OPTIMIZATION OF THERMAL COMFORT IN BUILDINGS *VIA* ANALYSIS OF A TROMBE WALL FOR ENHANCED ENERGY EFFICIENCY

by

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This study investigates heat transfer phenomena in a building envelope in Bechar, Southwest Algeria, under arid climatic conditions. The meteorological station Energarid provides precise recordings of solar radiation and outdoor temperature. A calibrated model is used to analyze diurnal temperature variations. Wall temperatures exposed to solar radiation are estimated using recorded data. The heating power requirements of the building envelope are determined through a thermal balance approach based on the regulatory technical document from the National Center for Building Studies and Integrated Research. Simulation results demonstrate favorable conditions for achieving thermal comfort, with elevated air temperatures and velocities at the outlet. Incorporating solar energy considerations into architectural design, such as double facades, south-facing orientations, and glazed surfaces, is crucial. These findings highlight significant energy-saving potential, particularly in the Bechar region.

Key words: *heat transfer, building envelope, arid climate, thermal comfort, solar energy*

Introduction

Algeria, renowned for its arid climate and abundant fossil fuel reserves, is currently confronting the implications of climate change and the imperative to curtail GHG emissions. Consequently, there has been a surge in attention towards the adoption of RES in order to tackle these exigencies. This scientific exploration focuses on Algeria renewable energy sec-

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tor, with a particular emphasis on the arid climate of the southern region, the residential sector electric consumption, and the role of Trombe walls in mitigating CO_2 emissions [1-3].

The arid climate of Algeria presents distinctive challenges in relation to the extensive deployment of RES. The scarcity of rainfall and high temperatures make conventional agricultural practices and water-intensive energy production methods impractical. However, the country vast potential for solar and wind energy offers promising solutions. By harnessing these renewable resources, Algeria can reduce its dependency on fossil fuels and contribute to global efforts in combating climate change [4-6].

Within the residential sector, electric consumption is a significant contributor to overall energy demand in Algeria. The rising population and increasing urbanization have led to an upward trend in energy consumption for households. This surge in demand, primarily fueled by conventional energy sources, has resulted in higher CO_2 emissions. The adoption of renewable energy technologies, such as solar panels and wind turbines, has the potential to alleviate pressure on the electricity grid and mitigate the ecological impact associated with conventional energy generation approaches [7-9].

The CO_2 emissions arising from the combustion of fossil fuels have been identified as a primary cause of climate change. In the Algerian context, the reliance on fuel for electricity production exacerbates the emission levels. However, one promising technology that has garnered considerable interest is the Trombe wall. Originally developed in the 1960's by engineer Felix Trombe, this passive solar heating system has been effectively employed in numerous countries with the objective of curbing energy usage and mitigating CO_2 emissions in residential settings [10-12].

The Trombe wall operates by capturing and storing solar energy during the day, which is then gradually released into the interior space during colder periods. Its construction typically consists of a dark-colored, heat-absorbing surface placed behind a transparent glazing layer. This design allows sunlight to pass through the glazing and heat the surface, which then radiates the stored heat indoors. The Trombe wall ability to regulate indoor temperatures without the need for active mechanical systems makes it an attractive solution for reducing energy consumption and reliance on fossil fuels [13-15].

Recent advancements in Trombe wall technology have further enhanced its efficiency and applicability. Researchers have explored novel materials and designs to optimize heat transfer, insulation properties, and overall performance. Additionally, the integration of Trombe walls with complementary sustainable technologies has exhibited synergistic effects, contributing to the reduction of energy consumption and the optimization of renewable resource utilization [16-19].

Ongoing research and development efforts in the field of Trombe walls have aimed to address specific challenges, such as optimizing the system for different climatic conditions, improving thermal storage capabilities, and enhancing overall integration with existing building structures. These advancements highlight the continued relevance and potential of Trombe walls as a sustainable solution for the residential sector, fig. 1.

In conclusion, Algeria endeavor to embrace RES plays a critical role in addressing the challenges associated with climate change and diminishing CO_2 emissions. The unique arid climate in southern Algeria, along with substantial electricity consumption within the residential sector and the constraints imposed by fossil fuel dependence, necessitates the adoption of innovative and sustainable approaches. The Trombe wall, with its long-standing history and evolving technology, offers a promising solution to harness solar energy efficiently, reduce energy consumption, and contribute to a greener future for Algeria.

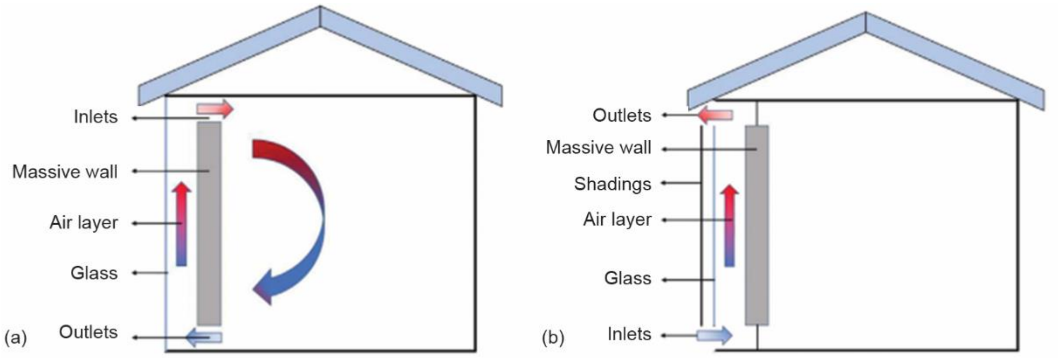

Figure 1. The ventilation strategy employed by the Trombe wall under (a) winter and (b) summer conditions [19]

In our preceding investigation, Bensafi *et al.* [20], our primary objective was to enhance our comprehension of the heat transfer mechanisms occurring through the exterior wall of a residential structure when subjected to solar flux. Building upon these findings, the present study endeavors to advance our understanding by analyzing real-world scenarios, specifically focusing on actual solar radiation levels and outside temperatures during the winter season. To accomplish this, we have developed a code capable of conducting a comprehensive analysis of the heat transfer process. By incorporating measured values of temperature and solar radiation, we have employed interpolation techniques to establish an equivalent temperature function for the exterior walls. This function serves as a practical representation of the thermal behavior exhibited by the walls under the specific prevailing conditions. Through our continued investigation under authentic conditions, our research aims to gain valuable insights into the effectiveness and performance of passive heating systems. By expanding our understanding in this area, we contribute to the development and optimization of energy-efficient solutions for residential buildings, thereby ensuring enhanced thermal comfort and reduced energy consumption.

System description: A comprehensive overview

Consider a flat glazed wall positioned directly facing south, constructed from a homogeneous and isotropic material, namely glass. The dimensions of the wall are such that its lateral extents significantly exceed its thickness, fig. 2.

This glazed wall experiences a winter solar flux, fig. 3, and is concurrently impacted by an external temperature that has been experimentally measured, fig. 4.

The transmittance of the solar flux through the glazing, as represented by the function shown in fig. 5, is directed towards a vertical wall that also faces south. This vertical wall consists of a homogeneous and isotropic material, specifically granite.

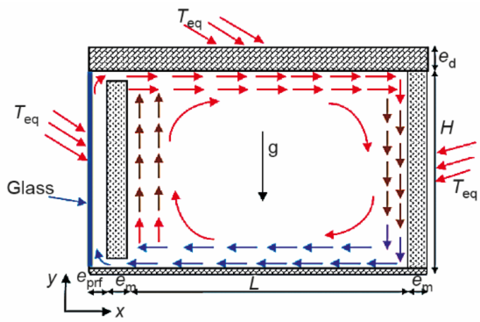

Figure 2. Examined physical model

The right and upper walls are both subject to solar radiation and are influenced by the external temperature variations. On the other hand, the lower floor is thermally insulated, effectively preventing energy exchange with the external environment (termed adiabatic).

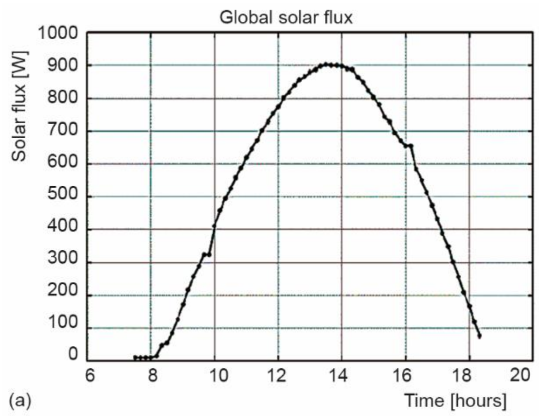

Figure 3. Winter solar flux incident on the glazed wall

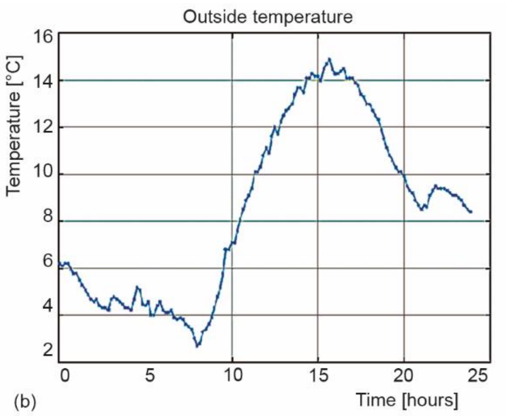

Figure 4. Experimental measurement of external temperature impact on the glazed wall

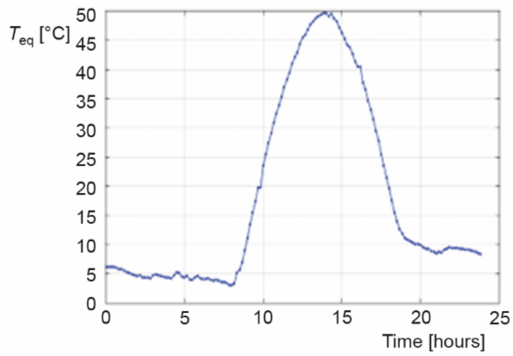

Figure 5. Equivalent temperature profile

Digital simulation: Computational modeling and analysis

The governing equations can be mathematically represented as follows:

– Continuity:

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{1}$$

– Momentum:

$$\rho\left[\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j}\right] = -\frac{\partial P}{\partial x_i} + \frac{\partial}{x_j}\left(\mu \frac{\partial u_i}{\partial x_j}\right) + F_i \tag{2}$$

– Energy:

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p u_j \frac{\partial T}{\partial x_j} = \frac{\partial}{\partial x_i}\left(\lambda \frac{\partial T}{\partial x_i}\right) \tag{3}$$

– The boundary condition:

The global solar flux $(x = e_{prf}, y = H - e_d)$:

$$G_s(i = 90°) \tag{4}$$

The equivalent temperature $(x = 0, y = H - e_d)$:

$$T_{eq} = T_{ex} + A\frac{G_s}{h_e} \tag{5}$$

The outdoor temperature is depicted in fig. 4. Through the application of polynomial interpolation, the equation describing the temperature at the end of the introduction to the boundary conditions has been derived.

$$T_{ex} = -0.0080t^3 + 0.25935t^2 - 1.7251t + 6.9712 \tag{6}$$

$$x = 0, \quad y = 0 \Rightarrow \frac{\partial T}{\partial y} = 0 \tag{7}$$

$$x = e_{prf} + e_m + L + e_m, \quad y = H \Rightarrow T_{eq}[G_s(t), \quad i = 0°, \quad \gamma = 0°] \tag{8}$$

$$x = e_m, \quad y = H - 2 \times e_m \Rightarrow T_{eq} \tag{9}$$

$$T_{eq} = 0.0042t^4 - 0.2230t^3 + 3.6569t^2 - 1.77035t + 21.7617 \tag{10}$$

$$x = e_{prf} + e_m + L + e_m, \quad y = H - e_d \Rightarrow T_{eq}[G_s(t); i = 0°; \gamma = 0°] \tag{11}$$

Findings and discussions

Analysis of the simulation results reveals several noteworthy observations pertaining to the performance of the Trombe wall. Firstly, in accordance with the Technical and Regulatory Document (DTR), the external temperature aligns with the baseline outdoor temperature. As a result, at time t = 0, the indoor temperature remains constant at 15 °C. However, after one hour of simulation, distinct thermal stratification becomes apparent.

Within the simulated space, the lower region exhibits a temperature of 4.4 °C, indicating the presence of colder air. Conversely, near the upper section, the temperature rises to 14 °C, resulting in a noticeable 31.43% disparity between the two levels. This disparity in temperature distribution underscores the establishment of a stratified thermal profile within the space.

An intriguing observation is the existence of relatively lower temperatures, ranging from 1-3 °C, in the space between the Trombe wall and the glazing. This phenomenon can be attributed to convective heat transfer occurring in this region, where heat is efficiently absorbed and stored within the wall. The resulting natural convection within the space facilitates temperature stratification, contributing to the observed thermal distribution, figs. 6(a) and 6(b).

Taken together, these findings offer valuable insights into the behavior of the simulated Trombe wall system, emphasizing the significant influence of natural convective processes on temperature stratification within the space. During noon, when the sun is positioned at a high angle in the sky and the outdoor temperature reaches its maximum, our simulation reveals significant thermal impacts on both the exterior walls and the indoor environment.

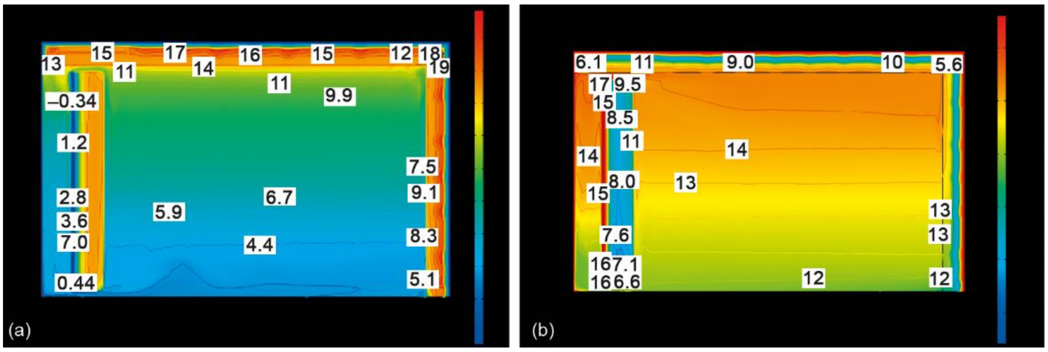

Figure 6. The indoor isotherm at two distinct time points; (a) 02:00 h and (b) 08:00 h

The Trombe wall system exhibits efficient absorption and storage of thermal energy as solar radiation penetrates the glazing. Consequently, there is a notable increase in the indoor temperature, ranging from 22 °C to 24 °C.

Furthermore, the direct exposure of the Trombe wall to solar radiation induces heating, particularly in the section facing the glazing. This localized heating effect contributes to the overall dynamics of heat transfer within the simulated space, fig. 7. These findings underscore the efficacy of harnessing solar energy through the Trombe wall, leading to enhanced thermal conditions within the building. The gradual storage and release of heat by the system contribute to the maintenance of a comfortable indoor environment, even under conditions of heightened solar intensity.

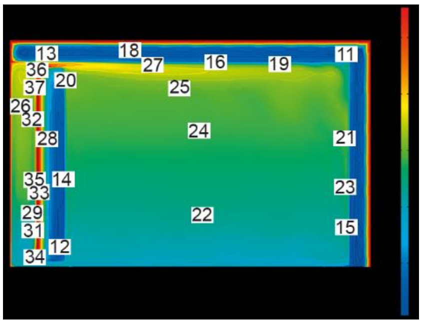

Figure 7. The indoor isotherm at 12:00 h

Figure 8 provides a detailed representation of the velocity distribution within the simulated space, illustrating the evolution of air-flow in relation to height. Notably, three distinct regions can be discerned, each possessing distinct characteristics and contributing to the overall patterns of air movement. The first region, located at the highest section of the room, corresponds to the region where hot air is expelled. This area is characterized by elevated velocities, signifying the upward displacement of heated air as a result of thermal buoyancy.

In contrast, the second region, located in the lower section of the room, corresponds to the area where cold air is drawn in. In this region, the velocities are comparatively higher than the surrounding areas, indicating the intake of cooler air. The third region, situated between the zone of hot air expulsion and the cold air intake zone, exhibits the presence of thermal stratification. Within this region, the influence of volume forces contributes to the formation of distinct air-flow patterns. Significantly, the velocities observed in this zone are noticeably lower, reflecting the effects of thermal stratification and the suppression of convective motion. These observations offer valuable insights into the complex air-flow dynamics within the simulated space, revealing the zones of heat exchange, air mass circulation, and the influence of volume forces on the overall velocity distribution.

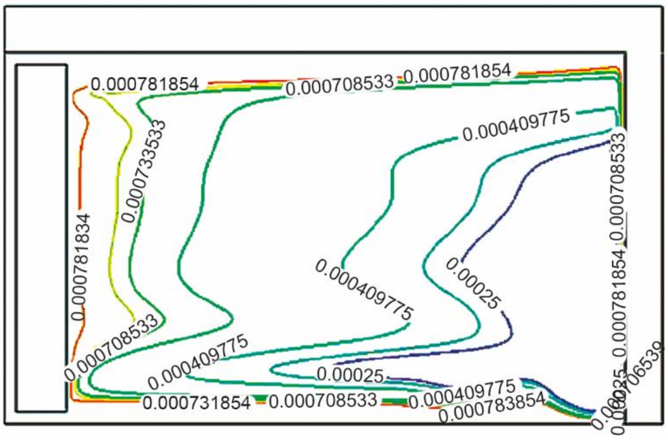

Figure 8. Spatial distribution of air inlet and outlet velocities within the enclosure

Figure 9 illustrates the temporal evolution of temperature in various regions between 8:00 a. m. and 2:00 p. m. Within the Trombe wall, the upper part exhibits a higher temperature profile, represented by the green line, in contrast to the lower part indicated by the red line. Moreover, the blue line depicts the overall average temperature variation across the entire location.

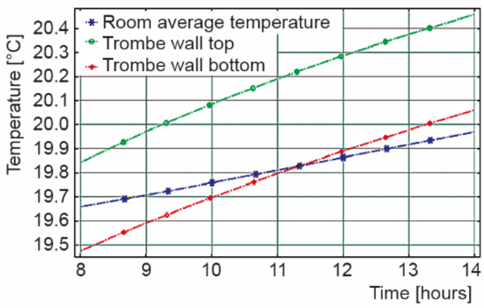

Figure 9. Temporal evolution of temperature from 8:00 a. m. to 2:00 p. m.

The temperature trends observed in fig. 9 unveil distinct thermal characteristics within different sections of the Trombe wall. The upper part experiences a significant increase in temperature, indicative of efficient heat absorption and retention. In contrast, the lower part displays a relatively lower temperature profile, suggesting heat dissipation and potential cooling effects. The average temperature variation, represented by the blue line, provides a comprehensive overview of the overall thermal dynamics experienced within the investigated location. These findings highlight significant temperature discrepancies across different regions of the Trombe wall, emphasizing the importance of careful monitoring and understanding of temperature distribution for effective heat management and energy optimization.

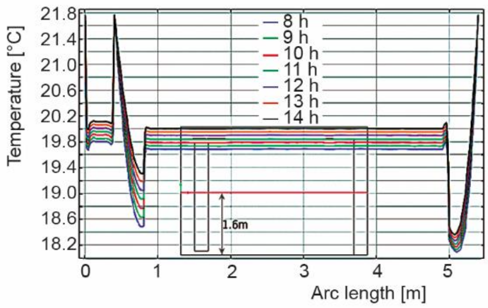

Figure 10. Temperature stratification along the red line from 8:00 a. m. to 2:00 p. m.

Figure 10 depicts the horizontal distribution of temperature at a height of 1.6 m above the floor, specifically highlighting the temperature changes between 8:00 a. m. and

2:00 p. m. These observations yield valuable insights into temperature stratification and the resulting thermal conditions within the investigated location.

The graph reveals a relatively minor variation in temperature along the horizontal axis, indicating a stable thermal environment. This uniform distribution of temperature implies a comfortable living situation for occupants within the space. The limited temperature fluctuations across the studied location signify a favorable thermal equilibrium, promoting a pleasant and consistent thermal experience for human habitation.

These findings emphasize the effectiveness of the Trombe wall system in maintaining a balanced temperature profile, contributing to improved comfort and livability within the simulated space. The ability to achieve temperature stability and minimize variations at a specific height above the floor highlights the potential advantages of incorporating such passive heating strategies in architectural design to create comfortable and energy-efficient living environments.

Future studies for optimizing thermal comfort in buildings via computational modeling of a Trombe wall passive heating system could include the following:

Experimental validation. Conducting field studies and experiments to validate the accuracy and performance of the computational models developed for the Trombe wall system. This would involve monitoring and analyzing real-world data from buildings equipped with Trombe walls to compare against the predictions of the computational models.

Optimization of design parameters. Investigating the impact of various design parameters on the performance of the Trombe wall system. This could include studying the effect of wall thickness, glazing materials, air gap size, absorber plate properties, and venting strategies on thermal comfort and energy efficiency. Optimization techniques such as GA or machine learning algorithms could be employed to identify the optimal design configurations.

Climate adaptation. Assessing the operational efficacy of the Trombe wall system across various climatic conditions and investigating potential modifications or adaptations to enhance its effectiveness in diverse environments. This could involve studying the system performance in extreme climates (*e.g.*, hot arid, cold arctic, and humid tropical) and developing climate-specific design guidelines for Trombe walls.

Integration with other passive strategies. Investigating the synergistic benefits of integrating the Trombe wall system with other passive heating and cooling strategies, such as natural ventilation, thermal mass, and solar shading. Assessing the combined effect of these strategies on thermal comfort, energy efficiency, and indoor air quality could provide valuable insights for designing holistic and optimized building envelopes.

Dynamic simulation and control. Developing dynamic simulation models that can accurately predict the transient behavior of the Trombe wall system under changing external and internal conditions. This could involve incorporating weather forecast data, occupancy patterns, and indoor heat gains/losses into the models to optimize control strategies, such as adaptive venting or PCM, to maintain optimal thermal comfort throughout the day and across seasons.

Economic and life cycle analysis. Conducting cost-benefit analyses and life cycle assessments to evaluate the economic viability and environmental sustainability of implementing Trombe wall systems in different building types and locations. Assessing factors such as initial costs, energy savings, maintenance requirements, and embodied energy would help decision-makers determine the long-term feasibility and benefits of adopting this passive heating technology.

Occupant comfort and perception studies. Conducting occupant surveys, questionnaires, and subjective evaluations to assess the perceived comfort levels and user acceptance of buildings equipped with Trombe wall systems. Understanding occupants comfort preferences, satisfaction, and behavior patterns would provide valuable feedback for refining the design and operation of the system to enhance occupant well-being.

Integration with active systems. Exploring the integration of Trombe wall systems with active heating, cooling, and renewable energy systems to develop hybrid solutions that optimize energy performance while maintaining thermal comfort. This could involve investigating strategies such as coupling the Trombe wall with solar photovoltaics, heat pumps, or geothermal systems to achieve a balance between passive and active energy management in buildings.

Retrofitting existing buildings. Developing guidelines and strategies for retrofitting existing buildings with Trombe walls to improve their thermal performance and energy efficiency. Assessing the challenges and opportunities of implementing passive heating systems in retrofit projects would be crucial for promoting sustainable building practices and reducing the environmental impact of the existing building stock.

Advanced materials and technologies. Investigating new materials, coatings, and technologies that can enhance the thermal efficiency and performance of Trombe walls. Researching emerging technologies such as smart glazing, transparent insulation materials, or phase-change materials integrated into the Trombe wall system could lead to significant advancements in optimizing thermal comfort and energy conservation in buildings.

These future studies would contribute to a deeper understanding of the Trombe wall system potential, leading to improved design guidelines, optimized control strategies, and enhanced energy efficiency in buildings

Conclusions

The simulations conducted in this study yield the following.

The thermal conditions at the upper apertures (representing areas of elevated temperature) exhibit a strong dependence on solar flux. The simulation results demonstrate relatively high air temperature and velocity at the outlet, which is conducive to optimal thermal comfort. The utilization of solar energy entails harnessing direct solar radiation, necessitating its careful integration into architectural design considerations (*e.g.*, double facades, south-facing orientation, glazed surfaces, *etc*.). The findings obtained for the Bechar region demonstrate encouraging potential for achieving energy savings.

The correlation between solar flux and temperature at the upper openings underscores the significance of solar energy utilization. The simulation outcomes indicate favorable conditions for achieving desirable thermal comfort, characterized by elevated air temperatures and velocities at the outlet. Therefore, incorporating solar energy considerations into architectural design, such as the incorporation of double facades, south-facing orientations, and glazed surfaces, becomes imperative. These findings, particularly when applied to the Bechar region, provide compelling evidence of substantial opportunities for energy savings.

References

[1] Bouraiou, A., *et al.*, Status of Renewable Energy Potential and UTILIZATION in Algeria, *Journal of Cleaner Production*, *246* (2020), Feb., pp. 119011

[2] Himri, Y., *et al.*, Review and Use of the Algerian Renewable Energy for Sustainable Development, *Renewable and sustainable energy reviews*, *13* (2009), 6-7, pp. 1584-1591

[3] Stambouli, A. B., Promotion of Renewable Energies in Algeria: Strategies and Perspectives, *Renewable and sustainable energy reviews*, *15* (2011), 2, pp. 1169-1181

[4] Boudalia, S., *et al.*, The Exploration and Exploitation of Shale Gas in Algeria: Surveying key Developments in the Context of Climate Uncertainty, *The Extractive Industries and Society*, *11* (2022), Sept., pp. 101115

[5] Aissa, R. B., Boutoutaou, D., Characterization of Groundwater in Arid Zones (Case of Ouargla Basin), *Energy Procedia*, *119* (2017), July, pp. 556-564

[6] Saheb Koussa, D., Koussa, M., GHGs (Greenhouse Gases) Emission and Economic Analysis of a GCRES (Grid-Connected Renewable Energy System) in the Arid Region, Algeria, *Energy*, *102* (2016), May, pp. 216-230

[7] Cai, Q., *et al.*, Promoting Wind and Photovoltaics Renewable Energy Integration Through Demand Response: Dynamic Pricing Mechanism Design and Economic Analysis for Smart Residential Communities, *Energy Part B*, *261* (2022), Dec., 125293

[8] Pallonetto, F., *et al.*, On the Assessment and Control Optimisation of Demand Response Programs in Residential Buildings, *Renewable and Sustainable Energy Reviews*, *127* (2020), July, 109861

[9] Yan-Ping, F., *et al.*, Energy-Efficiency Supervision Systems for Energy Management in Large Public Buildings: Necessary Choice for China, *Energy Policy*, *37* (2009), 6, pp. 2060-2065

[10] Krantz, G., *et al.*, Indirect CO_2 Emissions Caused by the Fuel Demand Switch in International Shipping, *Transportation Research Part D: Transport and Environment*, *102* (2022), Jan., 103164

[11] Yao, Y., *et al.*, Analysis of Energy, Exergy and CO_2 emissions in a fiberglass furnace with oxy-fuel combustion, *Fuel*, *348* (2023), Sept., pp. 128484

[12] Meng, H., *et al.*, Research on the behavior of CO_2 on Hydrogen-Fueled Wankel Rotary Engine Performance, *Fuel*, *335* (2023), Mar., 127036

[13] Sergei, K., *et al.*, A Review of the Current Work Potential of a Trombe Wall, *Renewable and Sustainable Energy Reviews*, *130* (2020), Sept., 109947

[14] Hsieh, S. S., Tsai, J. T., Transient Response of the Trombe Wall Temperature Distribution Applicable to Passive Solar Heating Systems, *Energy conversion and management*, *28* (1988), 1, pp. 21-25

[15] Wu, S. Y., *et al.*, Experimental Investigation on the Impact of Fin Structure Factors on the Finned-Trombe Wall Thermal Performance, *Journal of Building Engineering*, *70* (2023), July, 106402

[16] Bevilacqua, P., *et al.*, Summer and Winter Performance of an Innovative Concept of Trombe Wall for Residential Buildings, *Energy*, *258* (2022), Nov., 124798

[17] Pourghorban, A., Asoodeh, H., The Impacts of Advanced Glazing Units on Annual Performance of the Trombe Wall Systems in Cold Climates, *Sustainable Energy Technologies and Assessments*, *51* (2022), June, 101983

[18] Liu, H., *et al.*, The Performance Analysis of a High-Efficiency Dual-Channel Trombe Wall in Winter. *Energy*, *253* (2022), Aug., 124087

[19] Li, J., *et al.*, Thermal Comfort in a Building with Trombe Wall Integrated with Phase Change Materials in Hot Summer and Cold Winter Region Without Air Conditioning, *Energy and Built Environment*, Online first, https://doi.org/10.1016/j.enbenv.2022.07.007, 2022

[20] Bensafi, M., *et al.*, Modeling the Energy Effect of a Passive Heating System Provided with a Trombe Wall, *Int. J. Eng. Sci. Invent.*, *3* (2014), 7, pp. 66-71

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