Metrological uncertainty evaluation and statistical data for DHT11 and reference humidity sensors.</i>
Mean ($\bar{X}$)	51.18	53.45	55.72	
Standard Deviation (σ)	4.85	4.92	5.14	
Type A Uncertainty (u_A)	0.46	0.45	0.47	
Type B Measure Range ($\pm$)	1.15	5.00	5.00	
Type B Uncertainty ($\pm/\sqrt{3}$)	2.00	2.89	2.89	
Global Uncertainty (u_c)	1.24	2.92	2.93	
Relative Uncertainty (%)	2.42%	5.46%	5.26%	

In order to evaluate the performance of the DHT11 temperature sensor and assess its suitability for accurate thermal measurements, the DHT22 sensor was adopted in this study as the reference sensor due to its superior metrological characteristics demonstrated by the statistical analysis. The DHT22 exhibited the lowest relative uncertainty within the measurement system, reaching only 2.42% , with a combined uncertainty not exceeding 1.24 and a Type A uncertainty of 0.46. In addition, it showed a stable average temperature of approximately 51.18 $^{\circ}\text{C}$ with a standard deviation of 4.85, reflecting a high level of precision and consistency in the recorded measurements. This superior behavior can be attributed to the higher technical performance of the DHT22 in terms of response accuracy and signal stability.

In contrast, the statistical analysis of the DHT11 sensor revealed a clear positive systematic deviation relative to the reference measurements. The average recorded temperatures reached approximately 53.45 $^{\circ}\text{C}$ at point S2 and 55.72 $^{\circ}\text{C}$ at point S3, corresponding to deviations ranging between 2.27 $^{\circ}\text{C}$ and 4.54 $^{\circ}\text{C}$ compared with the DHT22 reference values. Furthermore, the magnitude of this deviation increased progressively from one measurement point to another, suggesting the presence of a temperature-dependent systematic error.

The DHT11 also exhibited higher standard deviation values of approximately 4.92 and 5.14 at S2 and S3 respectively, indicating greater dispersion and lower measurement stability compared with the reference sensor. This behavior was reflected in the combined uncertainty values, which reached approximately 2.92 and 2.93 exceeding more than twice the uncertainty

associated with the DHT22 sensor. Similarly, the relative uncertainty exceeded 5% reaching values of 5.46% and 5.26% compared with only 2.42% for the DHT22.

Nevertheless, these results indicate that the observed error is primarily systematic rather than purely random, which represents a favorable outcome for the calibration process. By applying the correction coefficients derived from the comparison between points S2 and S3, the systematic deviation can be significantly reduced, thereby improving the performance of the DHT11 sensor to a level suitable for medium-accuracy applications. However, the DHT22 remains the preferred option for applications requiring high precision and low measurement uncertainty.

3.6 Effect of Calibration on Temperature Measurement Accuracy

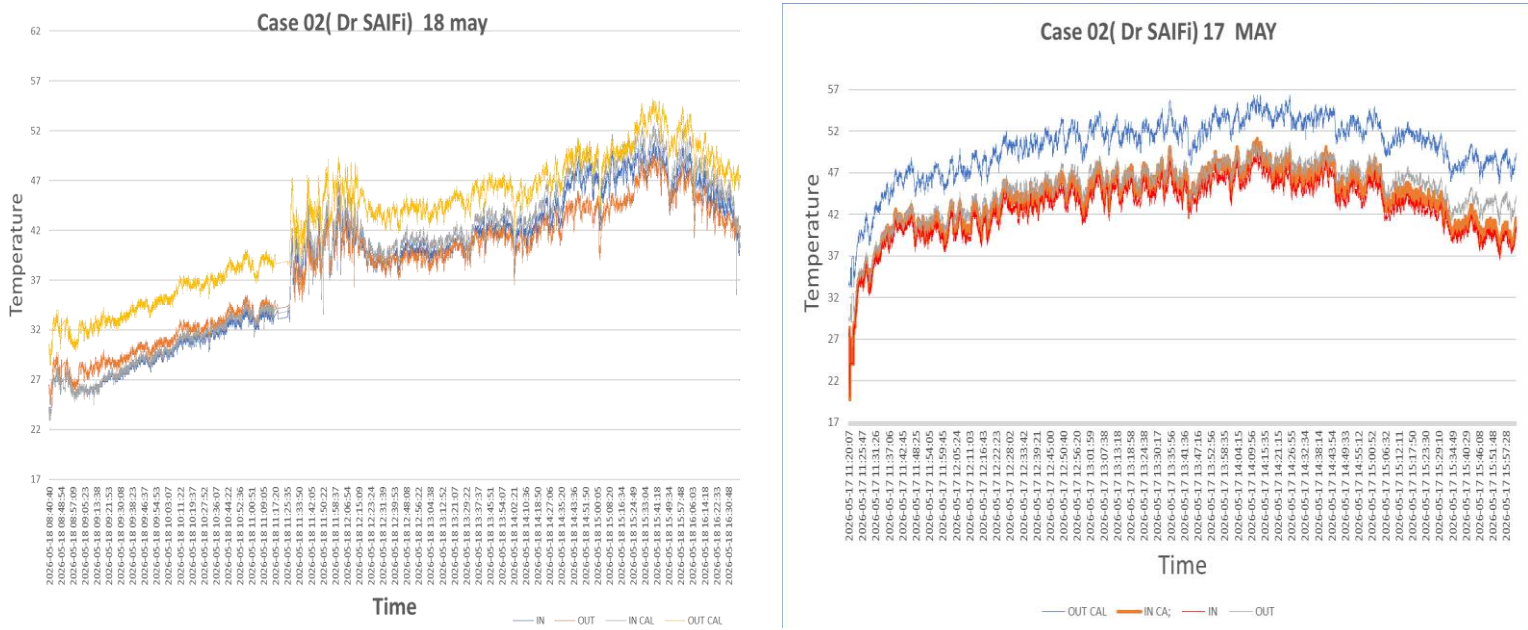


Figure 3-5 Comparative Analysis of Temperature Curves Before and After Calibration

a) Comparative Analysis of Temperature Curves Before and After Calibration 18 May

b) Comparative Analysis of Temperature Curves Before and After Calibration 17 May

This section presents a comprehensive analysis of the temperature curves recorded for Case 02 (Dr. SAIFI) during May 17 and May 18, 2026, considering both raw and calibrated data (IN, OUT, IN CAL, OUT CAL). The objective is to evaluate the thermal behavior of the system and assess the effectiveness of the calibration process in improving measurement reliability.

On May 17, the temperature profiles of all sensors exhibited a stable and continuous increase, starting from approximately 22°C and gradually reaching a steady range between 42°C and 52°C. The difference between raw and calibrated data remained generally within the global uncertainty limit of $u_c = 2.14^\circ\text{C}$, confirming the consistency and proper functioning of the measurement system under stable environmental conditions.

In contrast, the analysis of May 18 reveals a more complex thermal behavior characterized by two distinct phases separated by a short interruption period. During the first phase (from the beginning of the recording until approximately 12:00), the four curves show a regular and increasing trend similar to that of May 17, with deviations between raw and calibrated values remaining within acceptable uncertainty limits. However, between 12:00 and 12:30, a sudden interruption occurred due to a temporary loss of physical connection between the temperature sensor and the Arduino acquisition system. This resulted in the recording of non-physical and random values, representing digital noise rather than actual thermal behavior, clearly exceeding the uncertainty threshold u_c , and therefore these data were excluded from the statistical analysis.

During the second phase (from 12:30 until the end of the experiment), the system recovered normal operation, and the temperature curves resumed a physically consistent behavior, with values ranging between 37°C and 52°C. This increase is consistent with seasonal conditions and higher solar irradiance typical of May. Additionally, in this phase, the deviation between raw and calibrated data occasionally exceeded the uncertainty limit, highlighting the importance of the calibration equation in correcting systematic sensor errors and ensuring that the processed data accurately represent the real thermal behavior of the system. Overall, the comparison of both days confirms the reliability of the measurement system under stable

conditions and demonstrates the critical role of calibration in improving data accuracy and interpretability.

3.6 Thermal Comfort Analysis of a Wind Catcher–Solar Chimney System

This study, published by Saifi.N et al 2024, investigates the influence of time and outdoor climatic conditions on the performance of a passive ventilation system inside an experimental test cell in Ouargla, Algeria. The system combines a wind catcher, evaporative cooling, and a solar chimney to enhance natural ventilation and reduce indoor thermal loads. The study shows that system performance depends strongly on solar radiation, wind speed, ambient temperature, and relative humidity, which vary throughout the day. Experimental measurements revealed clear variations in temperature, humidity, and airflow rate, especially around midday, when solar radiation reaches its peak. The work therefore seeks to identify the periods of maximum efficiency in terms of thermal comfort and air renewal, and it is supported by CFD simulations to validate the experimental results[75].

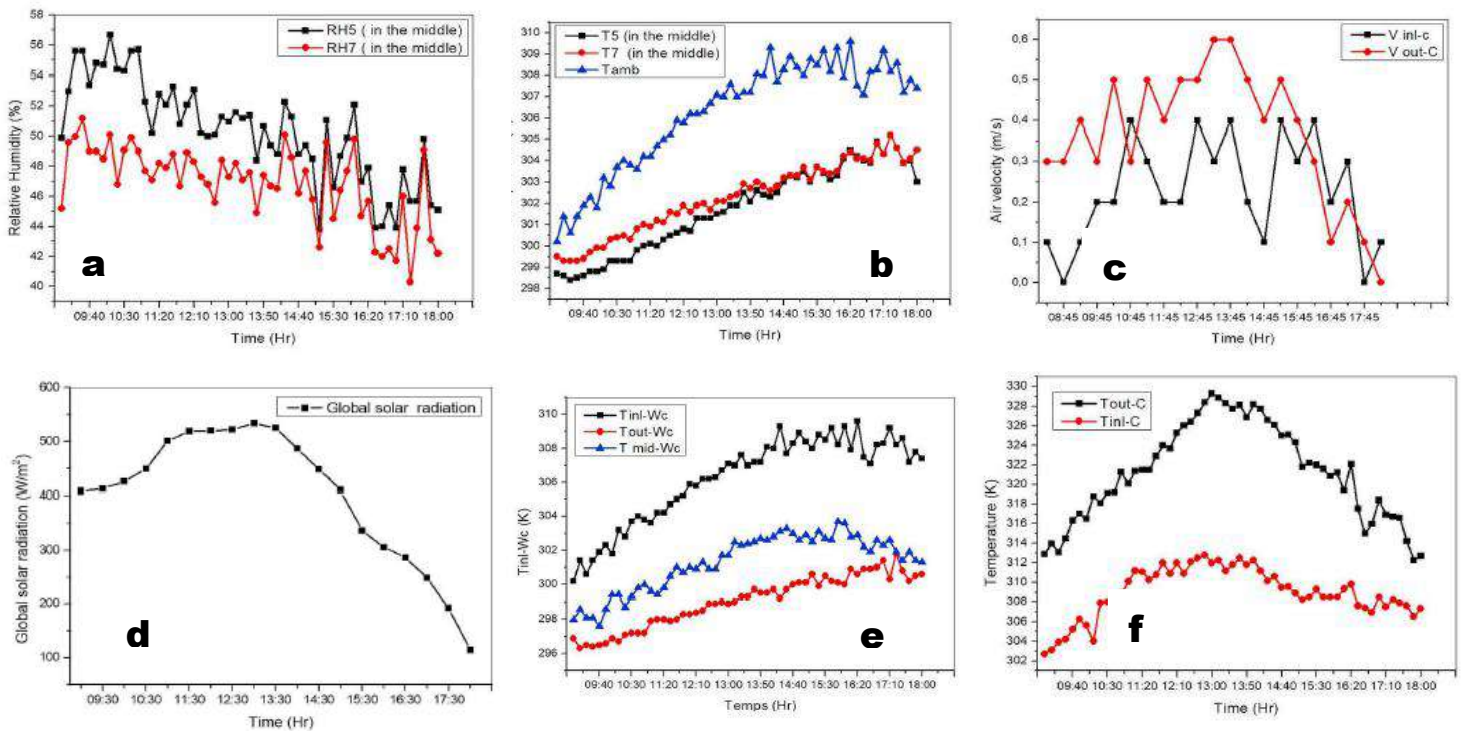


Figure 3-6 "Thermodynamic and environmental variables of the reference case used in the comparative study (adapted from Dr. Saifi's case / literature)".

Based on the results of the reference study, a digitalization process was carried out on the temperature and relative humidity curves using OriginLab in order to extract the experimental data and convert the graphical information into numerical values suitable for analysis and processing. Subsequently, the extracted values were plotted on the Givoni Bioclimatic Comfort Chart (Givoni Bioclimatic Chart) to evaluate the indoor thermal comfort conditions within the experimental cell. This analysis made it possible to determine the distribution of the experimental points with respect to the thermal comfort zone. The results showed that only a limited number of values were located inside the comfort zone compared to the total number of measurements recorded throughout the day, indicating that the conventional system was unable to provide adequate thermal comfort conditions. Based on these findings, the present study proposes the integration of a solar shading system (Brise-Soleil) into the conventional configuration, followed by a comparative analysis between the two cases: the system without shading and the system equipped with solar shading devices. The objective of this comparison is to evaluate the effect of the shading system on improving the thermal performance inside the experimental cell by increasing the number of values located within the thermal comfort zone and enhancing indoor comfort conditions during different periods of the day.

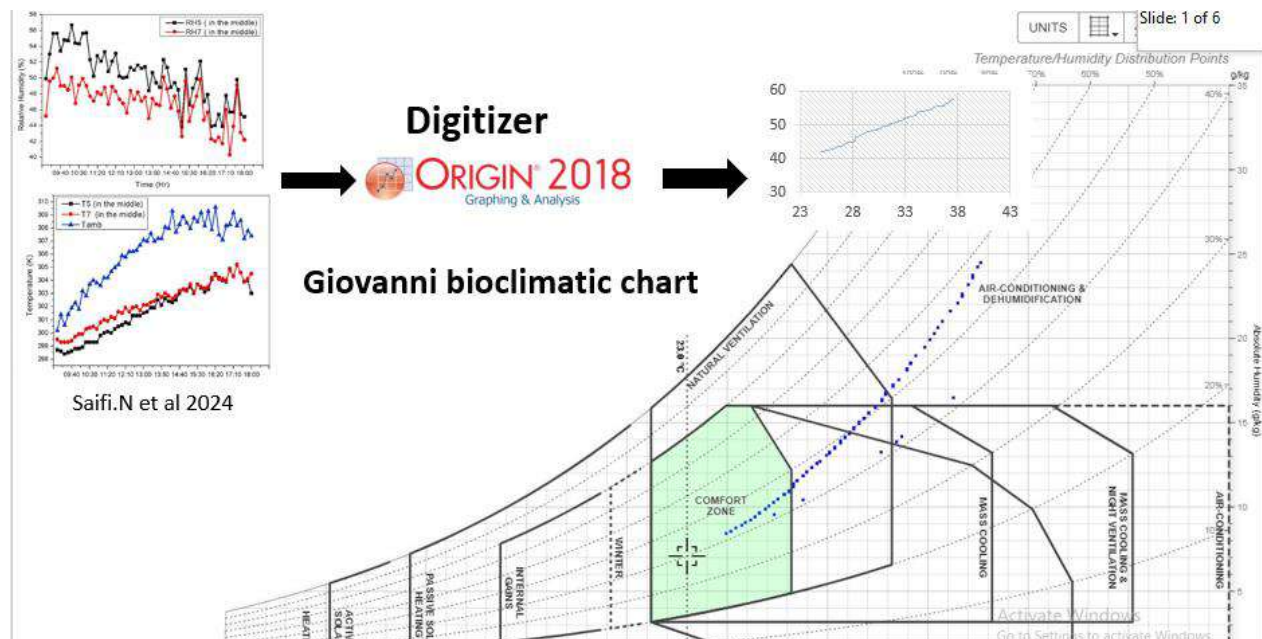


Figure 3-7 Workflow of extracting and plotting comparative study data onto the Giovanni bioclimatic chart.

3.7 Results and Discussion

3.7.1 Environmental Conditions

The climatic conditions recorded on May 17 and May 18 reveal two distinct environmental scenarios that significantly differ. Influenced the thermal behavior of the studied systems. On May 17, the average outdoor temperature reached 24.1°C, with a pronounced day–night fluctuation, as temperatures decreased to approximately 19°C during the early morning before rising to nearly 28°C at midday. The global horizontal irradiance (GHI) reached a peak value of approximately 900 W/m² during the noon period. However, the most remarkable characteristic of this day was the presence of exceptionally strong winds ranging between 4 and 6.5 m/s throughout the daytime period, making it a climatically exceptional day in terms of natural ventilation potential.

In contrast, May 18 was characterized by a slightly higher average outdoor temperature of 24.8°C and stronger solar radiation, with GHI values reaching approximately 950 W/m².

Nevertheless, the major difference compared with the previous day lies in the wind conditions, as wind speeds were considerably weaker, irregular, and did not exceed 2.5 m/s. Consequently,

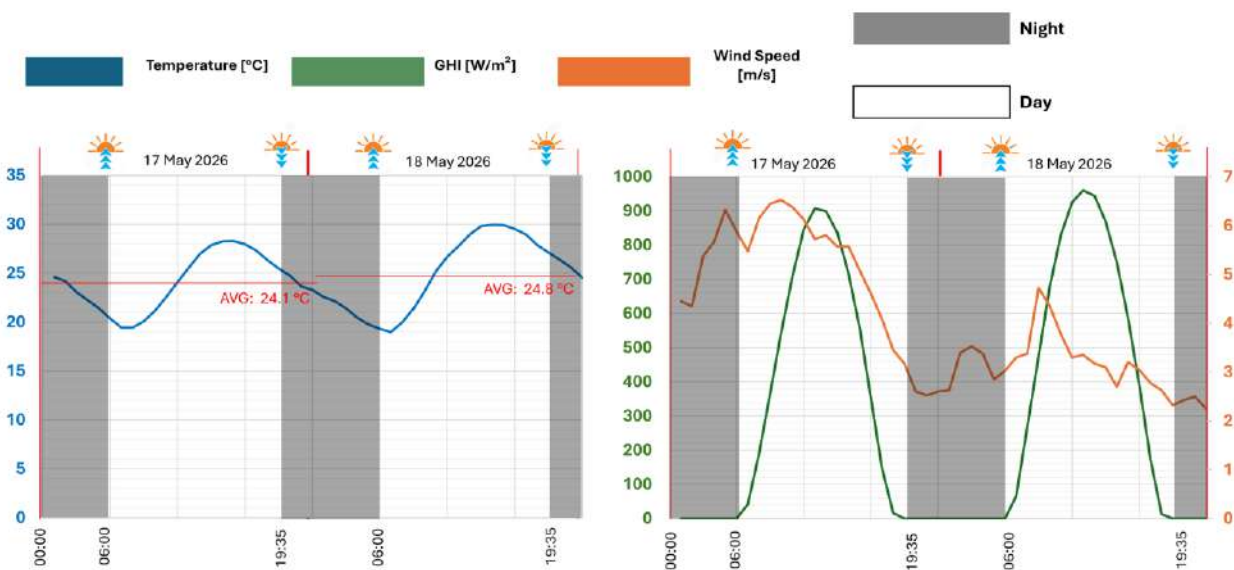


Figure 3-8 Reference Climatic data for the study area over two consecutive days (May 17–18, 2026)

this day can be considered less favorable for natural ventilation and more thermally stressful from a radiative perspective.

3.7.2 Experimental Results: Conf. Simple vs Conf. WC (17 May)

3.7.2.1 *Environmental Conditions*

The analysis focused on the peak thermal period extending from 11:02 to 16:19, corresponding to the most thermally stressful hours of the day and therefore providing the clearest representation of the systems' performance under maximum thermal load conditions. During this period, the day was characterized by strong winds ranging from 4 to 6.5 m/s, which significantly enhanced natural ventilation. It should also be noted that the OUT measurements correspond to the temperature of the external surface directly exposed to solar radiation, whereas the IN measurements represent the actual indoor air temperature within the occupied space.

3.7.2.2 *Temperature Analysis*

The temperature measurements revealed a substantial and profound difference in the behavior of the two systems during peak thermal hours. In the case of the conventional house configuration (Conf. Simple), the temperature of the external surface exposed to direct solar radiation (OUT) reached a peak value of approximately 47°C at midday, while the indoor temperature (IN) remained within a range of 30 to 36°C, maintaining a relatively stable difference of approximately 5 to 10°C. This thermal gap reflects the beneficial contribution of the thermal mass of the walls, enhanced by the natural ventilation promoted by the strong winds prevailing during that day. Nevertheless, these indoor temperature values remained relatively high and exceeded the acceptable thermal comfort limits under semi-arid climatic conditions. This demonstrates that the conventional house, even under exceptionally favorable wind conditions, was unable to provide a truly comfortable indoor environment.

In contrast, the WC system exhibited a completely different and highly dynamic response to climatic variations. The indoor temperature experienced an immediate and sharp decrease to nearly 21°C at the moment when evaporative cooling was activated around 11:30. This represents a notable thermal difference of approximately 9 to 11°C compared with the outdoor

temperature recorded at the same moment, highlighting the remarkable instantaneous cooling capacity of evaporative cooling when supported by sufficiently high wind velocities. Subsequently, the indoor temperature gradually increased and approached the outdoor temperature, maintaining a difference of only 1 to 3°C during the remainder of the peak period. This behavior indicates that the wind catcher successfully exploited the strong winds ranging from 4 to 6.5 m/s to enhance outdoor air extraction and force the airflow through the evaporative cooling pad before supplying it into the indoor space. As a result, the system ensured continuous indoor air renewal while effectively moderating indoor temperatures throughout the peak thermal hours. This performance clearly illustrates the fundamental advantage of the WC system, namely its ability to transform the kinetic energy of wind into effective cooling energy without any mechanical energy consumption.

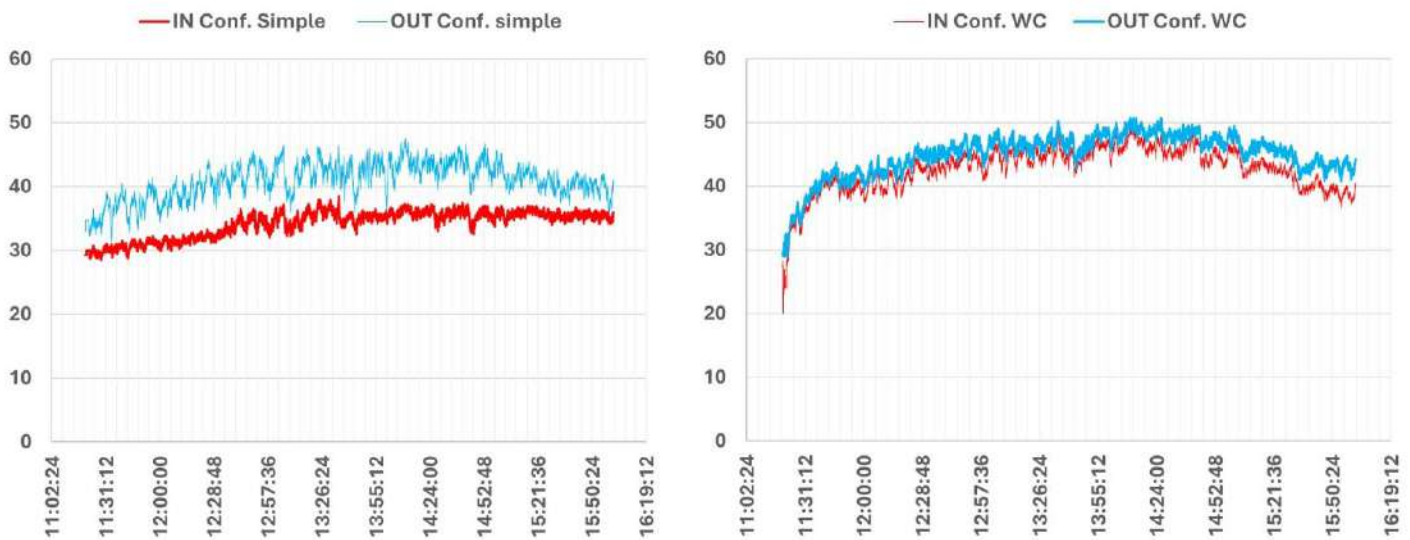


Figure 3-9 Experimental temperature profiles (IN/OUT) for simple and WC configurations during the testing period.

3.7.3 Experimental Results: Conf. Simple vs Conf. Shading (18 May)

3.7.3.1 *Environmental Conditions*

May 18 provided an important testing scenario for the solar shading system (Conf. Shading) under more challenging climatic conditions than those recorded on May 17. Although the average outdoor temperature was only slightly higher (24.8°C), the day was characterized by stronger solar radiation (~950 W/m²) and much weaker, irregular winds that did not exceed 2.5 m/s. Consequently, the shading system operated under higher radiative thermal loads with minimal natural ventilation support, meaning that its thermal performance primarily reflected its own passive cooling efficiency rather than favorable climatic assistance.

3.7.3.2 *Temperature Analysis*

The indoor and outdoor temperature measurements recorded on May 18 revealed a remarkable and representative thermal performance of both the solar shading system and the wind catcher configuration. In the reference conventional house configuration (Conf. Simple), recorded on the previous day, the outdoor temperature exceeded 47°C during peak hours while the indoor temperature remained between 30 and 36°C with the assistance of strong winds. In contrast, May 18 presented a more challenging climatic scenario characterized by stronger solar radiation and significantly weaker winds. Despite these unfavorable conditions, the solar shading system (Conf. Shading) demonstrated stable and efficient thermal behavior by maintaining indoor temperatures between 23 and 38°C throughout the day, with a thermal difference ranging from 4 to 8°C compared with the outdoor temperature, which peaked at approximately 40°C. This thermal gap was achieved through the dual function of the shading system: reducing direct solar radiation incident on the building envelope and minimizing the resulting indoor thermal loads, without relying on mechanical energy or external ventilation support.

Regarding the WC configuration on the same day, the results reveal a distinctly different behavior. The indoor and outdoor temperatures evolved almost in parallel throughout the measurement period, maintaining a narrow difference of only 1 to 3°C, with both reaching values between 40 and 50°C during peak hours. This near-convergence between IN and OUT indicates

that under low wind conditions, the wind catcher's evaporative cooling capacity was significantly reduced, as insufficient airflow through the cooling pad limits the system's ability to lower indoor temperatures effectively. This finding underscores the strong wind-dependency of the WC system and confirms that its performance is optimal only when wind velocities are sufficiently high to drive meaningful air exchange and evaporative cooling.

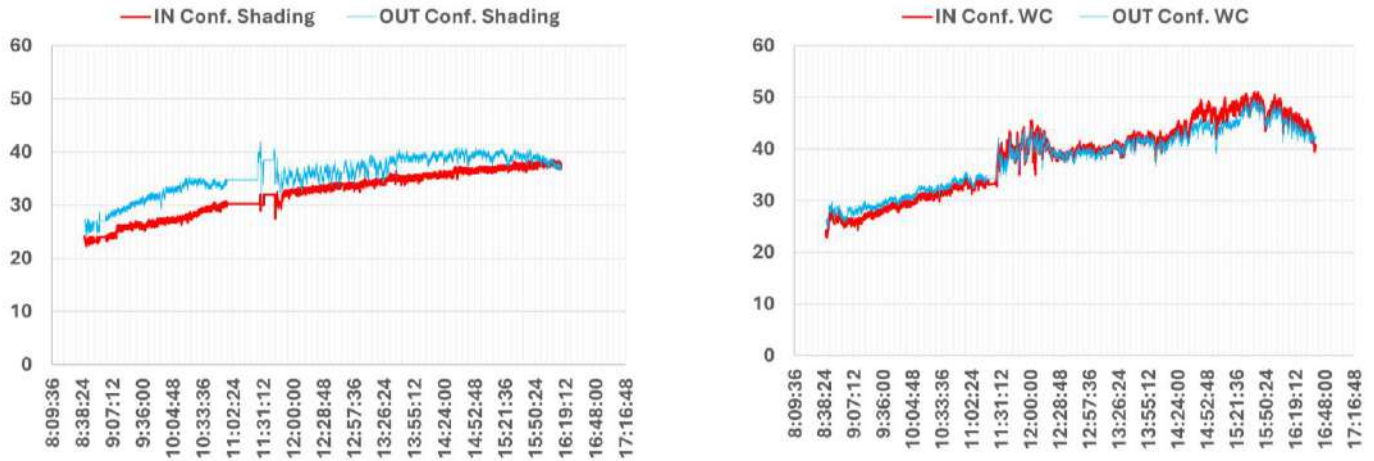


Figure 3-10 Experimental temperature profiles (IN/OUT) for shading and WC configurations during the testing period.

3.8 Psychrometric Analysis Using the Givoni Bioclimatic Chart

The Givoni bioclimatic psychrometric chart is considered one of the most accurate and comprehensive analytical tools for evaluating thermal comfort in occupied spaces. Rather than relying solely on air temperature, it simultaneously correlates temperature with both relative humidity and absolute humidity, thereby classifying thermal conditions into clearly defined zones, including the thermal comfort zone, natural ventilation zone, evaporative cooling zone, thermal mass cooling zone, and ultimately the mechanical air-conditioning zone. In the present study, this chart was employed to assess the performance of the three investigated systems and to determine the actual position of their indoor conditions within the thermal comfort map. This approach provides a deeper analytical dimension that goes beyond numerical values toward a comprehensive qualitative evaluation of indoor environmental quality[100].

3.8.1 Conf. Simple — 17 May

The psychrometric chart of the conventional house on May 17 revealed that the recorded data points were distributed along the outer boundaries of the green thermal comfort zone or even exceeded it toward the thermal mass cooling region, at dry-bulb temperatures ranging between 28 and 32°C, with extremely low relative humidity values not exceeding 22.49% and an enthalpy of 31.33 kJ/kg. This distribution indicates that the conventional house failed to achieve full thermal comfort even on a day characterized by exceptional wind conditions ranging from 4 to 6.5 m/s. These findings demonstrate that the thermal mass of the walls alone is insufficient to satisfy Givoni's thermal comfort criteria under semi-arid climatic conditions, while the severe dryness of the indoor air further intensifies the sensation of discomfort despite the relatively moderate temperatures.

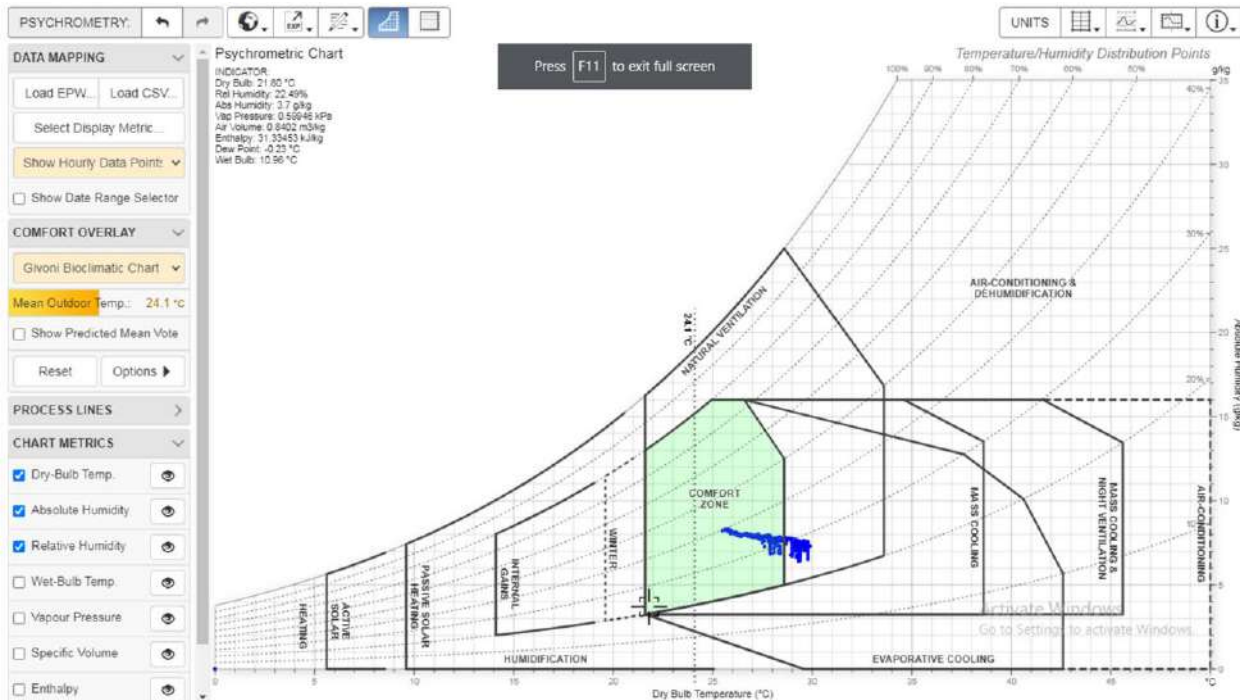


Figure 3-11 Hourly thermal comfort distribution on the Givoni bioclimatic chart for the simple configuration (May 17).

3.8.2 Conf. WC — 17 May

In contrast, the psychrometric chart of the WC system on the same day presented a completely different pattern, as the data points were concentrated deeply within the green thermal comfort zone and appeared more compact and homogeneous compared with those of the conventional house. This clearly illustrates the dual positive effect of the WC system, namely the continuous renewal of indoor air on the one hand and its cooling through evaporative processes on the other hand, while simultaneously exploiting strong wind conditions to enhance both mechanisms. The integration of the wind catcher, evaporative cooling, and solar chimney contributed to increasing indoor relative humidity to values more favorable for thermal comfort compared with the conventional house, thereby enabling the indoor conditions to comply clearly and measurably with Givoni's comfort criteria.

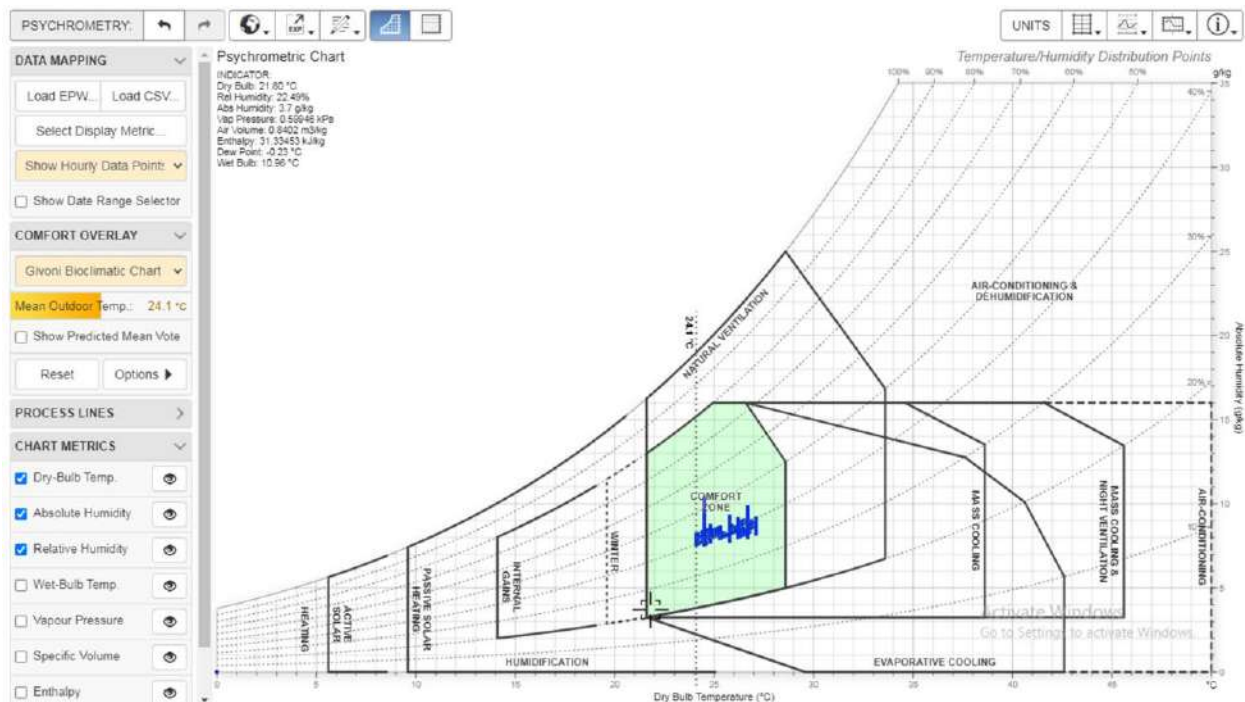


Figure 3-12 Hourly thermal comfort distribution on the Givoni bioclimatic chart for the WC configuration (May 17).

3.8.3 Conf. Shading — 18 May

The psychrometric chart of the solar shading system on May 18 provided decisive visual evidence of its effectiveness under more challenging climatic conditions. The recorded data points were concentrated within the green thermal comfort zone or along its lower boundaries, under an average outdoor temperature of 24.8°C, relative humidity of 40%, and an enthalpy of 41.18 kJ/kg, despite higher solar radiation reaching approximately 950 W/m² and the near absence of assisting winds, which did not exceed 2.5 m/s. This positioning within the comfort zone demonstrates the genuine cooling effect of the shading system through the reduction of direct solar radiation incident on the building envelope and the consequent decrease in indoor thermal loads, without relying on any auxiliary climatic factor or additional mechanical energy input.

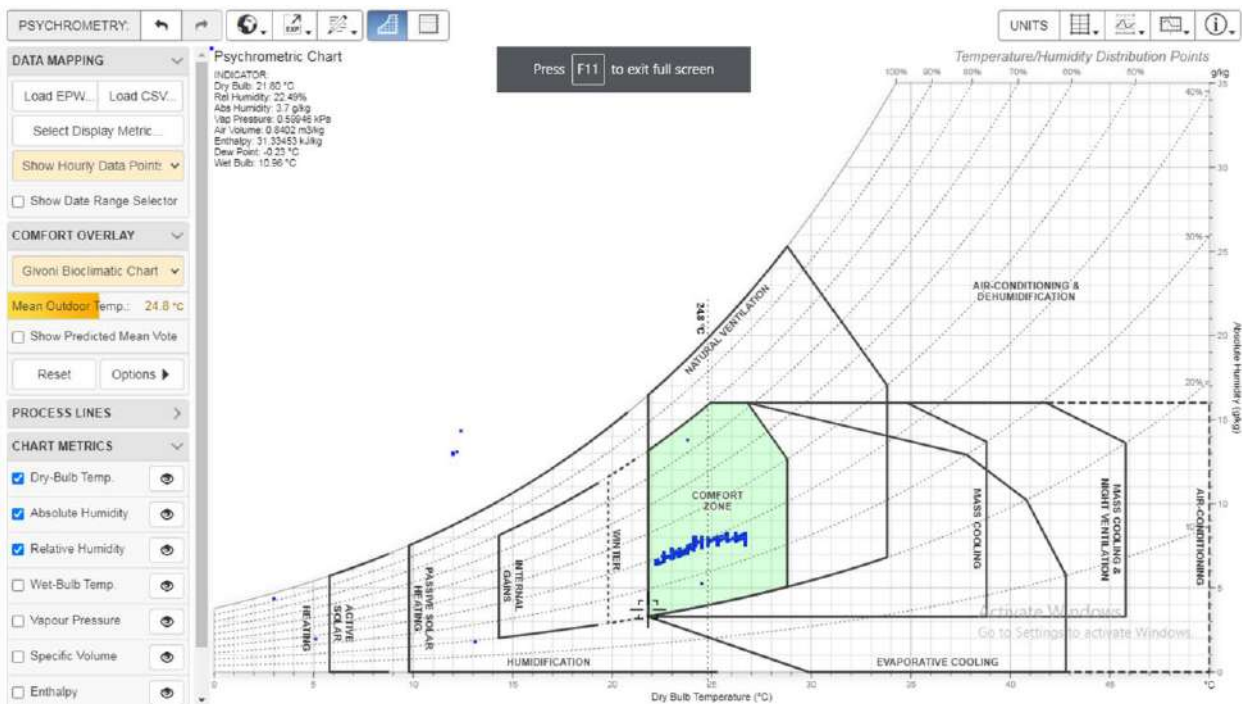


Figure 3-13 Hourly thermal comfort distribution on the Givoni bioclimatic chart for solar shading system configuration (May 18).

3.8.4 Comparative Discussion and Validation

The comparison between the three psychrometric charts gains additional scientific significance when confronted with the findings of the study conducted by Saifi et al., which investigated the WC system under different climatic conditions characterized by a much higher

average outdoor temperature of 33.5°C. The results of that study showed data points extending from within the comfort zone toward the cooling and dehumidification region in the upper-right section of the chart, indicating that the system achieved only partial thermal comfort under severe heat conditions and was unable to maintain it throughout the day. In contrast, the solar shading system examined in the present study exhibited data points that were more stable and consistently concentrated within the green comfort zone. Nevertheless, this comparison remains qualitative rather than quantitative due to the differences in experimental conditions between the two studies. Despite this limitation, the scientific implication remains evident: the solar shading system provides greater indoor thermal stability than the WC system operating alone under the moderate temperature conditions characteristic of the semi-arid climate of the study area. This reinforces its position

3.9 Comparative Discussion and Validation with Literature

This comparative discussion aims to synthesize the results obtained from both experimental days within a unified analytical framework in order to derive comprehensive scientific conclusions regarding the performance of the three investigated systems. Furthermore, the discussion seeks to relate these findings to relevant scientific literature to verify their reliability and highlight their contribution to the accumulated body of knowledge in the field of passive cooling and thermal comfort in semi-arid climate buildings. The discussion is based on three complementary analytical levels: indoor and outdoor temperature measurements, Givoni psychrometric charts, and the actual climatic conditions prevailing during the two measurement days. This multidimensional approach provides the conclusions with a robust and experimentally grounded basis.

3.9.1 Thermal Performance Comparison

The comprehensive comparison between the three systems reveals a clear performance hierarchy shaped by the prevailing climatic conditions. The conventional house (Conf. Simple), which represents the baseline reference case, demonstrated significant limitations in achieving thermal comfort. It relied entirely on the passive thermal mass of the walls, which provided a temperature difference ranging from 5 to 10°C between indoor and outdoor conditions. However, this reduction remained insufficient to reach the thermal comfort zone according to

Givoni's criteria, even on a day characterized by exceptionally strong winds. This finding demonstrates that a conventional building without any additional passive cooling strategy is incapable of providing a comfortable indoor environment under semi-arid climatic conditions.

In contrast, the WC system demonstrated a rapid and highly effective cooling capacity when favorable wind conditions were available. It recorded an exceptional instantaneous indoor temperature reduction of approximately 20°C at the moment of operation and maintained indoor conditions within Givoni's thermal comfort zone throughout the peak period. This performance was achieved by exploiting strong winds ranging between 4 and 6.5 m/s to enhance evaporative cooling efficiency and airflow extraction through the wind catcher.

On the other hand, the solar shading system (Conf. Shading) demonstrated superior thermal performance independent of changing climatic conditions. It achieved effective operation during a day characterized by stronger solar radiation and weaker natural ventilation, maintaining lower indoor temperatures with a difference reaching up to 8°C. Moreover, its psychrometric data points remained within the green thermal comfort zone in a more stable and consistent manner compared with the other two systems under their climatically favorable conditions.

3.9.2 Impact of Climatic Conditions on System Performance

The climatic contrast between the two measurement days provides an important methodological insight into understanding both the limitations and the actual capabilities of each system. The WC system is a highly dynamic solution that is extremely sensitive to instantaneous climatic variables. Its performance increases or decreases depending on wind availability, wind intensity, and the dryness of the outdoor air. Indeed, evaporative cooling progressively loses effectiveness as outdoor relative humidity increases and wind velocity decreases, which explains the decline in WC performance during the weak-wind conditions of May 18.

In contrast, the solar shading system is characterized as a stable passive system whose performance is largely unaffected by daily wind fluctuations. Its cooling mechanism is based on preventing direct solar radiation from reaching the building envelope, making it more reliable and stable in achieving thermal comfort regardless of the prevailing climatic conditions. This characteristic provides the shading system with a major competitive advantage in semi-arid

climates, where solar radiation constitutes the dominant and most persistent thermal factor throughout the summer season.

3.9.3 Validation

The findings of this study are consistent with the conclusions reported in the scientific literature concerning passive cooling systems in arid and semi-arid climates. The study conducted by Saifi et al., which investigated the WC system under much higher outdoor temperatures reaching 33.5°C, demonstrated that the system could achieve partial thermal comfort but failed to maintain it throughout the entire day under severe heat conditions. This observation is consistent with the present study, which also revealed a decline in WC performance in the absence of sufficient wind conditions.

Studies on solar protection systems have demonstrated that Brise-Soleil devices and shading louvers can effectively reduce solar gains and improve thermal comfort.

3.10 Conclusion

This experimental field study led to a set of accurate and reliable scientific findings that contribute to strengthening research knowledge in the field of passive cooling and thermal comfort in buildings located in semi-arid climates. The study was based on a comprehensive experimental comparison between three systems: the conventional house (Conf. Simple), the wind catcher system combined with evaporative cooling and a solar chimney (Conf. WC), and the solar shading system (Conf. Shading). The analysis relied on indoor and outdoor temperature measurements, Giovanni psychrometric charts, and the actual climatic data recorded during both measurement days.

The results demonstrated that the conventional house, representing the baseline reference case, failed to achieve complete thermal comfort even under exceptionally strong wind conditions ranging from 4 to 6.5 m/s. This finding highlights the limitations of relying solely on the passive thermal mass of walls to withstand the thermal stress characteristic of semi-arid climates.

The WC system, on the other hand, exhibited an immediate and highly efficient cooling capacity whenever favorable wind conditions were available. It achieved an exceptional indoor temperature reduction of approximately 20°C at the moment of operation and maintained its indoor conditions within Giovanni's thermal comfort zone. Nevertheless, its performance remained strongly dependent on wind availability and intensity, making it highly variable according to daily climatic conditions.

The most significant and prominent finding of this research is the documented thermal superiority of the solar shading system, which demonstrated stable and independent performance regardless of daily wind fluctuations. The system maintained indoor temperatures up to 8°C lower and kept its psychrometric data points within the green comfort zone during a day characterized by stronger solar radiation and weaker natural ventilation compared to the testing day of the conventional house, which had benefited from strong assisting winds yet failed to reach the same level of thermal performance. These results reinforce the position of the solar shading system as an effective, sustainable, and practically applicable passive architectural solution, offering low-cost implementation and experimentally proven thermal efficiency within the built environment of semi-arid climates in Algeria.

Furthermore, these findings open promising research perspectives toward integrating the solar shading system with the WC system into a comprehensive architectural design strategy that combines the stability of solar shading against solar radiation with the dynamic evaporative cooling effect during periods of wind availability. Such integration could potentially achieve superior and sustainable thermal performance capable of ensuring thermal comfort throughout the day and across the entire summer season in semi-arid climates.

General Conclusion

The present study was motivated by the need to reduce energy consumption in Algerian buildings, particularly under hot and arid climatic conditions that impose high thermal loads on building envelopes. In this context, passive cooling strategies, especially solar shading systems and natural convection phenomena, are essential for improving thermal comfort while reducing energy demand.

The main objective was to experimentally investigate natural convection inside a building enclosure under real climatic conditions while evaluating the thermal performance of a Brise-Soleil shading system. A secondary objective was to ensure reliable measurements through sensor calibration and uncertainty analysis. These objectives were achieved through a structured experimental methodology.

The experimental setup was developed at the Measurement Laboratory of the Institute of Applied Sciences and Techniques (ISTA) in Ouargla. It included thermocouples, DHT11/DHT22 humidity sensors, a pyranometer, and an anemometer. All sensors were calibrated against reference instruments, showing good linearity and reliability. A complete uncertainty analysis (Type A and Type B) was also performed to quantify measurement accuracy.

The results showed that the study period corresponded to typical hot and dry conditions, representative of Algerian summer climate. Significant differences were observed between the tested configurations (unshaded, white-coated, and Brise-Soleil shaded), where the shading system effectively reduced solar heat gain and improved indoor thermal comfort. Natural convection contributed to heat redistribution inside the enclosure, affecting vertical temperature profiles. Psychrometric analysis confirmed better comfort conditions in the shaded case. Calibration also significantly improved measurement accuracy by reducing systematic errors.

The originality of this work lies in its fully experimental approach under real climatic conditions, the integration of a rigorous metrological framework within building thermal analysis, and the comparative assessment of multiple configurations under identical environmental conditions, supported by psychrometric evaluation.

However, some limitations exist, including the use of a reduced-scale prototype, the limited measurement period, simplified boundary conditions without internal heat gains, and the restricted number of configurations.

Future work could focus on validating results using CFD simulations, optimizing Brise-Soleil geometry, conducting long-term seasonal studies, and developing adaptive smart shading systems capable of dynamic control based on solar conditions and thermal comfort requirements..

Recommendations and Future Work

Future studies are encouraged to improve the experimental methodology by increasing the number of measurement sensors, particularly temperature and relative humidity sensors, in order to obtain a more accurate representation of the indoor thermal conditions and their spatial distribution inside the enclosure. In addition, the integration of real-time monitoring and automated control systems is highly recommended to enhance the analytical capabilities of the experimental setup.

A promising future development would consist of directly connecting the measured environmental data to a psychrometric analysis platform based on the Givoni bioclimatic chart. Such an approach would allow the indoor thermal conditions to be visualized and tracked in real time according to their position within the thermal comfort zones defined by the chart.

This real-time monitoring framework could then be used to implement adaptive control strategies capable of automatically regulating shading devices or ventilation systems based on the actual thermal comfort state of the enclosure. Consequently, the system would dynamically respond to climatic variations while improving both thermal comfort and energy efficiency.

The integration of psychrometric analysis, real-time sensing, and adaptive passive cooling strategies represents a highly promising research direction for the development of intelligent and energy-efficient building envelopes in hot and arid climates.

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Annexes