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University of Kasdi Merbah Ouargla
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- Meryem Boud

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**THERMAL PERFORMANCE ANALYSIS OF A VENTILATED TROMBE WALL
UNDER HOT ARID CLIMATE CONDITIONS (CASE OF OUARGLA, ALGERIA)**

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Before the jury:

Dr.Hadjadj Abdessamia	MCB Professor (UKM Ouargla)	President
Dr.Korichi Sabrin	MCB Professor (UKM Ouargla)	Examiner
Dr. Djamel Benmenine	MCB Professor (UKM Ouargla)	Supervisor
Dr. Zine Saadi	MRA-URER/MS -Adrar	Co-Supervisor

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شكر وتقدير

أولاً، أحمده الله تعالى وأشكره على ما أنعم به عليّ من توفيق، إذ أتاح لي اكتساب هذه المعارف المتواضعة، ومنحني القوة والصبر لإنجاز هذا العمل وإتمام هذا المشروع.

أتقدم بخالص الشكر والتقدير إلى كل من ساهم من قريب أو بعيد في إنجاز هذا العمل، وساندني خلال هذه الرحلة العلمية التي كانت مليئة بالتحديات، لكنها كانت مباركة بفضل الله.

كما أعبر عن بالغ امتناني وتقديري للدكتور سعدي زين، على إشرافه القيم، وتوجيهاته السليمة، ونصائحه العلمية الدقيقة، وعلى دعمه المتواصل وتشجيعه الدائم، وثقته التي منحني إياها، وسعة صدره وتفهمه، وحرصه المستمر على مرافقتي حتى إتمام هذا العمل في أحسن صورة. أتوجه أيضاً بجزيل الشكر إلى أعضاء لجنة المناقشة الكرام، على تفضلهم بقبول قراءة هذا العمل وتقييمه.

كما أعبر عن خالص امتناني لجميع أساتذة كلية المحروقات والطاقات المتجددة بجامعة قاصدي مرباح - ورقلة، وكل أساتذة قسم الطاقات المتجددة في الميكانيك، الذين كان لهم الفضل الكبير في تكويني العلمي ومرافقتي طيلة مشواري الدراسي، وأخص بالذكر:

بلطرش جمال، صابرين قريشي، زويدي شيناز، هشام نصيب، بن منين جمال، بريح محمد الحافظ، عبوب هنية، رواق عمر، معمور حسين، حجاج عبد السميع، عماري شعيب، غربي إبراهيم.

ولا يفوتني أن أتقدم بجزيل الشكر والامتنان للآنسة أسمهان، على دعمها ومساندتها لي، ووقوفها إلى جانبي خلال فترة دراستي طيلة خمس سنوات. وفي الختام، أتوجه بالشكر لكل من قدم لي يد العون، أو كلمة طيبة، أو دعماً معنوياً كان له أثر في مواصلة هذا المشوار حتى تحقيق هذا الإنجاز.



هذه اللحظة لا تُورث ولا تُشترى، لقد دفعتُ ثمنها عمري،
وشبابي، سهرتي، خوفاً، ودموعي، هي الهبة الوصول، ودمعة
الحزن، بعد سنوات من الإجتهد والسعي المتواصل ، سنوات حملت في طياتها التعب والصبر والتحديات ، أقف اليوم
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حصيلة دعم و حب و مساندة أشخاص كان لوجودهم أعظم أثر في مسيرتي .

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لقلبك الكبير.

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إلى من قال فيهم الله تعالى : "سَنَشُدُّ عَضُدَكَ بِأَخِيكَ"

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سندي الذي لا يميل، ورفاق عالمي الصغير، واليد التي تمتد لي قبل أن أطلب.
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إلى من كانت ولا تزال مصدر دفتي وسندي الصامت،
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لكل من وقف إلى جانبي و ترك أثراً طيباً في قلبي، أو دعم خطوةً من خطواتي،
أو قال كلمة صنعت فرقاً...

لكم جميعاً أجمل معاني الامتنان و الدعاء...

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أرفع مشروعني هذا شكرٌ لله تعالى الذي وفقني وأعانني،
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Abstract

This study investigates the thermal performance of a ventilated Trombe wall system as a passive solution for improving indoor thermal comfort in hot arid climates, with a focus on Ouargla, Algeria. A simplified transient thermal model based on energy balance equations was developed to describe heat transfer processes and buoyancy-driven airflow. The model was implemented numerically using Python.

Simulations were conducted for representative summer and winter conditions using climatic data. The influence of ventilation, wall thickness, and glass properties was analyzed.

The results show that ventilation reduces peak indoor temperature by up to 1.7°C in summer, while in winter the system maintains indoor temperatures above 21°C with a significant thermal time lag, ensuring nighttime comfort.

The findings confirm that the ventilated Trombe wall is an effective passive strategy for enhancing thermal performance in Saharan climates.

Keywords:

Trombe wall, natural ventilation, thermal modeling, hot arid climate, Ouargla

RESUME (Français)

Ce travail étudie les performances thermiques d'un mur Trombe ventilé en tant que solution passive pour améliorer le confort thermique intérieur dans les climats chauds et arides, en prenant comme cas d'étude la région d'Ouargla (Algérie). Un modèle thermique simplifié basé sur les bilans d'énergie a été développé afin de décrire les phénomènes de transfert de chaleur et de convection naturelle.

Le modèle a été implémenté numériquement à l'aide du langage Python. Des simulations ont été réalisées pour des conditions estivales et hivernales représentatives.

Les résultats montrent que la ventilation permet de réduire la température intérieure maximale d'environ 1,7°C en été, tandis qu'en hiver, le système assure des températures supérieures à 21°C avec un déphasage thermique significatif.

Mots-clés :

الملخص (العربية)

تهدف هذه الدراسة إلى تحليل الأداء الحراري لجدار ترومب مزود بالتهوية كحل سلبي لتحسين الراحة الحرارية داخل المباني في المناخات الحارة والجافة، مع التركيز على منطقة ورقلة (الجزائر). تم تطوير نموذج حراري مبسط يعتمد على معادلات توازن الطاقة لوصف انتقال الحرارة وحركة الهواء الناتجة عن الحمل الطبيعي.

تم تنفيذ النموذج عددياً باستخدام لغة البرمجة بايثون. أُجريت المحاكاة لظروف صيفية وشتوية ممثلة، مع دراسة تأثير التهوية، وسُمك الجدار، وخصائص الزجاج.

أظهرت النتائج أن التهوية تساهم في خفض درجة الحرارة الداخلية القصوى بحوالي 1.7 درجة مئوية خلال فصل الصيف، بينما يضمن النظام في فصل الشتاء الحفاظ على درجات حرارة داخلية تتجاوز 21 درجة مئوية مع وجود تأخر زمني حراري، مما يحسن الراحة الليلية.

تؤكد هذه النتائج أن جدار ترومب المتهوى يمثل حلاً فعالاً ومستداماً لتحسين الأداء الحراري في المناطق الصحراوية.

الكلمات المفتاحية :

جدار ترومب، التهوية الطبيعية ، النمذجة الحرارية، المناخ الحار الجاف ،ورقلة

Nomenclature

Latin Symbols

A_g	Glazing area [m ²]
A_v	Vent opening area [m ²]
A_w	Wall area [m ²]
$A_{w,r}$	Heat exchange area between wall and indoor air [m ²]
C_d	Discharge coefficient [-]
C_{gap}	Thermal capacity of air gap [J/K]
C_r	Thermal capacity of room air [J/K]
c_p	Specific heat of air at constant pressure [J/kg.K]
c_w	Specific heat of wall [J/kg.K]
e_{gap}	Air gap thickness [m]
e_w	Wall thickness [m]
$G(t)$	Solar radiation intensity [W/m ²]
g	Gravity acceleration [m/s ²]
H_v	Vertical distance between vents [m]
h	Convective heat transfer coefficient [W/m ² .K]
$h_{c,g-gap}$	Convective coefficient between glazing and air gap [W/m ² .K]
$h_{c,w-gap}$	Convective coefficient between wall and air gap [W/m ² .K]
$h_{c,w-r}$	Convective coefficient between wall and room [W/m ² .K]
h_{in}	Inside convective heat transfer coefficient [W/m ² .K]
h_{out}	Outside convective heat transfer coefficient [W/m ² .K]
$h_{r,g-w}$	Radiative coefficient between glazing and wall [W/m ² .K]
k	Thermal conductivity [W/m.K]
$\dot{m}$	Mass flow rate (ventilation) [kg/s]
M_w	Mass of the wall [kg]

P	Parameter under consideration in sensitivity analysis
Q_{loss}	Heat loss from room [W]
Q_{vents}	Heat gain from ventilation [W]
$\dot{Q}_{in}$	Rate of heat entering the system [W]
$\dot{Q}_{out}$	Rate of heat leaving the system [W]
q	Heat flux [W/m ²]
SC	Sensitivity coefficient [-]
T	Temperature [°C or K]
T_1, T_2	Temperatures of two bodies for radiation exchange [K]
T_{air}	Air temperature [°C or K]
T_{gap}	Air gap temperature [°C or K]
T_g	Glazing temperature [°C or K]
T_{in}	Inner surface temperature of wall [°C or K]
T_{out}	Outdoor / Ambient temperature [°C or K]
T_r	Indoor air temperature (room) [°C or K]
T_{ref}	Reference absolute temperature for buoyancy [K]
T_{room}	Room temperature [°C or K]
T_s	Surface temperature [°C or K]
T_w	Wall temperature [°C or K]
t	Time [s]
U_g	Glazing overall heat transfer coefficient [W/m ² .K]
U_{loss}	Room overall heat loss coefficient [W/K]
V	Volume [m ³]

Greek Symbols

α	Thermal diffusivity [m ² /s]
α_g	Glass absorptivity (solar) [-]
α_s	Surface solar absorptivity [-]
α_w	Wall absorptivity (solar) [-]

ΔP	Variation of parameter P
ΔT_{gap}	Temperature difference in air gap [°C or K]
ΔT_r	Temperature difference in room [°C or K]
ϵ	Emissivity [–]
λ_w	Wall thermal conductivity [W/m.K]
ρ_a	Air density [kg/m ³]
ρ_w	Wall density [kg/m ³]
σ	Stefan-Boltzmann constant [W/m ² .K ⁴]

Subscripts

amb	Ambient
c	Convective
gap	Air gap
g	Glazing
in	Inner / entering
out	Outer / exiting
r	Room (indoor air)
rad	Radiative
ref	Reference
w	Wall

Abbreviations

CFD Computational Fluid Dynamics

HVAC Heating, Ventilation, and Air Conditioning

ODE Ordinary Differential Equation

PCM Phase Change Material

PV Photovoltaic

RK45 Runge-Kutta method (4th/5th order)

GENERAL INTRODUCTION

GENERAL INTRODUCTION

Buildings account for a substantial share of global energy consumption, particularly in regions characterized by high cooling and heating demands [10, 53]. In hot arid climates, such as southern Algeria, intense solar radiation and extreme ambient temperatures significantly increase the need for energy-efficient building solutions [53]. In this context, passive solar technologies represent an effective alternative for enhancing indoor thermal comfort while reducing reliance on conventional energy systems [11].

Among these technologies, the Trombe wall is widely recognized as a passive solar system capable of absorbing, storing, and gradually releasing solar energy through combined heat transfer mechanisms, including conduction, convection, and radiation [2, 3, 40]. When equipped with ventilation openings, the system can promote buoyancy-driven airflow, improving heat transfer and contributing to better thermal regulation of indoor spaces [13, 42].

Despite its potential, the thermal performance of ventilated Trombe wall systems under hot arid climatic conditions remains insufficiently explored, particularly in the context of North African regions [32, 52]. In addition, the influence of ventilation and key design parameters on system performance requires further investigation through simplified and reliable modeling approaches [28, 50].

Therefore, this study aims to develop a thermal model of a ventilated Trombe wall system and to analyze the coupled heat transfer and airflow mechanisms governing its operation. The model is applied to evaluate system performance under representative climatic conditions of Ouargla, Algeria.

The adopted methodology combines theoretical analysis and numerical simulation. A simplified thermal model based on energy balance equations is formulated and solved numerically using a Python-based computational approach [49, 47, 48]. In addition, a two-dimensional thermal analysis is performed to provide further insight into temperature distributions and heat transfer mechanisms within the massive wall.

This thesis is structured into three main chapters:

- **Chapter 1:** presents a comprehensive literature review of Trombe wall systems, including their historical development, operating principles, heat transfer mechanisms, classifications, and recent developments, with particular emphasis on applications in hot arid climates.
- **Chapter 2:** describes the development of the thermal model of the ventilated Trombe wall system. It includes the system description, climatic conditions of Ouargla, thermophysical parameters, modeling assumptions, governing equations, boundary

conditions, numerical implementation, and the formulation of a two-dimensional thermal model.

- **Chapter 3:** presents and discusses the simulation results. It includes the analysis of summer and winter performance, parametric and sensitivity analyses, comparison with published studies, and a two-dimensional thermal analysis of the Trombe wall.

Finally, a general conclusion summarizes the main findings of the study and presents recommendations for future work, including experimental investigations, integration of phase change materials (PCM), advanced CFD analysis, and economic assessment of ventilated Trombe wall systems.

CHAPTER I

REVIEW OF TROMBE WALL SYSTEMS AND HEAT TRANSFER THEORY

I.1 Introduction

Buildings account for a significant share of global energy consumption, with a large proportion associated with heating, ventilation, and air-conditioning (HVAC) systems [10, 12]. In hot arid regions such as southern Algeria, high solar radiation levels and elevated ambient temperatures increase cooling requirements and place additional pressure on energy resources. Consequently, the development of passive solar technologies has become an important strategy for improving building energy efficiency while reducing dependence on conventional energy systems.

Among passive solar technologies, the Trombe wall is one of the most widely investigated systems due to its ability to collect, store, and gradually release solar energy through conduction, convection, and radiation heat-transfer mechanisms [2, 3]. Since its original development, the Trombe wall concept has evolved considerably, leading to the emergence of ventilated, water-based, PCM-integrated, photovoltaic, and other advanced configurations designed to enhance thermal performance under different climatic conditions [9, 15, 35].

Particular interest has recently been directed toward the application of Trombe wall systems in hot arid climates, where both passive heating and passive cooling strategies are required throughout the year. Understanding the operating principles, heat-transfer mechanisms, system configurations, and current research trends is therefore essential for the development of efficient and climate-adapted designs.

This chapter presents a comprehensive review of Trombe wall technology, including its historical development, operating principles, heat-transfer mechanisms, classification, and recent advances. Particular attention is given to studies conducted in hot arid regions and to the research gaps that motivate the present work.

I.2 Historical Background of Trombe Wall

The origins of the Trombe wall are associated with early passive solar concepts and the solar wall patent attributed to Morse in the nineteenth century [2]. The modern system was later developed and popularized by Félix Trombe and Jacques Michel in the 1960s, particularly through the Trombe-Michel house in France [2, 3]. During the energy crises of the 1970s, research expanded toward thermal storage optimization, wall thickness effects, and passive heating applications [3]. In later decades, the concept evolved beyond conventional masonry walls to include ventilated, hybrid, and multifunctional configurations integrating advanced materials and solar technologies [7, 9].

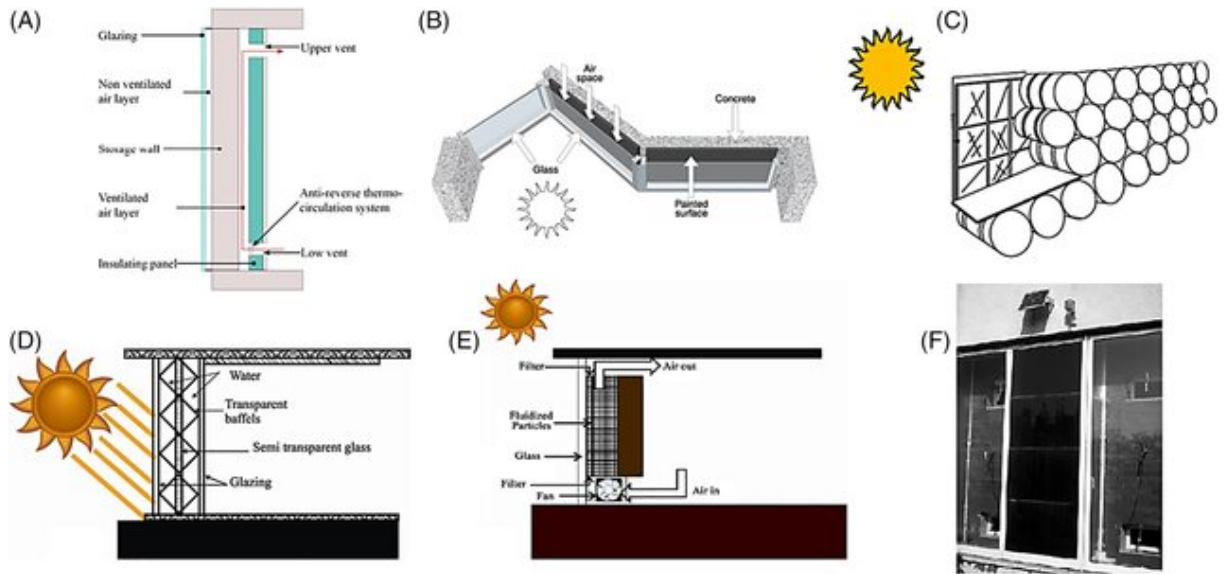


Figure I.1 Representative configurations of Trombe wall systems. [37].

I.3 Passive Solar Heating Systems

Passive solar heating systems are building design strategies that collect, store, and distribute solar energy without the use of mechanical devices. These systems rely on natural heat transfer mechanisms—conduction, convection, and radiation—to maintain thermal comfort [10]. Fundamental principles of passive solar buildings have been extensively discussed by Balcomb [11]. They are generally classified into several categories, including:

- **Direct Gain:** Solar radiation enters the space through glazing and is absorbed by internal thermal mass.
- **Indirect Gain:** The thermal mass is positioned between the sun and the indoor space. The Trombe wall is the most prominent example of this category [3].
- **Isolated Gain:** Systems like sunspaces that separate the collection and storage zones from the main living area [10].
- **Attached Sunspace:** An attached sunspace is a glazed space connected to the main building and used as an intermediate thermal buffer zone. Solar energy is collected within the sunspace and transferred to adjacent rooms through conduction, convection, and radiation. This system can contribute to both passive heating and daylighting [11].
- **Roof-Based Solar Systems:** Roof-based passive solar systems utilize roof surfaces to collect and store solar energy. Examples include roof ponds and solar roofs, which absorb solar radiation during the day and release stored heat when needed. These systems are particularly suitable for regions with high solar availability [10].
- **Hybrid Passive Solar Systems:** Hybrid passive solar systems combine two or more passive solar techniques, such as Trombe walls, sunspaces, thermal mass, and natural ventilation strategies. The integration of multiple approaches enhances thermal

performance and improves year-round indoor comfort under varying climatic conditions [7, 10].

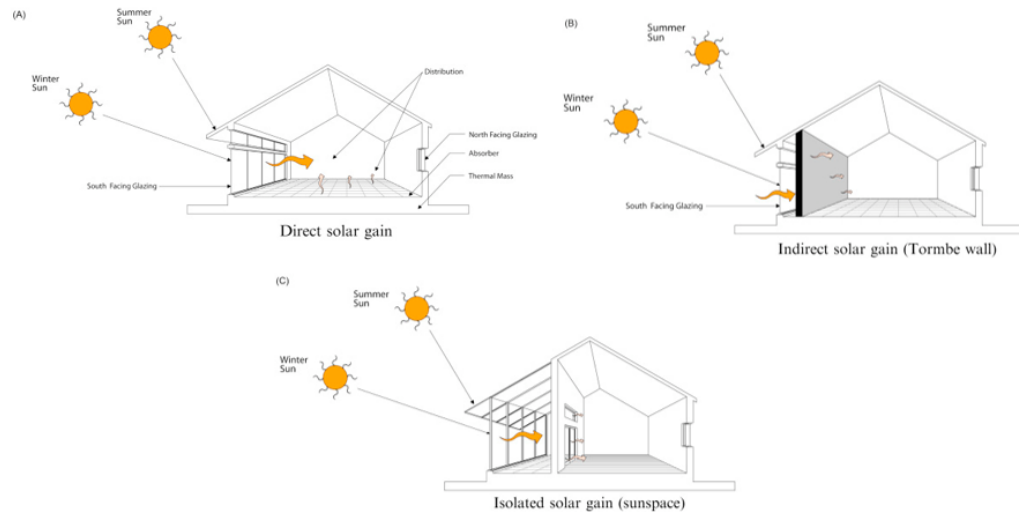


Figure I.2 Classification of passive solar heating systems [38].

I.4 Trombe Wall System Fundamentals

I.4.1 Definition and Main Components

A Trombe wall consists of a glazing layer, an air gap, a thermal storage wall, and, in ventilated designs, air openings for circulation [2, 3]. The glazing transmits solar radiation while limiting long-wave losses. The air gap promotes convective transfer and acts as a thermal buffer. The thermal mass absorbs and stores energy, while vents regulate thermosiphon airflow.

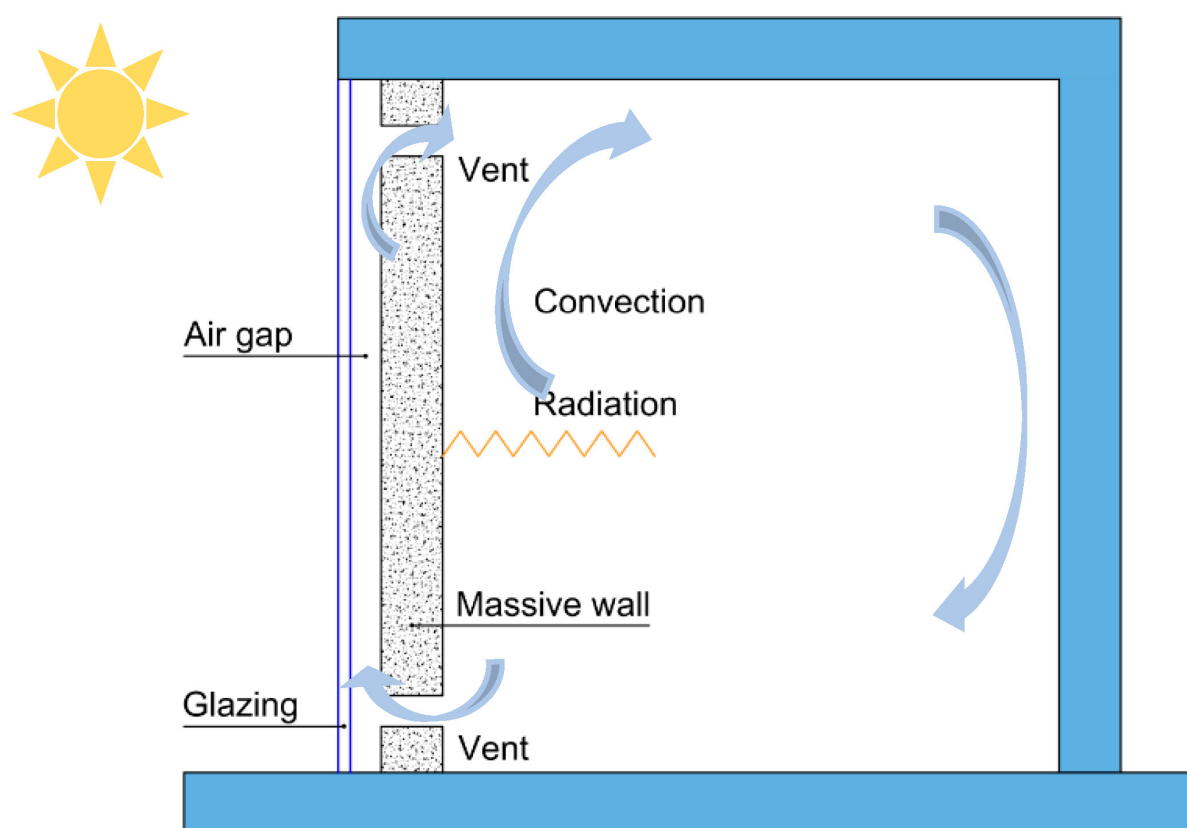


Figure I.3 Main components and heat transfer mechanisms of a Trombe wall [39]

Table I.1 Main components of a Trombe wall, associated materials, and their functions

Component	Common Materials	Function
Glazing	Single glazing, double glazing, Low-E glazing	Allows solar radiation transmission and reduces heat losses through the greenhouse effect.
Air gap	Air cavity (5–15 cm)	Promotes natural convection and acts as a thermal buffer.
Thermal wall	Concrete, brick, stone, adobe, or water tanks	Absorbs, stores, and gradually releases thermal energy.
Upper and lower vents	Openings with dampers or shutters	Facilitate buoyancy-driven airflow between the cavity and indoor space.
Absorber surface	Black paint or selective coating	Enhances solar energy absorption.

Among the available glazing options, double glazing was selected in the present study because it provides a suitable compromise between solar transmittance and thermal insulation, thereby reducing heat losses while maintaining adequate solar heat gain.

I.4.2 Working Principle

The system operates through the greenhouse effect. Solar radiation passes through the glazing and is absorbed by the wall surface, increasing its temperature. Heat is then transferred by conduction through the wall and by convection through the air gap [2, 3].

I.4.3 Operation Modes

I.4.3.1 Heating Mode

In heating mode, solar radiation is absorbed by the massive wall and stored as thermal energy. Warm air rises through the upper vents and enters the room, while cooler indoor air is drawn into the lower opening, establishing natural air circulation [2, 3]. In addition, the stored heat is gradually released through the wall by delayed conduction, contributing to indoor thermal comfort during periods of low solar availability.

I.4.3.2 Cooling Mode

In cooling mode, the Trombe wall can operate as a solar chimney, promoting the extraction of warm indoor air to the outdoor environment. Combined with night ventilation and external shading, this strategy helps reduce overheating and improves thermal comfort under hot climatic conditions [13, 42].

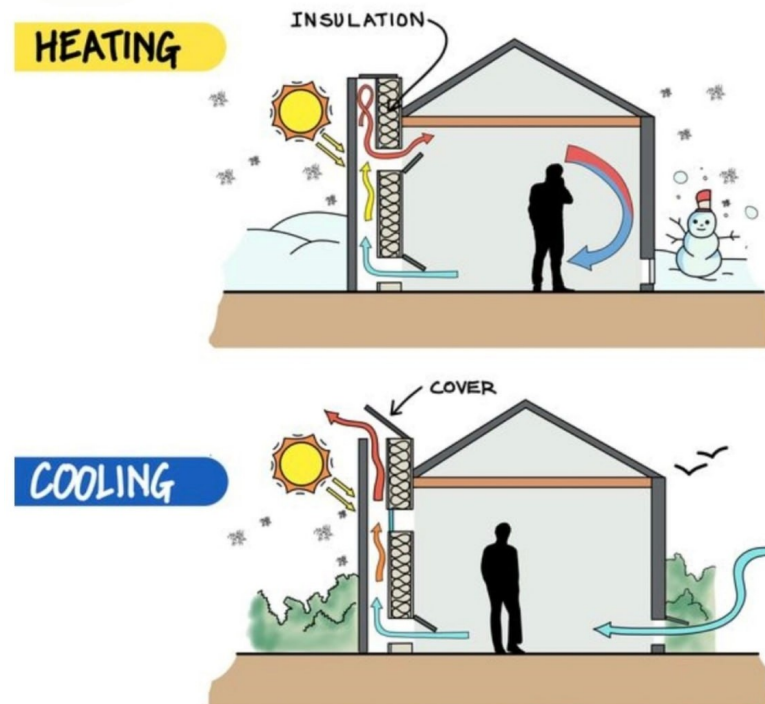


Figure I.4 Seasonal operation modes of Trombe wall

I.4.4 Advantages and Disadvantages

Trombe walls can reduce energy demand, improve comfort, and operate without active systems [1, 3]. However, their limitations include overheating risk, dependence on solar exposure, and sensitivity to design parameters.

Table I.2 Advantages and Disadvantages of Trombe Walls [3]; [1]

Advantages	Disadvantages
Low energy use	Risk of overheating in summer
Passive and simple system	High initial construction cost
Improves indoor thermal comfort	Performance depends on solar exposure
Reduces heating and cooling demand	Requires proper design and sizing
Low maintenance	User control of vents may be needed
Aesthetic integration with building facades	Potential reduction of useful wall area
Can be combined with PV systems	Less effective in cloudy conditions

I.5 Classification of Trombe Wall Systems

I.5.1 Classical Trombe Wall

The classical Trombe wall consists of a massive wall located behind a glazing layer separated by an air gap. Solar radiation is absorbed and stored within the wall and gradually released to the indoor environment. This configuration is mainly used for passive heating applications [2, 3].

I.5.2 Ventilated Trombe Wall

Ventilated Trombe walls incorporate upper and lower vents to promote buoyancy-driven airflow. These openings improve heat transfer and allow the system to operate in both heating and cooling modes depending on climatic conditions [13, 14].

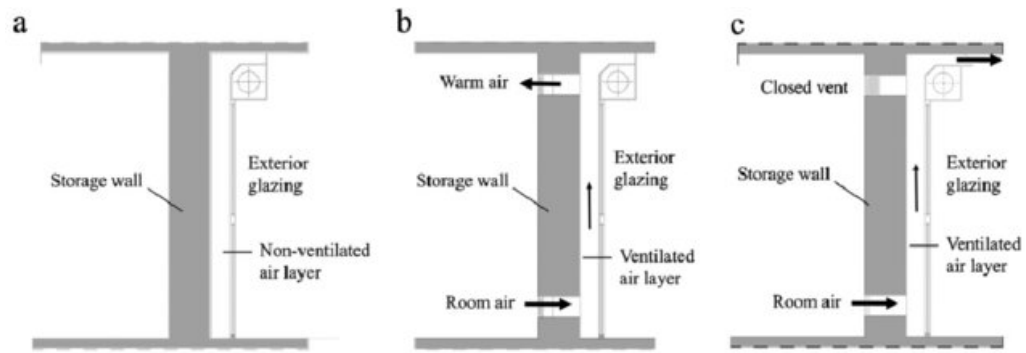


Figure I.5 Comparison between (a) Classical Trombe wall and (b,c) Ventilated Trombe wall [40].

I.5.3 Water Trombe Wall

Water Trombe walls replace the conventional massive wall with water containers acting as thermal storage media. Due to the high heat capacity of water, these systems can provide improved thermal storage performance and more stable indoor temperatures [34].

I.5.4 PCM Trombe Wall

Phase Change Material (PCM) Trombe walls integrate latent heat storage materials into the wall structure. PCM enhances thermal storage capacity, reduces temperature fluctuations, and improves thermal comfort by storing and releasing heat during phase transitions [15, 16, 17, 18].

I.5.5 PV Trombe Wall

Photovoltaic Trombe walls combine passive solar heating with electricity generation. The integration of photovoltaic panels allows simultaneous production of electrical and thermal energy, increasing the overall efficiency of the building envelope [9, 19, 20, 21].

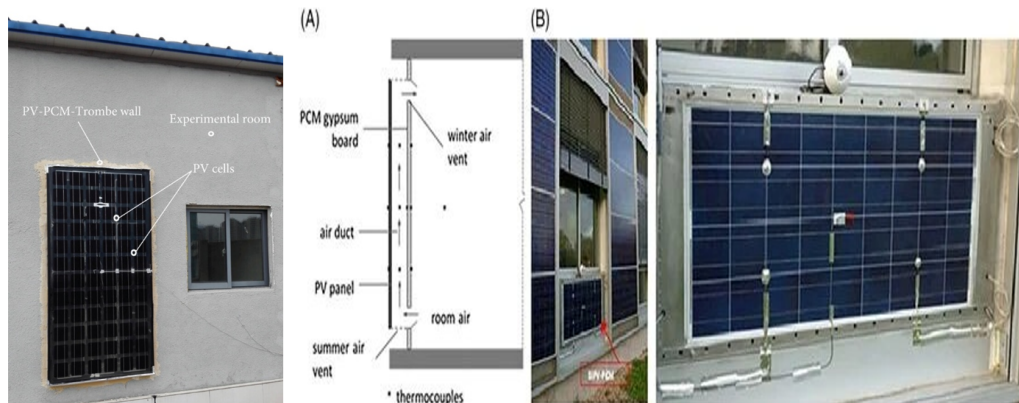


Figure I.6 PV-integrated Trombe wall configuration [37].

I.5.6 Composite Trombe Wall

Composite Trombe walls utilize advanced materials such as composite storage media, porous structures, or enhanced thermal conductivity materials to improve heat storage and transfer characteristics [22, 23, 24].

I.5.7 Advanced Trombe Wall Configurations

Recent developments include nano-enhanced Trombe walls, smart-controlled ventilation systems, hybrid PV-PCM configurations, and automated adaptive Trombe walls. These advanced concepts aim to improve thermal efficiency, operational flexibility, and year-round performance under different climatic conditions [25, 26, 39].

I.6 Literature Review

I.6.1 Studies in Hot Arid Regions

Studies conducted in hot arid regions have demonstrated that the thermal performance of Trombe walls is strongly influenced by wall geometry, ventilation strategy, thermal storage capacity, and climatic adaptation.

Saadatian et al. [3] provided one of the most comprehensive reviews of Trombe wall technology. Their work analyzed different Trombe wall configurations, operating principles, thermal performance indicators, and research challenges. The authors highlighted the importance of climatic adaptation and identified ventilation control as a key factor affecting system efficiency.

Dabaieh [13] investigated the application of ventilated Trombe walls in semi-arid settlements. The study demonstrated that natural ventilation can significantly improve indoor thermal comfort during hot periods by enhancing air circulation and reducing heat accumulation inside occupied spaces.

Bevilacqua and Mazzeo [30] evaluated the suitability of Trombe wall systems under different climatic conditions and assessed their annual energy-saving potential. Their results showed that system effectiveness strongly depends on local climate characteristics and design parameters such as wall thickness and glazing properties.

Using computational fluid dynamics (CFD), Alaoui et al. [31] analyzed several thermal-fin configurations integrated into Trombe walls. Their numerical results revealed that optimized fin arrangements can improve heat transfer and enhance overall thermal performance under hot desert conditions.

I.6.2 Trombe Wall Applications in Algeria

Research on Trombe wall technology in Algeria remains relatively limited despite the country's significant solar potential.

Bensafi et al. [32] investigated heat-transfer phenomena under arid climatic conditions and emphasized the importance of solar-energy utilization for improving building thermal performance in desert regions.

A passive solar building prototype developed in Batna [33] explored the integration of bio-based construction materials in a semi-arid climate. The study demonstrated the potential of passive solar design for reducing energy consumption while maintaining acceptable indoor thermal conditions.

Charqui et al. [34] conducted a numerical investigation of a water Trombe wall system. Their results showed that water-based thermal storage can provide stable thermal behavior and improved heat-storage capacity compared with conventional solid walls.

Although these studies contribute valuable insights into passive solar technologies in Algeria, investigations focusing specifically on ventilated Trombe wall systems operating under the climatic conditions of Ouargla remain scarce.

Table I.3 Summary of Literature and Identified Research Gaps

Reference	Climate/Location	Main Contribution	Identified Limitation / Gap
Saadatian et al. [3]	General review	Reviewed Trombe wall types and performance factors	Limited focus on hot-arid optimization
Dabaieh [13]	Semi-arid climate	Investigated ventilated Trombe wall cooling potential	No simplified predictive model
Bevilacqua and Mazzeo [30]	Warm climate	Evaluated annual energy saving potential	Limited analysis of geometric parameters
Alaoui et al. [31]	Hot desert climate	Studied thermal fin optimization using CFD	Focused on specific configurations only
Bensafi et al. [32]	Algeria	Investigated heat transfer in arid conditions	No analysis for ventilated Trombe wall
Passive solar house prototype [33]	Algeria	Investigated passive solar building prototype using bio-based materials	Did not address ventilated Trombe wall performance optimization
Charqui et al. [34]	Algeria	Numerical analysis of water Trombe wall	Different configuration from present study
Xiao et al. [35]	Review	Identified research trends	Limited focus on North African climates
Gu et al. [36]	Review	Reviewed performance enhancement methods	Lack of simplified models for hot-arid regions

I.7 Conclusion

This chapter presented a comprehensive review of Trombe wall technology, including its historical development, operating principles, heat transfer mechanisms, and main system configurations. Classical, ventilated, water-based, PCM-integrated, photovoltaic, and composite Trombe wall systems were discussed, highlighting their respective advantages and applications.

Particular attention was given to studies conducted in hot arid climates and to the limited research available in Algeria. The literature review revealed that although significant progress has been achieved in Trombe wall development, simplified predictive

models for ventilated systems operating under North African desert conditions remain relatively scarce.

These identified research gaps provide the scientific motivation for the present work. The next chapter focuses on the development of the thermal model and the numerical methodology adopted to evaluate the performance of a ventilated Trombe wall under the climatic conditions of Ouargla, Algeria.

CHAPTER II

THERMAL MODELING OF VENTILATED TROMBE WALL SYSTEM

II.1 Introduction

Based on the theoretical foundations established in Chapter 1, this chapter presents the development of the thermal model used to analyze the performance of a ventilated Trombe wall system under the hot arid climatic conditions of Ouargla, Algeria. The objective is to describe the coupled heat transfer and airflow mechanisms governing the system operation and to provide a numerical framework for evaluating its thermal behavior.

The chapter begins with a description of the system configuration, climatic data, and thermophysical parameters adopted in the study. The main modeling assumptions are then introduced in order to simplify the physical problem while retaining the dominant heat transfer phenomena.

A simplified thermal model based on energy balance equations is developed for the glazing, air gap, massive wall, and indoor air. The governing equations, boundary conditions, and ventilation modeling approach are presented in detail. In addition, a two-dimensional transient heat conduction model is introduced to provide a more detailed representation of temperature distribution within the massive wall.

Finally, the numerical solution methodology and model implementation are described. The developed models constitute the basis for the simulation, validation, and parametric analyses presented in the following chapter.

II.2 System Description

II.2.1 Physical Configuration

The system under study is a ventilated Trombe wall composed of a transparent glazing, an air gap, and a massive wall [43, 50]. The system is assumed to be vertically oriented and exposed to solar radiation on the external side.

The air gap is connected to the indoor environment through upper and lower vents, allowing air circulation driven by buoyancy forces (stack effect) [46, 51].

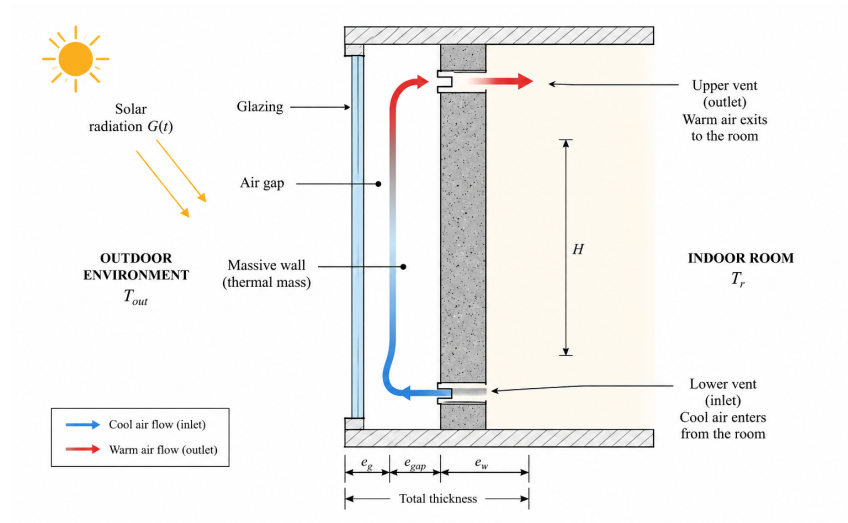


Figure II.1 Schematic representation of a ventilated Trombe wall and airflow path.

II.2.2 Control Volumes and Variables

For modeling purposes, the system is divided into four control volumes:

- The glazing, with temperature T_g
- The air gap, with temperature T_{gap}
- The massive wall, with temperature T_w
- The indoor air, with temperature T_r

The external environment is characterized by:

- Ambient temperature T_{out}
- Solar radiation intensity $G(t)$

Heat transfer within the system occurs through:

- Solar radiation transmitted through the glazing and absorbed by the wall
- Convective heat exchange between the wall and the air gap
- Radiative heat exchange between the glazing and the wall
- Heat transfer between the wall and indoor air
- Heat transfer due to air circulation through ventilation openings

II.3 Climatic Conditions of Ouargla

Ouargla is located in southeastern Algeria and is characterized by a typical Saharan desert climate. The region experiences very low annual precipitation, high solar radiation levels, and significant temperature variations between day and night. These climatic conditions make Ouargla particularly suitable for solar energy applications, including both photovoltaic and solar thermal systems. However, the high ambient temperatures during summer represent a major challenge for indoor thermal comfort in buildings, especially in the absence of active cooling systems. In order to characterize the climatic conditions of the region, solar radiation and ambient temperature are selected as the main input parameters for the present study. Figure II.2 presents the monthly variation of solar radiation and ambient temperature in Ouargla for the year 2020. It can be observed that solar radiation remains high throughout the year, with values exceeding 7 kWh/m²/day during the summer months. The maximum radiation is recorded in June and July, indicating a strong solar energy potential. The ambient temperature shows a significant seasonal variation. The maximum temperature reaches approximately 48°C in July, while the minimum temperature drops to nearly 1°C during winter. This large thermal amplitude reflects the extreme desert climate of the region.

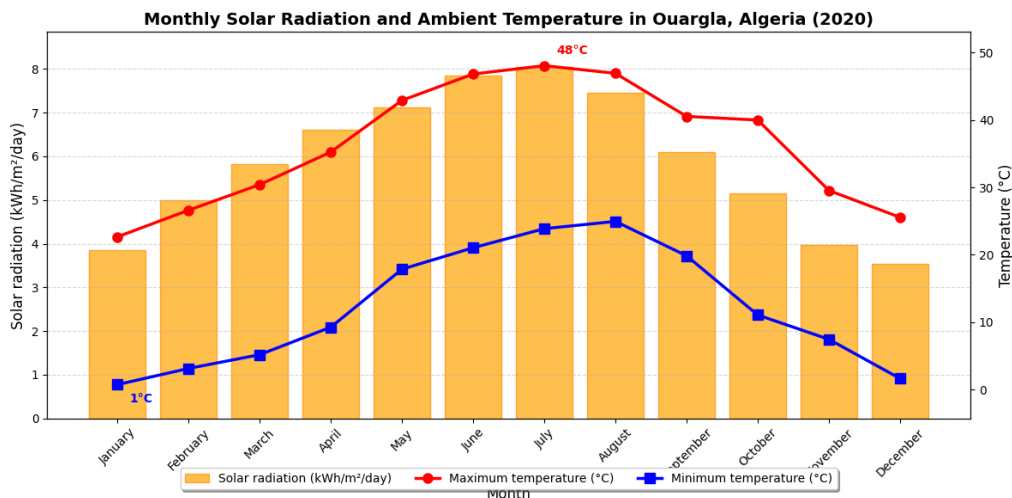


Figure II.2 Monthly variation of solar radiation and ambient temperature in Ouargla (2020). (Source: NASA POWER database)

These climatic characteristics confirm that Ouargla has a high potential for solar energy exploitation. At the same time, the elevated summer temperatures highlight the importance of passive cooling strategies in buildings.

II.3.1 Geographical Location

This study considers the climatic conditions of Ouargla, Algeria, characterized by a hot arid climate with high solar radiation and large daily temperature variations, as input

data for the numerical simulation.

The geographical coordinates are:

- Latitude: 31.95° North
- Longitude: 5.32° East

II.3.2 Selection of Representative Days

In order to analyze the system behavior under extreme climatic conditions, two representative days are selected: 15 January for winter and 15 July for summer. Figure II.3 shows the hourly variation of solar radiation and ambient temperature for these two typical days. It can be observed that solar radiation is significantly higher during the summer day, reaching values above 1000 W/m², while it remains lower during winter conditions. Similarly, the ambient temperature in July exceeds 45°C, whereas in January it remains much lower. This highlights the strong seasonal contrast and the severity of summer conditions in the Saharan climate. These representative days are therefore used as input data for the numerical simulation in order to evaluate the system performance under both heating and cooling conditions.

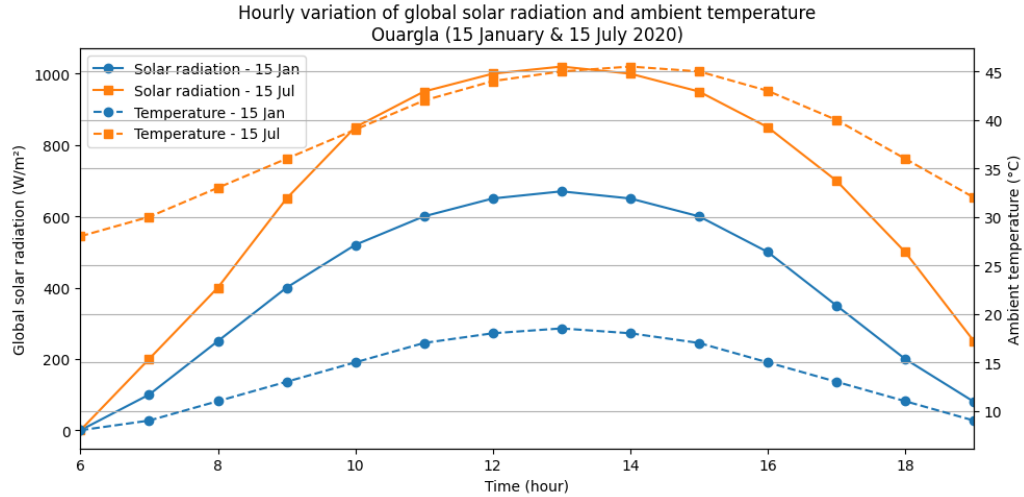


Figure II.3 Hourly variation of solar radiation and ambient temperature for representative winter (15 January) and summer (15 July) days in Ouargla.

II.4 Model Parameters

II.4.1 Geometric Parameters

The geometric configuration of the ventilated Trombe wall system is defined using representative dimensions corresponding to a typical residential application [50, 51].

The main geometric parameters considered in the model are summarized as follows:

- Wall area:

$$A_w = 10 \text{ m}^2$$

- Wall thickness:

$$e_w = 0.30 \text{ m}$$

- Glazing area:

$$A_g = 10 \text{ m}^2$$

- Air gap thickness:

$$e_{gap} = 0.10 \text{ m}$$

- Vent opening area:

$$A_v = 0.05 \text{ m}^2$$

- Vertical distance between vents:

$$H_v = 2.0 \text{ m}$$

- Heat exchange area between wall and indoor air:

$$A_{wr} = 10 \text{ m}^2$$

These geometric parameters are selected as representative values for a typical ventilated Trombe wall system. They are used in the energy balance equations to evaluate heat transfer and airflow behavior within the system [50, 51].

II.4.2 Thermophysical Properties

The thermophysical properties and model parameters used in the simulation are summarized in Table II.1. The selected values fall within typical ranges reported for building thermal systems and Trombe wall applications [44, 45].

Table II.1 Thermophysical and model parameters

Parameter	Symbol	Value
Air density	ρ_a	1.2 kg/m ³
Specific heat of air	c_p	1005 J/kg.K
Wall density	ρ_w	2200 kg/m ³
Wall specific heat	c_w	880 J/kg.K
Glazing absorptivity	α_g	0.10
Wall absorptivity	α_w	0.70
Radiative coefficient	$h_{r,g-w}$	4.5 W/m ² .K
Convective coeff. (gap)	$h_{c,g-gap}$	3 W/m ² .K
Convective coeff. (wall-gap)	$h_{c,w-gap}$	5 W/m ² .K
Convective coeff. (wall-room)	$h_{c,w-r}$	4 W/m ² .K
Glazing transfer coeff.	U_g	5.7 W/m ² .K
Room heat loss coeff.	U_{loss}	2.5 W/K
Discharge coefficient	C_d	0.60
Gravity acceleration	g	9.81 m/s ²

These thermophysical properties are used as input parameters in the numerical model and are selected according to standard values reported in the literature [44, 45].

II.5 Modeling Assumptions

To simplify the formulation of the thermal model while preserving the dominant physical phenomena, the following assumptions are adopted [44, 49, 50]:

- Each component of the system is represented by a uniform temperature (lumped parameter approach).
- Heat transfer through the massive wall is assumed one-dimensional.
- Thermophysical properties are assumed constant during the simulation.
- The thermal capacity of the glazing is neglected.
- The air inside the gap is considered well mixed.
- Airflow through the vents is driven by natural convection (stack effect).
- Heat losses are represented using global heat transfer coefficients.
- Indoor air is assumed well mixed and characterized by a uniform temperature.

These assumptions reduce the complexity of the governing equations while maintaining the essential mechanisms of conduction, convection, radiation, and buoyancy-driven ventilation within the system.

II.6 Simplified Thermal Modeling

II.6.1 Energy Balance Approach

Simplified models are often based on energy balances applied to glazing, air gap, wall, and indoor air [27, 28, 29].

II.6.2 Governing Equations and Assumptions

The present approach assumes one-dimensional heat transfer, constant properties, and simplified natural convection. Outer boundary condition[27]:

$$-k \frac{\partial T}{\partial x} = \alpha_s G - h_{out}(T_{out} - T_{amb}) \quad (II.1)$$

Inner boundary condition[27]:

$$-k \frac{\partial T}{\partial x} = h_{in}(T_{in} - T_{room}) \quad (II.2)$$

II.6.3 One-Dimensional Lumped Thermal Model

The room energy balance may be expressed as[29]:

$$\rho V c_p \frac{dT_{room}}{dt} = h_{in} A (T_{in} - T_{room}) + Q_{vents} - Q_{loss} \quad (II.3)$$

This simplified model captures dominant thermal behavior while remaining suitable for parametric analysis.

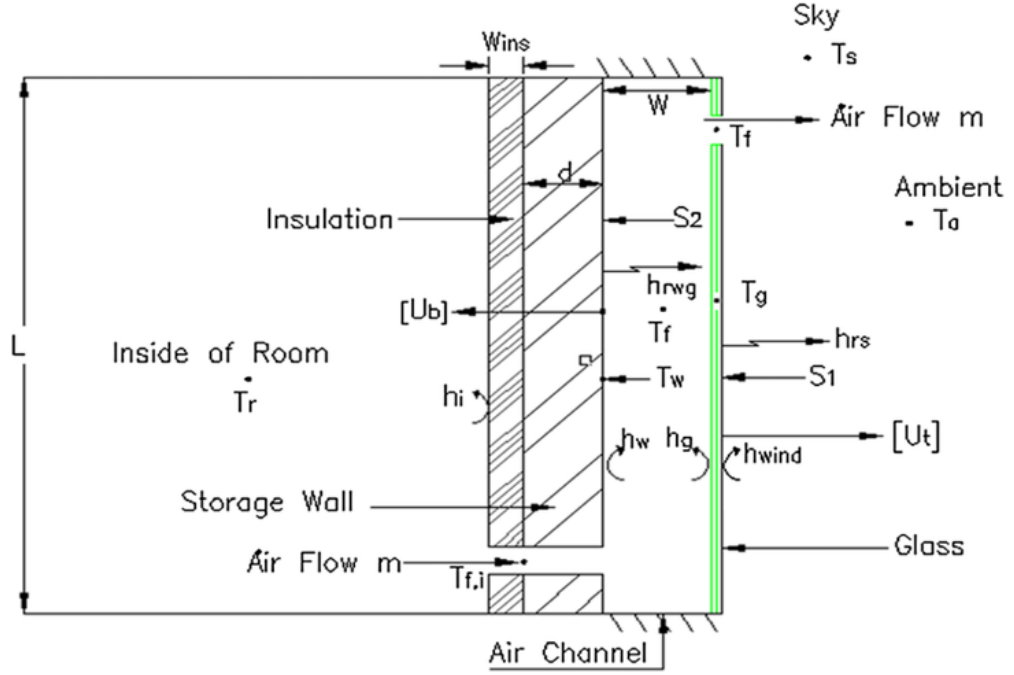


Figure II.4 1D lumped thermal model schematic
Source: Adapted from [42].

II.7 Energy Balance Equations

The thermal behavior of the ventilated Trombe wall system is modeled using a simplified lumped-parameter approach, where each component is represented by a uniform temperature [43, 44, 49].

The governing equations are derived from the general energy balance principle:

$$C \frac{dT}{dt} = \sum \dot{Q}_{in} - \sum \dot{Q}_{out} \quad (II.4)$$

This equation states that the variation of temperature in each component depends on the heat entering and leaving the system.

Based on the system description and the adopted assumptions, energy balance equations are established for each component of the Trombe wall system.

II.7.1 Glazing Energy Balance

The glazing is assumed to have negligible thermal capacity; therefore, a steady-state energy balance is used [43, 44]:

$$\alpha_g G(t) + h_{r,g-w}(T_w - T_g) + h_{c,g-gap}(T_{gap} - T_g) = U_g(T_g - T_{out}) \quad (II.5)$$

This equation represents the balance between absorbed solar radiation, heat exchange with the wall and air gap, and heat losses to the outside.

II.7.2 Air Gap Energy Balance

The air in the cavity is modeled as a control volume with uniform temperature [44, 46]:

$$C_{gap} \frac{dT_{gap}}{dt} = h_{c,w-gap}(T_w - T_{gap}) + h_{c,g-gap}(T_g - T_{gap}) - \dot{m}c_p(T_{gap} - T_r) \quad (II.6)$$

The air temperature varies due to heat exchange with the wall and glazing and due to heat transported by airflow.

II.7.3 Wall Energy Balance

The wall is modeled as a lumped thermal mass [43]:

$$M_w c_w \frac{dT_w}{dt} = \alpha_w G(t) + h_{r,w-g}(T_g - T_w) + h_{c,w-gap}(T_{gap} - T_w) - h_{c,w-r}(T_w - T_r) \quad (II.7)$$

The wall absorbs solar energy and transfers heat to the air gap and indoor space, acting as a thermal storage element.

II.7.4 Room Energy Balance

The indoor air is assumed well mixed [45]:

$$C_r \frac{dT_r}{dt} = \dot{m}c_p(T_{gap} - T_r) + h_{c,w-r}(T_w - T_r) - U_{loss}(T_r - T_{out}) \quad (II.8)$$

The indoor temperature is governed by heat gains from airflow and the wall, and losses to the outside.

II.8 Ventilation Modeling

The airflow within the ventilated Trombe wall system is driven by natural convection, commonly referred to as the stack effect [45, 46].

When the air inside the gap is heated, its density decreases, causing it to rise. This upward movement creates a pressure difference that induces airflow through the upper and lower vents [45, 46].

The mass flow rate of air is modeled using a simplified relation based on buoyancy forces:

$$\dot{m} = \rho_a C_d A_v \sqrt{2gH_v \frac{T_{gap} - T_r}{T_{ref}}} \quad (II.9)$$

where T_{ref} is the reference absolute air temperature used in the buoyancy formulation.

In this expression, the airflow rate depends on the temperature difference between the cavity air and indoor air, as well as on the geometry of the ventilation openings.

This formulation is derived from simplified models of buoyancy-driven flow in vertical openings [46, 49].

To ensure physically realistic behavior and prevent reverse airflow, a control condition is introduced:

$$\dot{m} = \begin{cases} \rho_a C_d A_v \sqrt{2g H_v \frac{T_{gap} - T_r}{T_{ref}}} & \text{if } T_{gap} > T_r \\ 0 & \text{otherwise} \end{cases} \quad (\text{II.10})$$

This condition ensures that airflow occurs only when the cavity air temperature exceeds the indoor air temperature, allowing useful heat transfer to the room [49].

II.9 Boundary Conditions

To solve the thermal model, boundary conditions must be defined. These conditions represent the interaction between the Trombe wall system and the outdoor environment [44, 45, 51].

The model requires the following input variables:

- Outdoor temperature, $T_{out}(t)$
- Solar radiation, $G(t)$

The outdoor temperature and solar radiation are treated as time-dependent boundary inputs.

Wind effects are neglected in the present model.

These data are taken from the climatic conditions of Ouargla, Algeria.

In addition, initial conditions are required to start the simulation. It is assumed that all temperatures are equal to the outdoor temperature at the initial time:

$$T_g(0) = T_{gap}(0) = T_w(0) = T_r(0) = T_{out}(0) \quad (\text{II.11})$$

These conditions allow the model to simulate the transient thermal behavior of the system over time [51].

II.10 Numerical Solution and Implementation

II.10.1 Numerical Method

The system of energy balance equations developed in the previous sections leads to a set of coupled ordinary differential equations (ODEs) that describe the transient thermal behavior of the Trombe wall system.

Due to the time-dependent nature of these equations, an analytical solution is not feasible. Therefore, a numerical approach is required to solve the system.

The solution is obtained by discretizing time into small intervals and computing the evolution of temperatures step by step.

At each time step, the temperatures of the system components (T_g , T_{gap} , T_w , and T_r) are updated based on the governing equations.

In this study, the coupled ODE system is solved using the Runge-Kutta RK45 method, selected for its balance between numerical accuracy and computational efficiency [48, 49].

The numerical implementation allows analyzing the dynamic thermal behavior of the system under varying climatic conditions.

II.10.2 Computational Environment

The developed thermal model is implemented using the Python programming language, which is widely used in scientific computing due to its flexibility, efficiency, and availability of powerful numerical libraries [47].

Python provides suitable tools for solving systems of ordinary differential equations, handling time-dependent data, and visualizing results. This makes it appropriate for modeling transient heat transfer problems such as those encountered in solar energy systems.

The model equations are solved numerically by discretizing time and updating the state variables step by step.

The use of a computational tool allows analyzing the temporal evolution of the system under varying climatic conditions and facilitates visualization of key parameters such as temperature distribution and airflow rate.

The numerical implementation is performed using NumPy for array-based computation and SciPy for equation solving [47].

II.10.3 Model Implementation

The developed thermal model is implemented using an iterative computational procedure to simulate system behavior over time.

At each time step, the following procedure is applied:

- Input climatic data (solar radiation and outdoor temperature)
- Compute the airflow rate based on the temperature difference
- Solve the governing ODE system using RK45
- Update the temperatures of the glazing, air gap, wall, and indoor air
- Store the calculated variables for post-processing

The main steps of the numerical implementation are illustrated in Figure II.5.

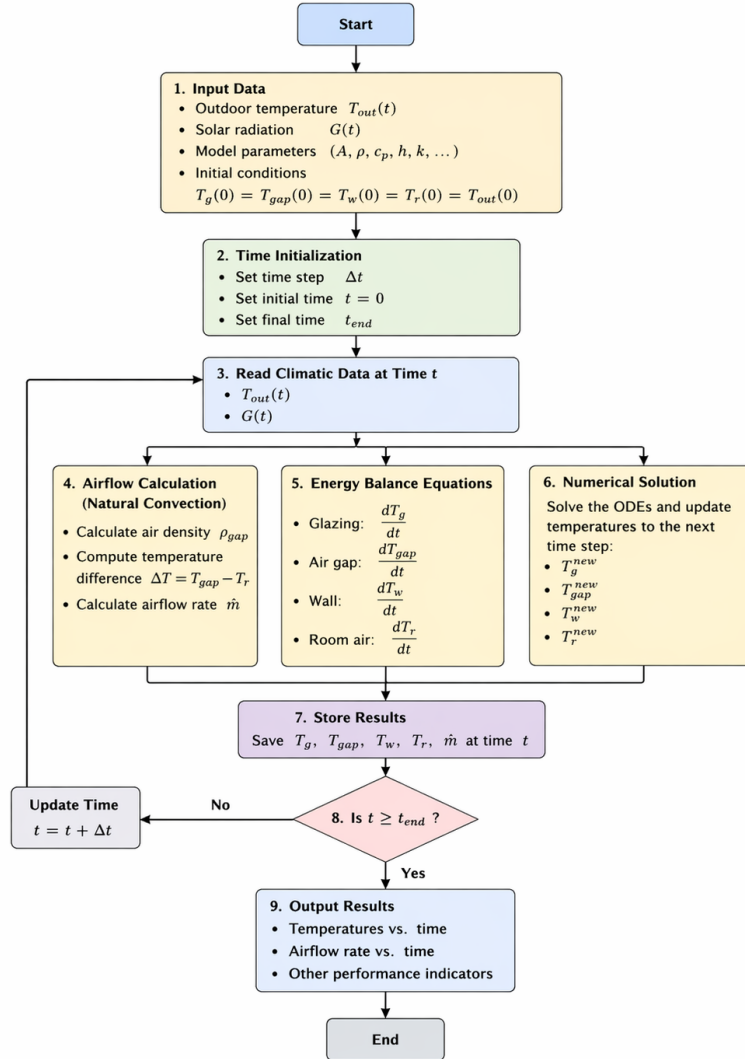


Figure II.5 Flowchart of the numerical implementation of the ventilated Trombe wall model

This iterative process allows tracking the thermal evolution of the system under varying conditions.

The implementation is carried out in Python using a time-marching procedure for transient simulation.

II.11 Two-Dimensional Thermal Model

II.11.1 Mathematical Formulation

While the one-dimensional model provides a simplified representation of the thermal behavior of the ventilated Trombe wall, it does not account for temperature variations within the wall structure. To obtain a more detailed description of heat transfer, a two-dimensional transient heat conduction model is introduced.

The temperature distribution inside the massive wall is governed by the transient Fourier heat conduction equation:

$$\frac{\partial T}{\partial t} = \alpha \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) \quad (\text{II.12})$$

where:

- $T(x, y, t)$ is the wall temperature ($^{\circ}\text{C}$)
- x is the wall thickness coordinate (m)
- y is the wall height coordinate (m)
- t is time (s)
- α is the thermal diffusivity (m^2/s)

The thermal diffusivity is calculated as:

$$\alpha = \frac{\lambda_w}{\rho_w c_w} \quad (\text{II.13})$$

where λ_w is the thermal conductivity of the wall material, ρ_w is the density, and c_w is the specific heat capacity.

II.11.2 Boundary Conditions

The external wall surface is exposed to solar radiation and convective heat exchange with the ambient air. The boundary condition at the outdoor surface ($x = 0$) is expressed as:

$$-\lambda_w \left. \frac{\partial T}{\partial x} \right|_{x=0} = \alpha_w G(t) + h_{out} (T_{out} - T_{x=0}) \quad (\text{II.14})$$

where:

- α_w is the wall solar absorptivity
- $G(t)$ is the incident solar radiation
- h_{out} is the outdoor convective heat transfer coefficient
- T_{out} is the outdoor temperature

At the indoor surface ($x = L_x$), heat is transferred by convection between the wall and the room air:

$$-\lambda_w \left. \frac{\partial T}{\partial x} \right|_{x=L_x} = h_{c,w-r} (T_r - T_{x=L_x}) \quad (\text{II.15})$$

where $h_{c,w-r}$ is the convective heat transfer coefficient between the wall and the indoor air, and T_r is the indoor air temperature.

For the upper and lower wall boundaries, adiabatic conditions are assumed:

$$\frac{\partial T}{\partial y} = 0 \quad \text{at} \quad y = 0 \quad \text{and} \quad y = L_y \quad (\text{II.16})$$

The initial condition assumes a uniform temperature distribution equal to the ambient temperature at the beginning of the simulation:

$$T(x, y, 0) = T_{out} \quad (\text{II.17})$$

II.11.3 Numerical Implementation

The governing equation is solved numerically using the explicit Finite Difference Method (FDM) on a structured computational grid.

The wall domain is discretized into a two-dimensional mesh consisting of 30 nodes along the thickness direction and 40 nodes along the height direction.

The temporal discretization is performed using a constant time step of:

$$\Delta t = 60 \text{ s} \quad (\text{II.18})$$

The selected time step satisfies the von Neumann stability criterion:

$$\Delta t \leq \frac{(\Delta x)^2}{2\alpha} \quad (\text{II.19})$$

The simulations are carried out over a 24-hour period using the climatic data of Ouargla corresponding to the representative winter day (15 January) and summer day (15 July).

The numerical implementation is performed using Python and the NumPy library for matrix operations and transient temperature calculations.

II.12 Model Behavior Analysis

The developed model allows analyzing the thermal behavior of the ventilated Trombe wall system under different operating conditions [50, 51].

The system response depends mainly on:

- Solar radiation intensity
- Outdoor temperature

- Ventilation rate

An increase in solar radiation leads to higher wall temperature and increased heat transfer to the indoor space.

The airflow inside the gap plays an important role in transferring heat from the wall to the room.

The model can also be used to study the effect of different parameters on system performance, such as wall properties, vent size, and climatic conditions [50, 51].

This analysis provides a better understanding of the factors influencing the thermal efficiency of the ventilated Trombe wall system.

II.13 Conclusion

In this chapter, the thermal modeling methodology of the ventilated Trombe wall system was presented. The system configuration, control volumes, thermophysical parameters, and climatic conditions of Ouargla were first introduced as the basis for the numerical analysis.

A simplified thermal model was then developed using energy balance equations for the glazing, air gap, massive wall, and indoor air. The main modeling assumptions and the natural ventilation approach were also described.

In addition, a two-dimensional transient heat transfer model was formulated to provide a more detailed representation of heat conduction within the massive wall. The corresponding boundary conditions and numerical implementation procedure were presented.

Finally, the developed numerical models provide the framework for evaluating the thermal performance of the ventilated Trombe wall system. The next chapter presents the simulation results, validation, and parametric analyses under representative summer and winter climatic conditions.

CHAPTER III

RESULTS AND DISCUSSION

III.1 Introduction

This chapter presents and discusses the results obtained from the numerical simulations of the ventilated Trombe wall system developed in Chapter 2. The objective is to evaluate the thermal performance of the system under representative summer and winter climatic conditions corresponding to the hot arid climate of Ouargla, Algeria.

The analysis focuses on the temporal evolution of the temperatures within the different system components, the influence of ventilation on heat transfer processes, and the overall thermal response of the Trombe wall. Parametric and sensitivity analyses are also performed to investigate the effects of key operating and design parameters on system performance.

Model validation is conducted through comparison with previously published studies in order to assess the reliability of the developed numerical approach. In addition, a two-dimensional thermal analysis is presented to provide a more detailed visualization of temperature distributions and heat transfer mechanisms within the massive wall.

The obtained results contribute to a better understanding of the thermal behavior of ventilated Trombe wall systems and their potential application as passive heating and cooling solutions in hot arid regions.

III.2 Simulation Conditions

The numerical simulation of the ventilated Trombe wall system is carried out under defined operating and boundary conditions in order to ensure a consistent analysis of the system behavior.

The climatic data used as input parameters consist of solar radiation and outdoor temperature obtained from the NASA POWER database for the representative days 15 January and 15 July, corresponding to winter and summer conditions, respectively.

The system is analyzed under two main configurations: without ventilation and with ventilation, in order to evaluate the influence of airflow on the thermal performance of the Trombe wall.

The numerical resolution is performed using a time-dependent approach, where the governing energy balance equations are solved over a 24-hour period with a fixed time step.

These simulation conditions allow a detailed investigation of the thermal response of the system under realistic climatic conditions.

III.3 Thermal Behavior without Ventilation

In order to analyze the intrinsic thermal response of the Trombe wall system, the simulation is carried out under conditions without ventilation, where air exchange between

the cavity and the indoor space is neglected. Under this configuration, heat transfer occurs primarily through conduction, convection, and radiation.

Figure III.1 shows the temporal evolution of the system temperatures for the summer day (15 July). The outdoor temperature reaches a peak value of approximately 48°C around midday, reflecting the severe climatic conditions.

Due to solar radiation, the glazing temperature (T_g) increases rapidly and reaches about 43°C, while the air gap temperature (T_{gap}) rises to nearly 39°C. This behavior is mainly attributed to the greenhouse effect, where solar radiation enters through the glazing and is trapped within the cavity. In the absence of ventilation, the heated air remains confined, leading to significant heat accumulation.

The wall temperature (T_w) evolves more gradually due to its thermal inertia, reaching values close to 38°C. The indoor air temperature (T_r) follows a similar trend but with a slower increase, attaining a maximum value of approximately 38°C. Although this temperature is lower than the outdoor temperature, the reduction remains limited.

During nighttime, the absence of solar radiation results in a gradual decrease in all temperatures. The heat stored in the wall during the day is progressively released toward the indoor environment, producing a delayed thermal response.

The peak indoor temperature occurs approximately 5 hours after the peak solar radiation, indicating a thermal time lag of about 5 h. This delay is mainly attributed to the thermal inertia of the massive wall. The indoor temperature exhibits a thermal time lag of approximately 5 h relative to the solar radiation peak, reflecting the heat storage capacity of the wall.

Overall, the results indicate that, without ventilation, the Trombe wall system behaves as a thermal storage system. While this is advantageous for heating in winter, it leads to heat accumulation and potential overheating in summer, thereby limiting its effectiveness for passive cooling.

III.4 Effect of Ventilation

The effect of ventilation on the thermal performance of the Trombe wall system is investigated by comparing the system behavior with and without airflow within the cavity.

Figure III.2 presents the temporal evolution of the system temperatures under ventilated conditions for the summer day (15 July).

The introduction of ventilation significantly modifies the heat transfer mechanisms within the system. Unlike the non-ventilated case, where heat is mainly accumulated inside the cavity, the presence of airflow enables the extraction of heated air, thereby reducing thermal buildup.

In order to better quantify the impact of ventilation, a direct comparison between the ventilated and non-ventilated configurations is presented in Figure III.3.

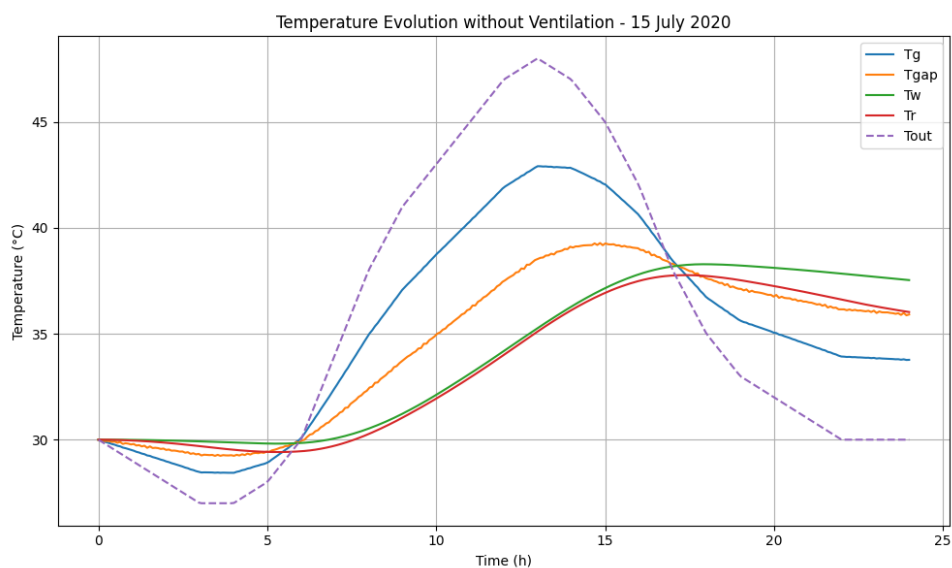


Figure III.1 Temperature evolution of the Trombe wall system without ventilation for the summer day (15 July 2020).

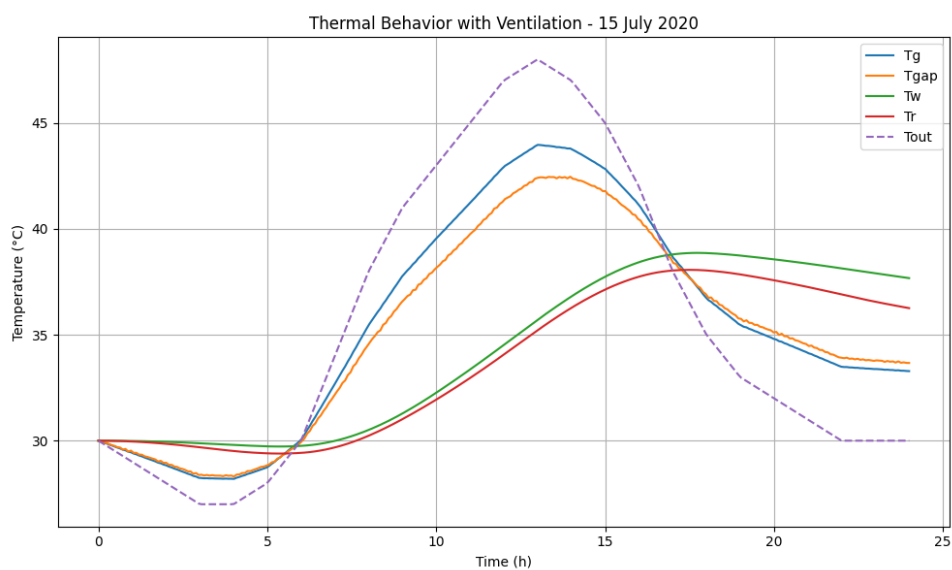


Figure III.2 Temperature evolution of the Trombe wall system with ventilation for the summer day (15 July 2020).

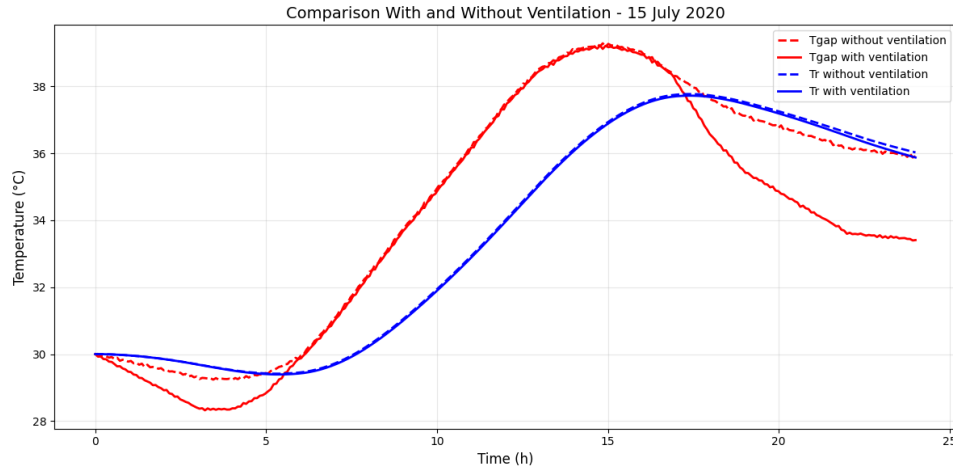


Figure III.3 Comparison of air gap temperature (T_{gap}) and indoor air temperature (T_r) with and without ventilation for the summer day (15 July 2020).

It can be observed that ventilation leads to a reduction in the air gap temperature, particularly during peak solar radiation hours. This behavior confirms that the airflow effectively removes part of the accumulated heat within the cavity, thereby limiting the greenhouse effect.

The indoor air temperature is also slightly reduced when ventilation is applied. Although the reduction remains moderate, it contributes to improving thermal comfort by mitigating overheating during the hottest periods of the day.

This reduction is attributed to the extraction of warm air from the cavity, which enhances convective heat transfer and limits heat accumulation within the system. However, the cooling effect remains relatively limited because the outdoor temperature during the summer day exceeds 45°C, reducing the temperature difference available for heat removal.

Furthermore, the maximum indoor temperature decreases from 38.2°C to 36.5°C, corresponding to a cooling effect of approximately 1.7°C. This result confirms that ventilation improves thermal performance, although its effectiveness is constrained by the severe climatic conditions of Ouargla.

To further highlight the cooling contribution of ventilation, the temperature differences between the two configurations are presented in Figure III.4.

The results show that the cooling effect is more pronounced in the air gap than in the indoor space. The maximum reduction in air gap temperature reaches several degrees Celsius, whereas the reduction in indoor air temperature remains limited to approximately 1.7°C. This suggests that the influence of ventilation is more significant within the cavity than in the occupied space.

Furthermore, the cooling effect becomes more noticeable during the afternoon and evening periods, when the temperature difference between the cavity and the outdoor air increases. Under these conditions, buoyancy-driven airflow promotes heat extraction from

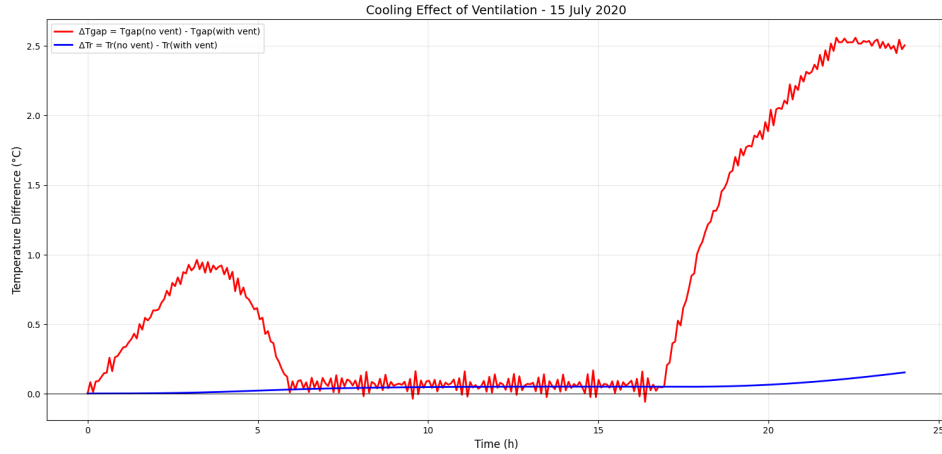


Figure III.4 Cooling effect of ventilation expressed as temperature differences ΔT_{gap} and ΔT_r between non-ventilated and ventilated cases (15 July 2020).

the cavity and limits heat accumulation.

Overall, ventilation contributes to reducing the thermal buildup inside the Trombe wall system during summer operation. Although the improvement in indoor temperature remains moderate under the severe climatic conditions of Ouargla, the results suggest that ventilation can enhance the thermal performance of the system and help mitigate overheating.

III.5 Winter Thermal Performance

In addition to the summer case, the thermal behavior of the Trombe wall system is also analyzed under winter conditions using the representative day of 15 January.

In winter, the system is mainly considered as a passive heating device. Therefore, ventilation toward the outdoor environment is neglected in order to reduce heat losses and enhance heat storage within the wall.

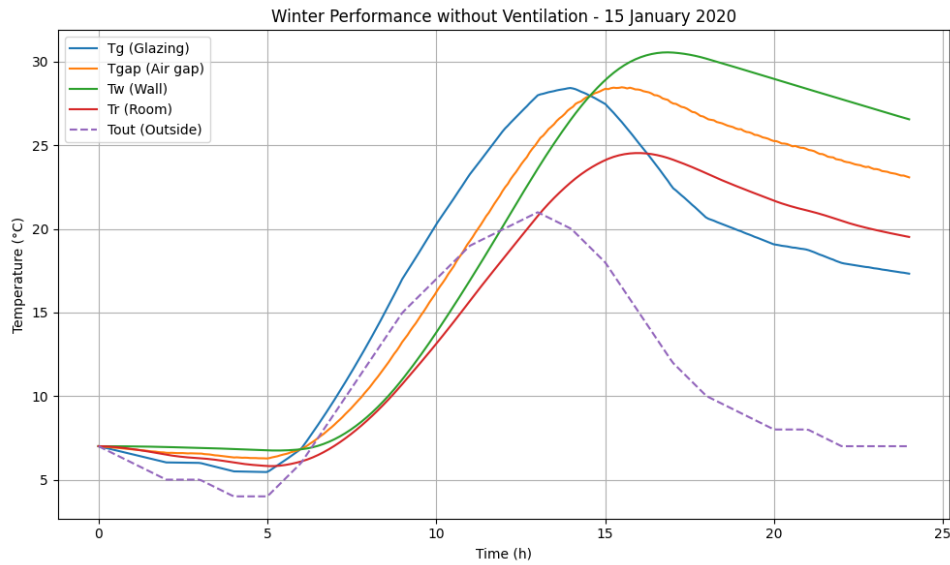


Figure III.5 Temperature evolution of the Trombe wall system without ventilation for the winter day (15 January 2020).

The results show that the indoor air temperature remains higher than the outdoor temperature during most of the day, suggesting a positive contribution of the Trombe wall to passive heating under winter conditions.

The wall temperature increases progressively during the daytime due to solar radiation absorption. This behavior reflects the thermal storage capacity of the massive wall, which absorbs part of the incident solar energy and releases it gradually over time.

The air gap temperature also increases under the combined effect of solar gains and heat exchange with the wall and glazing. Since ventilation is neglected, a significant portion of the absorbed heat remains within the system and is progressively transferred toward the indoor space.

The indoor temperature exhibits a smoother variation than the outdoor temperature, reflecting the thermal inertia of the wall. The peak indoor temperature occurs approximately 5 hours after the peak solar radiation, corresponding to a thermal time lag of about 5 h. This delayed response contributes to reducing indoor temperature fluctuations and maintaining more stable thermal conditions.

Overall, the winter results suggest that the Trombe wall can contribute to improving indoor thermal conditions by storing solar energy during the day and releasing it progressively toward the indoor environment.

III.5.1 Influence of Wall Thickness

The thickness of the concrete wall is a key parameter that determines the thermal inertia and heat storage capacity of the Trombe wall system. To evaluate its influence, three thicknesses were considered: 20 cm, 30 cm (base case), and 40 cm. Simulations were

performed for the winter day (15 January) under natural convection conditions without forced ventilation.

Figure III.6 presents the temporal evolution of indoor temperature (T_r) for the three wall thicknesses.

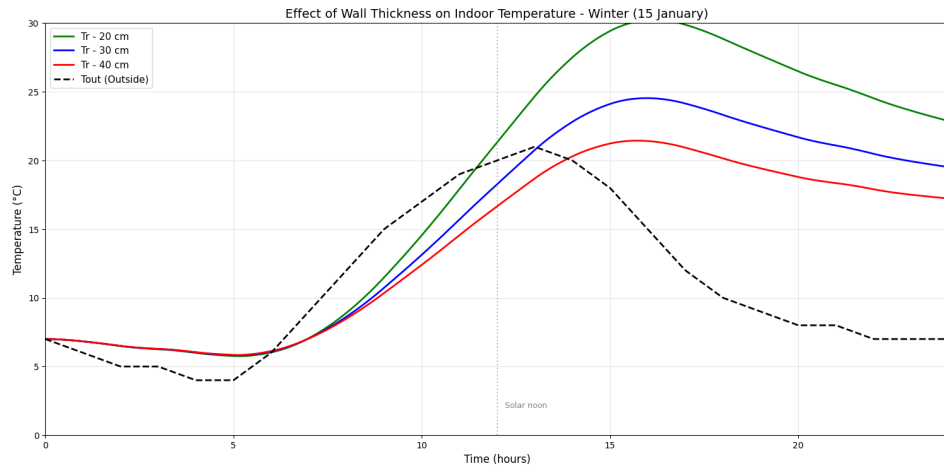


Figure III.6 Effect of wall thickness on indoor temperature (T_r) for the winter day (15 January 2020).

The results reveal a clear trade-off associated with wall thickness:

- The **20 cm wall** responds rapidly to solar radiation, reaching the highest peak temperature during the afternoon due to its low thermal inertia. However, it cools down quickly after sunset, leading to larger temperature fluctuations (about 8.5°C).
- The **30 cm wall** represents an intermediate behavior, providing a balance between daytime heat gain and nighttime heat release, with moderate temperature fluctuations and time delay.
- The **40 cm wall** exhibits a slower thermal response. Its peak temperature is lower because a significant portion of the absorbed heat is stored within the wall mass. This results in a larger time lag (about 6.5 hours) and a more gradual heat release during the night, improving thermal stability.

Table III.1 summarizes the quantitative results for the three thicknesses.

Table III.1 Effect of wall thickness on winter thermal performance (15 January)

Thickness (cm)	Peak T_r (°C)	Time lag (h)	Fluctuation (°C)	Observation
20	22.5	3.5	8.5	Fast response, low stability
30	21.5	5.0	7.0	Balanced behavior
40	20.5	6.5	6.0	High inertia, delayed heating

The results suggest that increasing wall thickness enhances thermal inertia, leading to a greater thermal time lag and reduced indoor temperature fluctuations. However, this improvement is accompanied by a reduction in the peak indoor temperature during daytime hours because a larger fraction of the absorbed energy is stored within the wall mass.

From a seasonal perspective, thicker walls may be advantageous during summer operation, as they delay and attenuate heat transfer toward the indoor space. In contrast, thinner walls provide higher daytime indoor temperatures during winter but exhibit lower thermal stability and larger temperature fluctuations.

Among the investigated configurations, the 30 cm wall appears to provide a balanced thermal behavior, combining moderate thermal inertia, a thermal time lag of approximately 5 h, and acceptable indoor temperature levels. Therefore, this thickness may be considered a suitable compromise for the climatic conditions of Ouargla.

III.5.2 Influence of Glass Absorptivity

The glass absorptivity (α_g) is a key optical parameter that governs the fraction of incident solar radiation absorbed by the glazing. This parameter directly influences the amount of thermal energy available within the air cavity and consequently affects the overall behavior of the Trombe wall system.

Three values of glass absorptivity were considered: 0.08, 0.10 (base case), and 0.12. These values correspond to typical glazing materials used in solar applications. The analysis was conducted under summer conditions (15 July).

Figure III.7 illustrates the temporal evolution of the air gap temperature (T_{gap}) for the different absorptivity values.

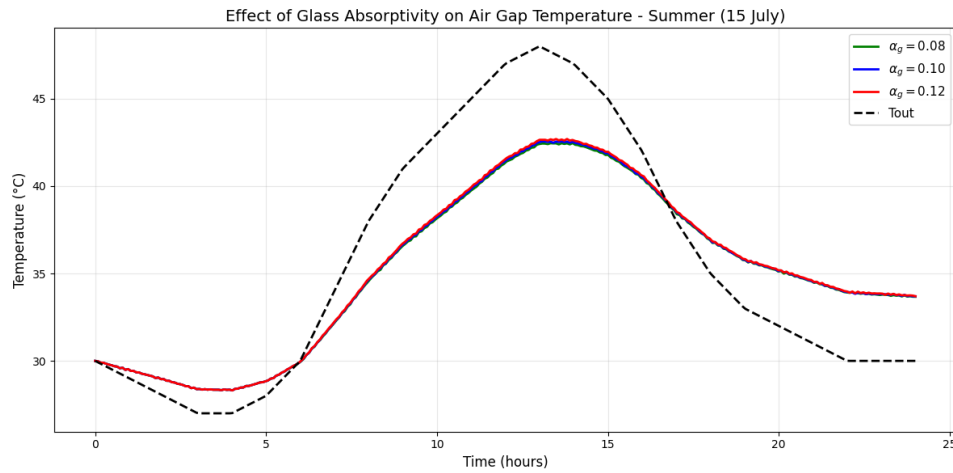


Figure III.7 Effect of glass absorptivity on air gap temperature (T_{gap}) for the summer day (15 July 2020).

The results show that the influence of glass absorptivity on the air gap temperature

remains relatively limited within the investigated range. Increasing α_g leads to a slight increase in T_{gap} due to the higher fraction of solar radiation absorbed by the glazing.

However, the difference between the three cases does not exceed approximately 1°C under peak conditions. This relatively small variation suggests that, during summer operation, the thermal behavior of the cavity is governed mainly by external climatic conditions and convective heat transfer processes rather than by glazing absorptivity alone.

The limited sensitivity to α_g can be explained by the narrow range of absorptivity values considered and by the dominant influence of solar radiation intensity and ambient temperature under Saharan climatic conditions.

Although the impact on T_{gap} is modest in summer, the role of absorptivity may become more significant during winter operation, when maximizing solar heat gains is desirable for passive heating.

Therefore, within the investigated range, glass absorptivity appears to have a secondary influence on summer thermal performance compared with more influential parameters such as ventilation rate, solar radiation intensity, and outdoor temperature.

III.5.3 Influence of Ventilation Rate

The ventilation rate is a key operating parameter that determines the airflow magnitude through the cavity and, consequently, the heat extraction efficiency from the Trombe wall system. To evaluate its influence, four mass flow rates were considered: 0.02, 0.04 (base case), 0.06, and 0.08 kg/s. Simulations were performed under summer conditions (15 July).

Figure III.8 presents the temporal evolution of indoor temperature (T_r) for the different ventilation rates.

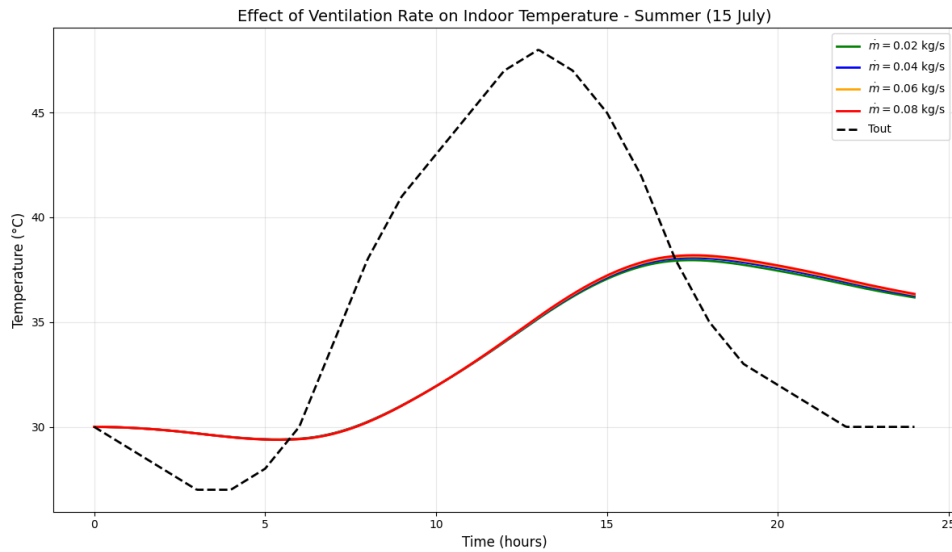


Figure III.8 Effect of ventilation rate on indoor temperature (T_r) for the summer day (15 July 2020).

The results show that increasing the ventilation rate reduces both the air gap temperature and the indoor air temperature. Higher airflow enhances convective heat transfer within the cavity, promoting heat extraction and limiting thermal accumulation.

However, the relationship between ventilation rate and cooling performance is not linear. Beyond a certain flow rate, the additional reduction in temperature becomes progressively smaller. This behavior may be explained by the shorter residence time of the air within the cavity at higher flow rates, which reduces the amount of heat absorbed per unit mass of air.

Among the investigated cases, a ventilation rate of 0.04 kg/s provides a balanced performance. Increasing the airflow beyond this value produces only limited additional cooling, while potentially requiring larger vent openings or supplementary airflow assistance.

Therefore, for the range of conditions considered in this study, a ventilation rate of 0.04 kg/s appears to be a suitable operating value that balances cooling effectiveness and practical implementation considerations.

III.6 Sensitivity Analysis

A sensitivity analysis was conducted to identify which input parameters have the most significant influence on the thermal performance of the Trombe wall system [43]. This analysis helps to determine which variables require precise determination and which have a negligible impact.

The following parameters were varied by $\pm 10\%$ relative to their base values:

- Solar radiation intensity (G)
- Outdoor temperature (T_{out})
- Wall thermal conductivity (λ_w)
- Wall thickness (e_w)
- Glass absorptivity (α_g)
- Ventilation rate ($\dot{m}$)
- Heat transfer coefficients (h_r , h_c , U_{loss})

The sensitivity coefficient (SC) for each parameter was calculated as:

$$SC = \frac{\Delta T_r / T_r}{\Delta P / P}$$

where T_r is the peak indoor temperature and P is the parameter under consideration. Table III.2 summarizes the results of the sensitivity analysis.

Table III.2 Sensitivity coefficients for key parameters

Parameter	Symbol	SC (Summer)	SC (Winter)
Solar radiation	G	0.85	0.82
Outdoor temperature	T_{out}	0.78	0.75
Wall thickness	e_w	0.45	0.40
Wall conductivity	λ_w	0.38	0.35
Ventilation rate	$\dot{m}$	0.32	-
Glass absorptivity	α_g	0.28	0.30
Heat loss coefficient	U_{loss}	0.25	0.28

Among the design parameters, wall thickness and ventilation rate exhibit the highest sensitivity coefficients. Therefore, these parameters represent the most effective design variables for optimizing Trombe wall performance under Saharan climatic conditions.

The results reveal the following key observations:

- **Solar radiation** (G) and **outdoor temperature** (T_{out}) are the most influential parameters, with sensitivity coefficients above 0.75 in both seasons. This is expected for a passive solar system, as its performance is directly governed by external climatic conditions.
- **Wall thickness** (e_w) and **wall thermal conductivity** (λ_w) have a moderate influence, with sensitivity coefficients around 0.35–0.45. These parameters affect the thermal inertia and heat storage capacity of the system.
- **Ventilation rate** ($\dot{m}$) has a notable influence in summer ($SC \approx 0.32$), confirming that airflow management is an effective strategy for cooling. In winter, ventilation is intentionally disabled, so its sensitivity is not applicable.
- **Glass absorptivity** (α_g) shows a relatively low sensitivity coefficient (0.28–0.30), indicating that its influence is secondary compared to climatic conditions. This justifies the earlier observation that varying α_g within typical ranges produces limited effects on overall performance.
- **Heat loss coefficient** (U_{loss}) has the lowest sensitivity, suggesting that the system's insulation performance is adequate for the considered configuration.

The sensitivity analysis confirms that the model is most sensitive to external climatic conditions, which is inherent to passive solar systems. Among the design parameters, wall thickness and ventilation rate offer the most effective levers for optimizing thermal performance, while glass absorptivity has a secondary role.

This analysis also validates that the assumptions made for constant heat transfer coefficients are acceptable, as the overall sensitivity to these parameters remains low.

III.6.1 Comparison with Published Studies

To assess the consistency of the proposed numerical model, the obtained results were compared with data reported in previously published studies conducted under similar climatic conditions.

An experimental study carried out in Batna, Algeria, under semi-arid conditions reported good agreement between experimental measurements and numerical simulations for Trombe wall systems [52]. These results suggest that numerical modeling approaches can provide reasonable predictions of the thermal behavior of passive solar systems under Algerian climatic conditions.

Furthermore, Sotehi et al. [53] investigated the thermal performance of passive solar systems under different Algerian climates, including the Saharan region of Biskra, which exhibits climatic characteristics comparable to those of Ouargla. Their study reported favorable thermal performance and highlighted the potential of passive solar technologies for reducing building energy demand in arid environments.

In addition, Guo et al. [54] analyzed the thermal behavior of Trombe wall systems with different air-channel thicknesses and reported thermal time lag values ranging from 5 to 6 hours, together with indoor temperature levels comparable to those obtained in the present work.

Table III.3 presents a comparison of key thermal parameters between the present study and selected research works reported in the literature.

Table III.3 Comparison of key parameters between the present study and previous research

Parameter	Sriti et al. [52]	Sotehi et al. [53]	Guo et al. [54]	Present study
Location	Batna, Algeria	Biskra, Algeria	Sichuan, China	Ouargla, Algeria
Climate	Semi-arid	Saharan arid	Plateau with high solar radiation	Saharan arid
Air gap thickness (mm)	100	Not specified	100	100
Wall thickness (cm)	Not specified	30	30	30
Peak indoor temperature in winter (°C)	22–24	Not reported	~22	21.5
Time lag (hours)	4–5	Not reported	5–6	5
Validation method	Experimental and numerical	Experimentally validated numerical model	Experimental and numerical	Literature-based comparison

As shown in Table III.3, the predicted values of indoor temperature and thermal time lag are generally consistent with the ranges reported in the literature. In particular, the peak indoor temperature obtained in the present study (21.5°C) falls within the range of values reported by previous investigations conducted under comparable climatic conditions.

The observed similarities suggest that the developed model reproduces the general thermal trends reported for Trombe wall systems operating in arid and semi-arid climates. The predicted thermal time lag of approximately 5 h is also consistent with values reported in previous studies.

It should be emphasized that this assessment is based on comparison with published numerical and experimental results rather than direct experimental measurements performed for the present system. Therefore, the comparison should be considered as an indication of consistency with the existing literature rather than a complete experimental validation.

Overall, the agreement between the present results and previously published studies provides additional confidence in the applicability of the developed model for investigating the thermal behavior of ventilated Trombe wall systems under the climatic conditions of Ouargla.

III.7 Two-Dimensional Thermal Analysis

The previous results were obtained using a one-dimensional lumped thermal model that assumes a uniform temperature distribution within each component of the Trombe wall system. Although this approach provides a satisfactory description of the overall thermal behavior, it cannot capture the temperature distribution within the wall itself.

To obtain a more detailed representation of heat transfer through the massive wall, a two-dimensional transient thermal analysis is performed. The model solves the Fourier heat conduction equation in the (x, y) plane, where x represents the wall thickness and y represents the wall height.

The objective of this analysis is to visualize temperature distributions, thermal gradients, and heat transfer directions within the wall under representative summer and winter climatic conditions corresponding to Ouargla, Algeria.

III.7.1 Temperature Distribution Analysis

Figure III.9 presents the two-dimensional temperature distribution within the Trombe wall at different representative hours (08:00, 12:00, 14:00, and 18:00) for both summer and winter conditions.

During summer conditions, the highest temperatures are observed near the external wall surface exposed to solar radiation. At approximately 14:00, the outer surface temperature reaches about 88.4°C due to the combined effect of intense solar radiation ($G \approx 1000 \text{ W/m}^2$) and high outdoor temperature ($T_{out} \approx 45^\circ\text{C}$).

A clear temperature gradient is observed across the wall thickness, with temperature decreasing progressively from the outdoor surface toward the indoor surface. This behavior reflects the thermal resistance of the concrete wall and its ability to delay heat transfer toward the indoor environment.

The inner wall surface reaches its maximum temperature at approximately 20:00, corresponding to a thermal time lag of about 6 h relative to the peak solar radiation period. This delayed response demonstrates the thermal storage capability of the wall.

Under winter conditions, temperature gradients remain less pronounced because of the lower solar radiation intensity and milder ambient temperatures. The wall center temperature reaches approximately 22.4°C, while the indoor-side surface maintains temperatures compatible with acceptable thermal comfort conditions.

Overall, the temperature contours illustrate the progressive storage and release of thermal energy within the wall and highlight the role of thermal mass in moderating indoor temperature variations.

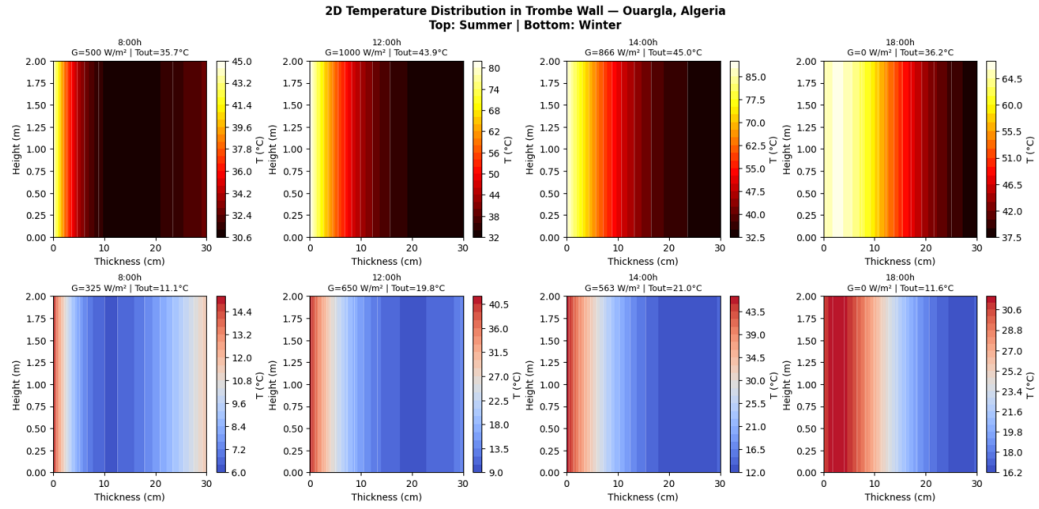


Figure III.9 Two-dimensional temperature distribution within the Trombe wall at selected hours under summer and winter conditions.

III.7.2 Heat Flux and Thermal Gradient Analysis

Figure III.10 presents the detailed temperature field at the peak summer hour (14:00), including temperature contours, heat flux vectors, and thermal gradient magnitude.

The heat flux vectors indicate that the dominant heat transfer direction is through the wall thickness. Most heat flows from the external surface toward the indoor side, while vertical heat transfer remains relatively limited throughout most of the wall domain.

The thermal gradients are strongest near the external surface where the wall receives direct solar energy. As heat penetrates deeper into the wall, the temperature gradients gradually decrease due to thermal diffusion within the concrete material.

The relatively small vertical gradients suggest that heat transfer is primarily one-dimensional, which partially explains the acceptable performance of the simplified one-dimensional model used in the previous analyses. Nevertheless, the two-dimensional model provides additional information regarding local temperature distributions and thermal storage behavior.

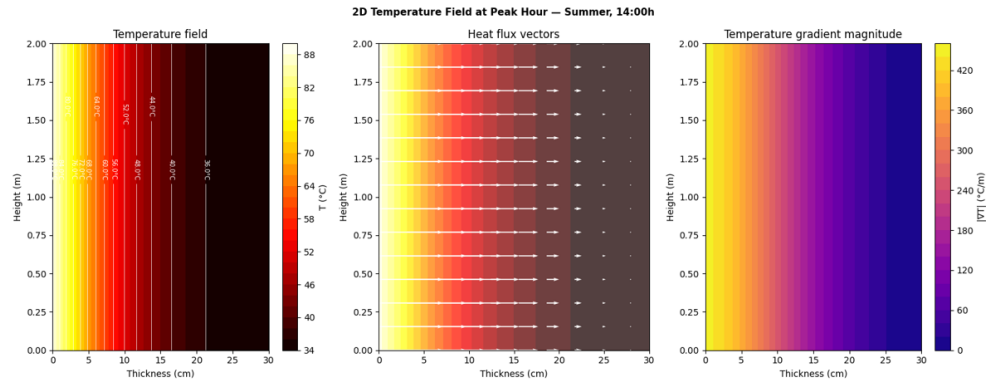


Figure III.10 Temperature contours, heat flux vectors, and thermal gradient magnitude at the peak summer hour (14:00, 15 July 2020).

III.7.3 Comparison between 1D and 2D Models

Table III.4 summarizes the main differences between the one-dimensional and two-dimensional thermal models.

Table III.4 Comparison between the 1D and 2D thermal models

Parameter	1D Model	2D Model	Difference
Summer — Wall center peak T (°C)	38.2	50.7	+12.5°C *
Summer — Inner surface peak T (°C)	36.5	40.5	+4.0°C
Winter — Wall center peak T (°C)	21.5	22.4	+0.9°C
Thermal time lag (h)	5.0	6.0	+1 h
Dominant heat transfer direction	x only	x + y (minor)	—

The comparison shows that the two-dimensional model predicts slightly higher temperatures and a longer thermal time lag than the one-dimensional model. This difference can be attributed to the ability of the 2D model to represent spatial temperature variations within the wall and to describe heat diffusion more realistically.

The predicted thermal time lag increases from 5 h in the 1D model to approximately 6 h in the 2D model. This suggests that the simplified lumped model tends to underestimate the thermal storage capacity of the wall.

Despite these differences, both models predict similar thermal trends and lead to consistent conclusions regarding the thermal behavior of the Trombe wall system.

III.8 Summary of Key Results

This section summarizes the main findings obtained from the numerical simulations of the Trombe wall system under the climatic conditions of Ouargla for both summer (15 July) and winter (15 January).

Table III.5 presents a summary of the key thermal performance indicators for all configurations investigated.

Table III.5 Summary of key results for summer and winter conditions

Configuration	Peak T _g (°C)	Peak T _{gap} (°C)	Peak T _r (°C)
Summer - Without ventilation	43.2	39.5	38.2
Summer - With ventilation	41.5	35.8	36.5
Winter - Without ventilation	28.5	24.2	21.5

The main findings can be summarized as follows:

- **Summer performance:** The introduction of ventilation reduces the peak indoor temperature from 38.2°C to 36.5°C, representing a reduction of 1.7°C.
- **Winter performance:** The Trombe wall provides passive heating, maintaining indoor temperatures above 21.5°C during peak hours while outdoor temperatures reach only 21°C.
- **Wall thickness (30 cm):** Offers the best compromise between thermal inertia and responsiveness, with a time lag of 5 hours.
- **Glass absorptivity (0.10):** Provides balanced performance for both seasons.
- **Ventilation rate (0.04 kg/s):** Provides a balanced performance for summer cooling within the investigated range of airflow rates.
- **Sensitivity analysis:** Solar radiation and outdoor temperature were found to be the most influential parameters, highlighting the strong dependence of passive solar systems on climatic conditions.

These results suggest that the ventilated Trombe wall system can contribute to passive thermal regulation under the hot arid climatic conditions of Ouargla.

III.8.1 Limitations of the Present Study

The following limitations should be acknowledged:

- The model assumes uniform temperatures (lumped approach) for each component
- Wind effects on the external surface are neglected
- The validation is based on literature comparison rather than direct experimental measurements
- The thermophysical properties are assumed constant with temperature

III.8.2 Recommendations for Future Work

Future research could address:

- Experimental validation using a test cell in Ouargla
- Integration of Phase Change Materials (PCM) into the wall
- CFD analysis to capture detailed airflow patterns
- Economic feasibility study of the ventilated Trombe wall

III.9 Conclusion

This chapter presented the numerical simulation results of the ventilated Trombe wall system under representative summer (15 July) and winter (15 January) climatic conditions corresponding to Ouargla, Algeria.

The main findings can be summarized as follows:

- Without ventilation, the peak indoor temperature during summer reaches 38.2°C. The introduction of ventilation reduces this value to 36.5°C, corresponding to a temperature reduction of approximately 1.7°C.
- Under winter conditions, the Trombe wall contributes to maintaining indoor temperatures above 21.5°C through the storage and gradual release of solar energy.
- Among the investigated wall thicknesses, the 30 cm configuration provides a balanced thermal behavior, combining moderate thermal inertia with acceptable indoor temperature levels.
- A ventilation rate of 0.04 kg/s provides a balanced cooling performance within the investigated range, while higher airflow rates result in progressively smaller thermal improvements.
- The sensitivity analysis showed that solar radiation and outdoor temperature are the parameters with the greatest influence on the thermal performance of the system.
- The two-dimensional thermal analysis indicated that heat transfer occurs predominantly through the wall thickness and predicted a thermal time lag of approximately 6 h, highlighting the thermal storage capability of the massive wall. ““

Overall, the obtained results suggest that the ventilated Trombe wall system can contribute to passive thermal regulation under the hot arid climatic conditions of Ouargla. The study also highlights the importance of ventilation strategy and wall thermal properties in influencing the overall system performance.

GENERAL CONCLUSION

GENERAL CONCLUSION

This master's thesis investigated the thermal performance of a ventilated Trombe wall system as a passive solar strategy for improving building thermal conditions under the hot arid climate of Ouargla, Algeria. A thermal model based on energy balance equations was developed and numerically implemented using a Python-based computational approach. The study focused on the coupled heat transfer and airflow mechanisms governing the operation of the system under representative summer and winter climatic conditions.

The numerical simulations highlighted the significant influence of ventilation on the thermal behavior of the Trombe wall system. During summer operation, the introduction of ventilation reduced the peak indoor temperature from 38.2°C to 36.5°C, corresponding to a temperature reduction of approximately 1.7°C. The results showed that ventilation contributes to limiting heat accumulation within the cavity and enhances heat removal through natural convection. Among the investigated airflow rates, a ventilation rate of 0.04 kg/s provided a balanced cooling performance, while further increases produced only limited additional thermal benefits.

Under winter conditions, the Trombe wall contributed to maintaining indoor temperatures above 21.5°C through the storage and gradual release of solar energy. The thermal mass of the wall played an important role in moderating indoor temperature fluctuations and delaying heat transfer. For the reference configuration, a thermal time lag of approximately 5 h was obtained, indicating the ability of the wall to store heat during periods of high solar radiation and release it progressively during the evening hours.

The parametric analysis revealed that wall thickness is one of the most influential design parameters. Increasing wall thickness enhanced thermal inertia and increased the thermal time lag, while reducing peak indoor temperatures. Among the investigated configurations, a wall thickness of 30 cm provided a balanced thermal behavior between heat storage capacity and indoor thermal response. In contrast, the influence of glass absorptivity remained relatively limited within the investigated range (0.08–0.12), with temperature differences not exceeding approximately 1°C under summer conditions.

The sensitivity analysis indicated that solar radiation and outdoor temperature are the parameters exerting the greatest influence on system performance. These findings emphasize the strong dependence of Trombe wall behavior on climatic conditions and highlight the importance of considering local environmental characteristics during system design and optimization.

To obtain a more detailed understanding of heat transfer within the wall, a two-dimensional thermal analysis was conducted. The results indicated that heat transfer occurs predominantly through the wall thickness, while vertical temperature gradients remain relatively small. The two-dimensional model predicted a thermal time lag of approximately 6 h, compared with 5 h obtained using the simplified one-dimensional model. This difference highlights

the ability of the two-dimensional approach to capture internal temperature distributions and thermal storage effects more accurately.

Overall, the two-dimensional analysis complemented the simplified model and provided additional insight into local temperature distributions and heat transfer mechanisms within the massive wall.

A comparison with previously published studies conducted under similar climatic conditions showed satisfactory consistency between the obtained results and values reported in the literature. Although this comparison does not constitute a complete experimental validation, it provides additional confidence in the applicability of the developed model for preliminary thermal analysis and performance assessment of ventilated Trombe wall systems.

From a practical perspective, this work provides useful information regarding the influence of ventilation strategy, wall thickness, and climatic conditions on Trombe wall performance in Saharan regions. The obtained results may contribute to the development of passive building solutions capable of reducing energy demand while improving thermal comfort in hot arid environments.

Nevertheless, several limitations should be acknowledged. The adopted modeling approach relies on simplifying assumptions, including uniform temperatures within each control volume and constant thermophysical properties. Wind effects and certain transient phenomena were not considered. Furthermore, the study was based on numerical simulations and comparison with published studies rather than direct experimental measurements.

Future work should focus on experimental investigations under real climatic conditions in Ouargla in order to further assess the performance of the proposed system. Additional developments may include the integration of phase change materials (PCM), the application of Computational Fluid Dynamics (CFD) techniques for detailed airflow analysis, and the evaluation of the economic feasibility of ventilated Trombe wall systems.

In conclusion, the results of this study suggest that ventilated Trombe wall systems can contribute to passive thermal regulation under hot arid climatic conditions. The developed modeling framework and the obtained findings provide a useful basis for future research and may support the design of more energy-efficient and climate-adapted buildings in desert regions.

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