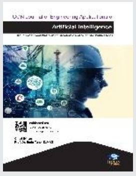

ICON Journal of Engineering Applications of Artificial Intelligence
Volume 01 | Issue 01 | 2025
e-ISSN: 3051-3820
p-ISSN: 3051-3812
Journal homepage: https://iconpublishers.com/icon-j-eng-app-ai/

DOI: 10.5281/zenodo.15857811

Research Article

A Numerical Investigation on the Effect of Enhanced Convection to Improve the Performance of a Photovoltaic-Trombe Wall System

Iman Shemshadi *
M.Sc., Department of Mechanical Engineering, Payame Noor University, Tehran, Iran.

Corresponding author: Iman Shemshadi
M.Sc., Department of Mechanical Engineering, Payame Noor University, Tehran, Iran

Received Date: 05 June 2025
Published Date: 11 July 2025

Abstract

Trombe-photovoltaic wall is one of the most efficient and simple methods of providing house heating today. Usually, hot air enters the interior through an opening and causes the environment to heat up. In this study, a fan was used to create enhanced convection and better heat transfer in the Photovoltaic-Trombe wall. The environmental conditions are such that the temperature and solar radiation are stable and with little change. This study was conducted numerically and proportionally to the city of Tehran and on a cold autumn day. Examining the results in two forced and free circulation modes showed that using a fan, in addition to increasing the heat transferred to the room, also leads to improved solar panel performance. Also, during peak hours of sunlight radiation, when the panel temperature increases and its efficiency decreases, using a fan will increase the panel efficiency by about 0.5 percents and the power output by about 40 Watts due to the cooling action on the panel surface. The results indicate that the Photovoltaic-Trombe wall in Tehran can be a sustainable and suitable solution for generating heat in buildings.

Keywords: Heat Transfer, Building Heating, Thermal Convection, Photovoltaic-Trombe Wall.

1. INTRODUCTION

Trombe walls are a passive solar heating technology widely used in energy-efficient building design. Developed in the 1960s by Félix Trombe, these walls capitalize on the greenhouse effect by absorbing solar radiation through a glass-paneled façade and storing heat in a thermal mass, which is released gradually to the interior of the building. In recent decades, research into Trombe walls has expanded to include variations incorporating photovoltaic (PV) panels and phase change materials (PCM) to enhance both their thermal and electrical performance (Ali et al., 2020). This section reviews key developments in Trombe wall technology, focusing on the integration of PCM and photovoltaic elements, and their advantages for sustainable building design. been shown in reference [19] that the most important factor affecting heat absorption is the air gap between the thrombus wall and the glass wall. Reference [17] has investigated the effect of the location of inlet and outlet valves in the solar wall by using computational fluid dynamics solution through the finite volume method. Reference [1] has simulated a solar chimney in hot and humid regions by using Fluent software and investigated the effect of air temperature on the efficiency of the wall. Analytical methods are part of very important methods in studying the study of thrombus wall. In references [5] and [4], an analytical method to solve the slow and unsteady flow for natural displacement heat transfer has been presented. These methods are based on the use of similar variables in solving the governing differential equations.

1.1 Trombe Wall Functionality and Design

A Trombe wall typically consists of a thick masonry wall painted black or coated to absorb maximum sunlight, placed behind a glass pane that creates a greenhouse effect by trapping heat (Hu et al., 2017). This heat is stored within the thermal mass during the day and is slowly transferred to the interior through conduction, convection, or radiation, providing consistent warmth even after sunset (Saadatian et al., 2012). The passive nature of Trombe walls makes them an efficient, low-maintenance solution for reducing heating demand in buildings, particularly in climates with significant diurnal temperature variations (Ellis, 2003). Over the years, numerous studies have refined the Trombe wall concept to enhance its efficiency under various climatic conditions. For example, Charqui et al. (2023) focused on optimizing the thermal behavior of Trombe walls under unsteady conditions, suggesting new strategies to improve their heat storage capacity and responsiveness to temperature fluctuations. Wang et al. (2020) provided a detailed classification of Trombe walls, exploring various modeling methods and evaluation metrics that highlight the versatility and effectiveness of these systems in different building contexts.

1.2 Integration of Phase Change Materials (PCM)

Phase change materials (PCM) have been increasingly integrated into Trombe wall designs to enhance thermal performance. PCMs are substances that absorb or release significant amounts of latent heat during phase transitions, typically between solid and liquid states. When incorporated into a Trombe wall, PCMs can increase the wall's heat storage capacity, providing greater thermal stability and extending the duration of heat release (Xiong et al., 2021). Research by Pomianowski et al. (2013) and Jin et al. (2013) emphasizes the importance of the location and configuration of PCMs in building walls. When used effectively, PCMs can smooth temperature variations and maintain more consistent indoor temperatures. A study by Xiong et al. (2021) showed that PCM-enhanced Trombe walls could outperform traditional designs in terms of heat storage, significantly reducing energy demand for heating and cooling.

The application of PCMs also allows for better thermal regulation in buildings located in regions with extreme temperature variations. Demirbas (2006) provided a comprehensive overview of PCM technology, highlighting its potential for improving the efficiency of passive solar systems like Trombe walls. The combination of PCM and Trombe walls has been shown to improve the thermal performance by up to 30%, especially in climates where daily temperature swings are common (Ahmed et al., 2019).

1.3 Photovoltaic-Trombe Wall (PV-TW) Systems

Photovoltaic (PV) Trombe walls (TWs) combine the passive solar heating capabilities of traditional Trombe walls with the energy-generating potential of photovoltaic panels. PV-TWs integrate solar panels into the façade, which convert sunlight into electricity while still allowing heat to be absorbed by the wall behind them. This hybrid system enhances the overall energy efficiency of the building by simultaneously providing electrical power and thermal energy (Ji et al., 2007; Agrawal & Tiwari, 2010). The inclusion of PV in Trombe walls addresses several challenges associated with passive solar systems, such as overheating during the summer months. By generating electricity and shading the thermal mass behind the glass, PV panels can reduce excessive heat gain while simultaneously producing renewable energy (Koyunbaba & Yılmaz, 2012). Studies by Irshad et al. (2015) and Hu et al. (2017) have shown that PV-TW can reduce cooling loads and enhance the overall sustainability of buildings, making them especially effective in climates with both heating and cooling requirements.

In addition, integrating photovoltaic systems into Trombe walls improves the overall aesthetic appeal and design flexibility of building façades, offering architects more options for incorporating renewable energy technologies into urban environments (Peng et al., 2013). Moreover, these systems can be coupled with additional technologies such as air vents or DC fans to further optimize thermal and electrical performance, as demonstrated by studies on PV-TW systems in composite climates (Ji et al., 2007).

1.4 Advantages of PV-TW

The combination of PV panels with Trombe walls offers several distinct advantages. First, it maximizes the utility of solar energy by capturing both thermal and electrical energy, thus improving the energy efficiency of the building envelope (Ji et al., 2007; van Helden et al., 2004). This dual-purpose system can significantly reduce a building's reliance on external energy sources, contributing to lower energy costs and reduced carbon emissions. Second, PV-TW provide better control over indoor temperatures. By generating electricity that can be used to power cooling or ventilation systems, PV-TW reduce the risk of overheating in warm climates. This was evident in studies by Irshad et al. (2014), which demonstrated that PV-TW could enhance comfort in tropical and temperate climates by regulating heat and electricity simultaneously. Finally, PV-TW enhance the lifespan of solar panels by providing passive cooling. As solar panels tend to lose efficiency at higher temperatures, the air circulation between the glass and the wall in a Trombe system can help maintain optimal operating conditions for the PV cells (Koyunbaba et al., 2013). This cooling effect, coupled with the shading provided by the panels, improves the overall longevity and performance of the solar energy system.

Citation: Shemshadi, I. (2025). A Numerical Investigation on the Effect of Enhanced Convection to Improve the Performance of a Photovoltaic-Trombe Wall System. In ICON Journal of Engineering Applications of Artificial Intelligence (Vol. 1, Number 1, pp. 8–18). https://doi.org/10.5281/zenodo.15857811

In summary, Trombe walls represent an effective and versatile solution for passive solar heating in buildings. By integrating phase change materials (PCM) and photovoltaic (PV) systems, researchers have significantly enhanced the performance of these walls, making them more adaptable to diverse climatic conditions and increasing their overall energy efficiency. PCM-enhanced Trombe walls offer improved thermal storage, while PV-TW provide the dual benefits of electricity generation and passive heating. These advancements underscore the ongoing importance of Trombe walls in the pursuit of sustainable and energy-efficient building designs.

In the PV-TW system, photovoltaic (PV) cells are installed on the south side of the building, acting as thermal absorbers. There are two air vents for winter heating and two additional vents for summer cooling. During winter, the heating vents are opened, and in summer, they are closed. This setup not only generates heat and electricity but also cools the PV cells, thereby increasing electrical efficiency. It has been reported that by reducing the PV panel temperature by 15°C through a well-designed PV-TW structure, a 3.8% increase in PV module output power can be achieved. Jie et al., (2007) used a crystalline silicon (c-Si) solar cell on the glass surface of a Trombe wall to produce both electricity and heat. The results indicated that this method had low thermal efficiency because the solar cell prevented sunlight from passing through the wall. The air inside the channel absorbs heat from the PV panel and then releases it into the room, while in the summer, the heat is transferred from the PV panel to the outside environment (Jie at al., 2007). The PV-TW system is more efficient than separate solar thermal and electrical systems as it is cheaper, more environmentally friendly, and better suited for individual homes or buildings (Helden at al., 2004).

The heating performance of this wall is similar to that of a classic Trombe wall, but PV cells also use a portion of the solar energy to generate electricity. This means that the heating efficiency of a PV Trombe wall is lower than that of a classic Trombe wall. However, two key advantages of the photovoltaic Trombe wall have encouraged further research into this technology. First, the electricity generated can be used for other purposes, such as powering household appliances. Second, the system helps reduce excessive heat during the summer, as some of the solar energy is converted into electricity. Therefore, due to the multifunctional needs of both heating and electricity, as well as the comprehensive benefits of power generation and preventing overheating, many studies on Trombe walls have focused on this type (PV-TW) (Wang et al., 2020).

During the design of a PV-TW system, glass properties such as the number of glass layers, glazing thickness, and types of glass (single-glazed, double-glazed, and argon-filled double-glazed) significantly affect the amount of solar radiation absorbed and transmitted, as well as the heat transfer between the interior and the environment. Ahmad et al., (2019) conducted an experimental and theoretical study on the impact of glass coatings on the performance of a PV-TW system. The results revealed a conflicting effect of the glass coating in terms of indoor thermal comfort and electricity generation. Irshad et al., (2015) presented a simulated model of a room equipped with a PV-TW system. They evaluated the performance of three different glazing types (single-glazed, double-glazed, and argon-filled double-glazed PV-TW), and the results showed that argon-filled double glazing significantly reduced the cooling load and room temperature while enhancing the electrical efficiency of the PV panel.

Additionally, Irshad et al., (2014a) studied the performance of a building integrated with a PV-TW system in terms of energy consumption, potential cost savings, and CO2 emission reductions for different configurations (single-glazed, double-glazed, and argon-filled double-glazed). The TRNSYS program was used in this study, and the results confirmed that using argon-filled double glazing in warm climates is economically viable in terms of energy savings and CO2 emissions reduction. A life cycle cost (LCC) analysis compared the energy savings of different PV-TW glazing types with conventional houses. The results showed energy savings of 22.18%, 18.94%, and 6.52% for argon-filled double-glazed PV-TW, double-glazed PV-TW, and single-glazed PV-TW, respectively. Irshad et al., (2014b) also examined the impact of different types of PV glass (single-glazed, double-glazed, and argon-filled double-glazed) on reducing thermal load and generating electrical power. The results demonstrated that argon-filled double glazing significantly lowered the average air channel temperature.

Citation: Shemshadi, I. (2025). A Numerical Investigation on the Effect of Enhanced Convection to Improve the Performance of a Photovoltaic-Trombe Wall System. In ICON Journal of Engineering Applications of Artificial Intelligence (Vol. 1, Number 1, pp. 8–18). https://doi.org/10.5281/zenodo.15857811

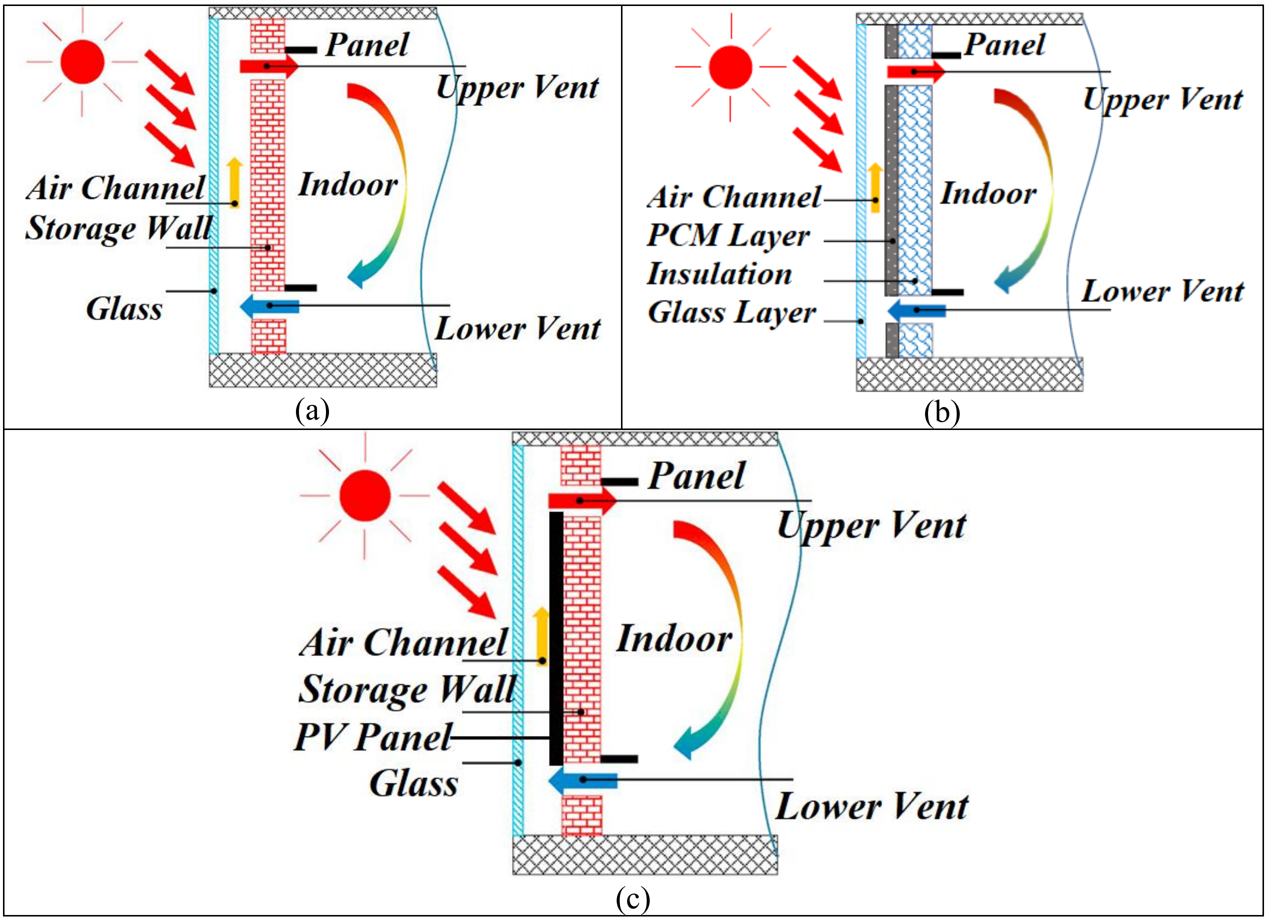

Figure 1. Classical Trombe wall (a), Classical Trombe wall with PCM (b), PV-TW (c) [6]

The PV-TW wall is an innovative advancement of the traditional Trombe wall. The solar cells in the PV-TW systems can simultaneously convert solar radiation into both electricity and heat. From an architectural and aesthetic standpoint, the PV-TW wall is far more suitable than other Trombe walls, and it efficiently utilizes solar energy for both cooling and heating in different climatic regions. In addition to producing heat and electricity, the PV-TW system cools the PV cells, which increases their electrical efficiency. Moreover, it expels the warm air inside the channel from the PV panel, making the system more efficient than separate solar thermal and electrical systems.

By reviewing studies on the PV-TW system, it can be concluded that the optimal size of the PV-TW system was found to be 37%, which refers to the ratio of the PV-TW surface area to the area of the other walls in the room. The thickness of the air channel between the solar cells and the multi-layer facade greatly influences the thermal performance of the PV-TW. The ideal air channel thickness for local climate conditions was determined to be 0.06 meters. Additionally, the electrical output of the PV-TW system in summer decreased by 2% after using thermal insulation. The use of shading curtains in summer and thermal insulation during both summer and winter is recommended for optimal performance.

The effect of mirrors on a PV-Trombe wall has been explored in various studies, and according to the references you provided, mirrors can enhance the performance of such systems. The study of Wang et al. (2020) provides a comprehensive classification and evaluation of different Trombe wall systems, including experimental assessments and modeling methods. Mirrors can play a role in improving the solar energy capture of Trombe walls by increasing the amount of sunlight directed onto the wall's surface, thereby enhancing both thermal and electrical performance in PV-Trombe wall systems (Wang et al., 2020). Ji et al. (2007) had a study on PV-TW assisted with a DC fan. They investigated ways to improve the system's efficiency. While this specific reference focuses on the role of a fan in air circulation, reflective surfaces like mirrors could similarly increase the amount of solar radiation received by the PV panels, improving electrical output and heat generation. The experimental and numerical study by Stazi et al. (2012) examined the behavior of solar walls in buildings with various insulation levels. While mirrors weren't a primary focus, reflective surfaces could be incorporated to increase sunlight absorption, enhancing the overall performance of Trombe walls, especially in less insulated buildings where maximizing solar energy is crucial. Abdullah et al. (2022) directly assessed the impact of reflective mirrors on the performance of a PV-Trombe wall. The results showed that mirrors significantly improved the system's efficiency by reflecting additional sunlight onto the PV panels. This not only increased the electrical power output but also enhanced the thermal performance of the system, as more solar radiation was directed to the wall. The use of mirrors helped reduce energy losses, making the system more effective in harnessing solar energy.

2. Methodology

In this study, a composite wall has been used to improve the thermal properties of PV-TW (Figure 2). Cold air starts moving from the floor of the room due to its lower density and after heating in the PV-TW channel, it moves towards the top of the channel due to expansion. In the meantime, due to passing over the surface of the photovoltaic panel and also the sun's radiation, it gets warmer and finally enters the room through the upper vent, leading to an increase in the room temperature. The wall investigated in this study is considered as three layers. The properties of the different layers of the wall are shown in Table 1. In general, it is very important to improve the wall conditions in a way that increases the heat generation in the air duct of the PV-TW system. This is why in many studies, various compositions have been used to increase the thermal resistance of the wall and, as a result, increase the share of heat transfer through the vent.

Table 1. properties of the composite wall presented in Figure 2.

Layer	Thickness [cm]	Material	Heat Transfer Coefficient k [W/m.K]
1	10	Brick (without air holes)	0.765
2	7	Mineral Wool	0.036
3	3	Gypsum	0.202

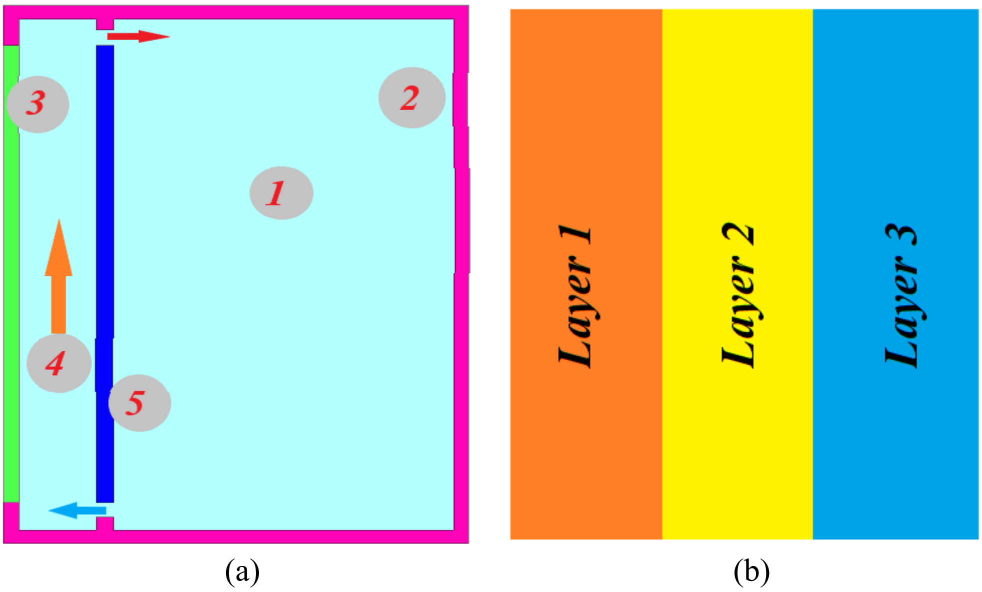

Figure 2. (a), The PV-TW model of this study; 1) Room, 2) Room Walls, 3) PV Panel, 4) Air Chanel, 5) Composite Wall; (b), The Wall Composition

The wall consists of three layers, and the equations related to the energy balance of each layer can be simply presented as follows (Bergman et al., 2011).

$$mC\frac{\partial T}{\partial t} = Q_{in} - Q_{out} \quad (1)$$

Where m is the mass of the layer in question, C is the specific heat coefficient, Q_{out} is the amount of heat output from the layer, and Q_{in} is the amount of heat input to the layer. Heat transfer from the inner layer of the wall to the room environment and from the air inside the duct to the outer layer of the wall takes place as convection heat transfer. The governing relationship is as follows:

$$Q_{Conv} = h_{Conv} A_w \Delta T \quad (2)$$

In this regard, h is the convective heat transfer coefficient and A is the wall area. Heat transfer between the wall layers is also carried out by conduction, which can be presented as follows.

$$Q_{Cond} = kA_w \frac{\partial T}{\partial x} \quad (3)$$

In order to calculate the Nusselt and Reynolds numbers in different flow regimes inside the channel, studies from Holman (2009) and Jaber & Ajib (2011) can be used. Also, in order to calculate the air properties and heat losses in the channel, work by Duffie et al., (2020) can be used. One of the most important parts of the simulation is related to the calculation and modeling of solar radiation. The book from Khatib (2016) has been used for this purpose.

In order to carry out this study, first the astronomical parameters of the amount of solar irradiance and the position of the sun relative to the terrestrial observer must be calculated. This is done using a simple astronomical model. For an observer who is on a certain point of the earth, the side angle (θ) and the elevation angle (α) are two parameters that determine the position of the sun. The side and elevation angles can be determined according to the astronomical relationships governing the movement of the sun around the earth and according to the geographical location of the test site (Khatib, 2016). The elevation angle is the angle of the sun's height in the sky, which is measured relative to the horizon. The elevation angle α can be calculated as:

$$\sin\alpha = \sin L \sin\delta + \cos L \cos\delta \cos\omega \qquad (4)$$

where L is the latitude, δ is the declination angle of the sun, and ω is the hour angle. The declination angle δ is the angle between the earth-sun vector and the equatorial plane and is calculated as follows:

$$\delta = 23.45^{\circ} \sin\left[\frac{2\pi(N-81)}{365}\right] \qquad (5)$$

where N is the calendar year. The hour angle ω is the angular displacement of the sun from the local point and can be evaluated as follows:

$$\omega = 15^{\circ} \sin(AST - 12) \qquad (6)$$

AST is true solar time and is determined by the daily apparent movement of the sun. true time is calculated based on the apparent day and is the time interval between two consecutive returns of the sun to the local meridian. The true solar time AST is evaluated as:

$$AST = LMT + EoT \pm \frac{4^{\circ}}{LSMT - LOD} \qquad (7)$$

where LMT is the local meridian time, LOD is the longitude and EoT is the equation of time. The LMT parameter is the local standard meridian time used for a specific time zone and is similar to the primary meridian used for Greenwich mean time

$$LSMT = 15^{\circ} T_{GMT} \qquad (8)$$

where T_{GMT} is the time relative to Greenwich. The time equation EoT is the difference between the mean and true times of the sun, both of which occur at a certain geographic longitude at a real moment, and is evaluated as follows (Khatib, 2016):

$$EoT = 9.89 \sin(2B) - 7.53 \cos B - 1.5 \sin B \qquad (9)$$

Where,

$$B = \frac{2\pi}{365}(N-81) \qquad (10)$$

The side angle θ is calculated as:

$$\sin\theta = \frac{\delta \sin\omega}{\cos\alpha} \qquad (11)$$

The calculations presented in this section provide the user with the angles needed to adjust the dish. In this way, these angles can be calculated at all hours of the day and using a controller, it can be transferred to a small motor to move the dish at certain time intervals so that it is in the optimal position in terms of sunlight. It should be kept in mind that the angle of the sun is different in different days of the year. Thus, for each day of testing, the local time should be taken into account, then the settings of the device should be applied according to the changes in the angle of the sun. Solar irradiance G is evaluated as follows (Khatib, 2016):

$$G = G_0\left[1 + 0.0333 \cos\left(\frac{360N}{365}\right)\right] \sin L \sin\delta + \cos L \cos\delta \cos\omega \qquad (12)$$

G_0 is the solar constant and it is usually considered equal to 1367. Finally, with the amount of solar irradiance and also the power produced by the panel ($P=V\,I$ where V is the voltage and I is the current), the power generation efficiency η (in percentage) can be obtained

$$\eta = \frac{P}{G} \times 100 \quad (13)$$

The power generation efficiency is a very important parameter, since it can be used for other applications in the PV-TW system.

3. Result and Discussion

The results presented here were derived from observations conducted on a typical autumn day in Tehran, characterized by stable and moderate temperature fluctuations. The relationship between solar radiation and ambient air temperature is illustrated in Figure 3. As depicted, the temperature variation throughout the day is approximately 7 degrees Celsius, while the maximum solar radiation recorded is below 1200 watts per square meter. Given that Tehran's climate rarely experiences temperatures significantly outside this range, and that the majority of the year features normal temperature conditions (ranging from 10 to 30 degrees Celsius), it becomes crucial to assess the performance of the Trombe-photovoltaic wall under these specific environmental circumstances. Notably, the peak air temperature reaches 17.2 degrees Celsius at around 2 PM, coinciding with maximum solar radiation of 1115 watts per square meter observed at noon.

In this study, first, the natural convection mode was simulated before exploring the forced convection mode to analyze the impact of fan assistance. Figure 4 illustrates the temperature profiles of both the inner and outer surfaces of the room wall under natural convection conditions. The data reveals that during peak sunlight hours, the inner surface temperature of the wall in forced convection mode is approximately 1.5 degrees Celsius higher than in natural convection mode. This finding underscores the significant role a fan can play in enhancing heat transfer efficiency.

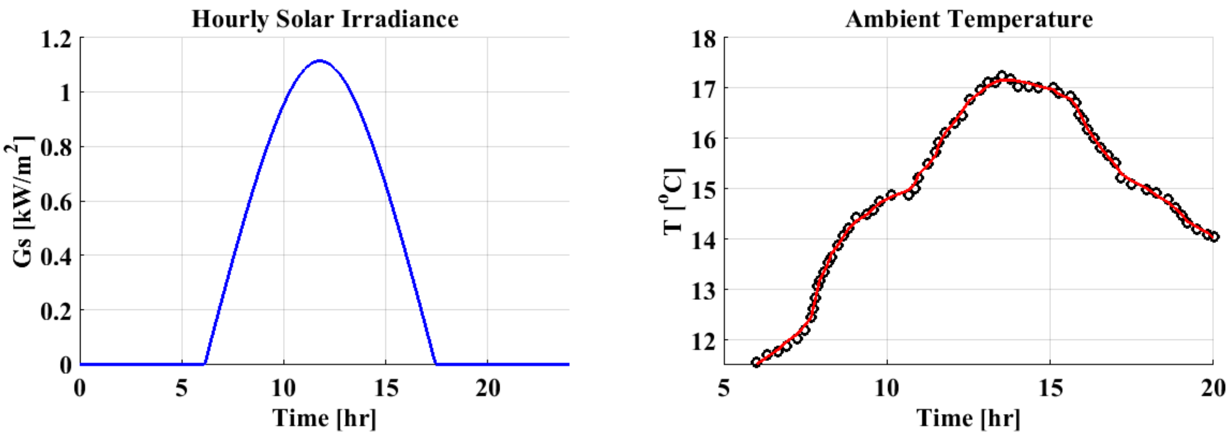

Figure 3. the variation of ambient temperature and solar irradiance in a mild day

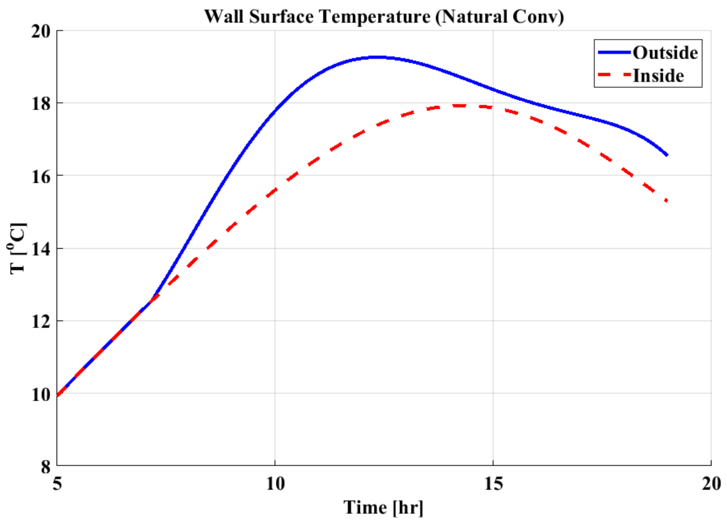

Figure 4. wall surface (Inner & Outer) temperature in natural convection mode

Further analysis is provided in Figure 5, which depicts the heat flux entering the room via both the vent and the wall. The data clearly indicates that the rate of heat transfer through the vent is substantially greater than that through the wall. This observation is further corroborated by Figure 6, which reinforces the conclusion drawn from our calculations: in natural convection mode, heat transfer through the wall accounts for only about 2% of total heat transfer. Therefore, employing a fan to optimize heat transfer conditions is not only logical but also a highly effective strategy.

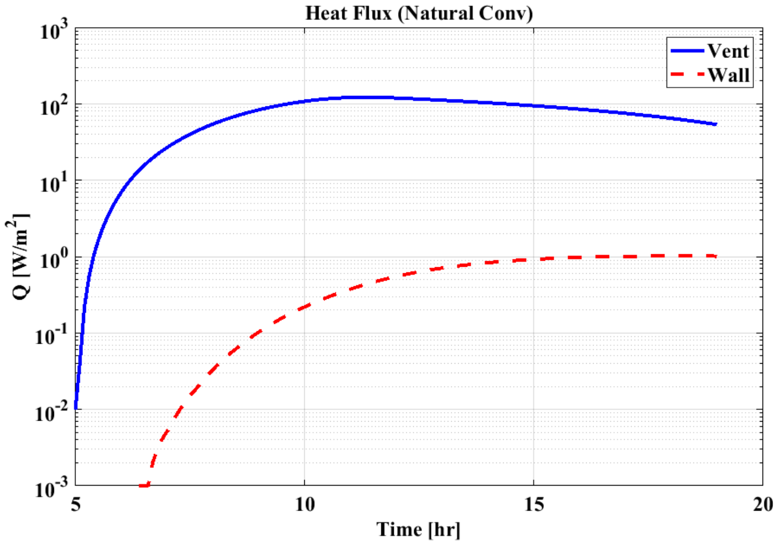

Figure 5. heat fluxes to the room through the vent and across the wall

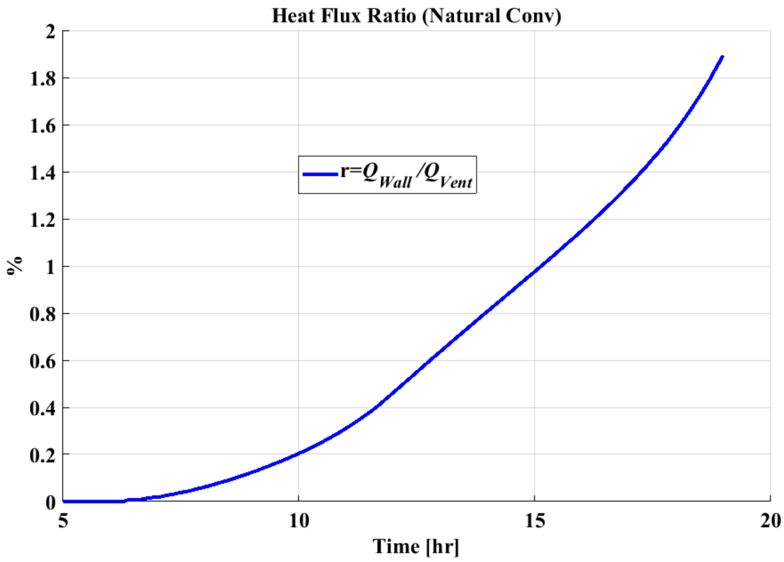

Figure 6. heat flux ratio (wall over vent) in natural convection mode

Figure 7 presents the output power of the solar panel alongside its efficiency metrics. The dimensions of the panel utilized in this study are set at 1.8 square meters. Given the relatively low efficiency rates of solar panels, it becomes imperative to implement cooling strategies to enhance their performance and output. This study specifically examines how the introduction of a fan can amplify airflow within the PV-TW (Photovoltaic-Trombe Wall) channel. The findings indicate that improved airflow within this channel positively influences solar panel performance. As illustrated in Figure 7, utilizing a fan to induce forced convection results in an approximate increase of 0.5% in efficiency during peak solar radiation hours, translating to an additional output power of around 40 watts. This boost in power generation is particularly advantageous for operating the fan and enhancing the overall efficiency of the PV-TW system.

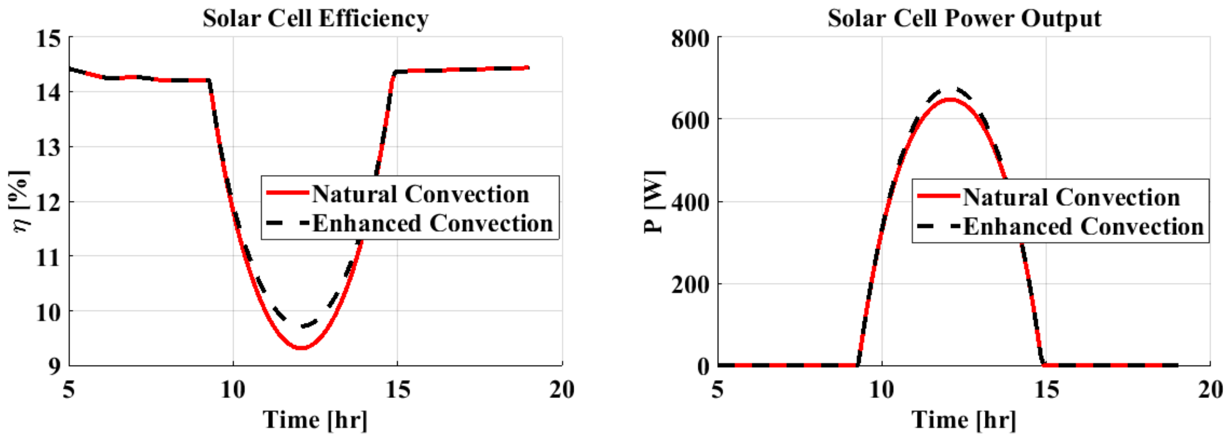

Figure 7. the solar cell power output and efficiency in Natural and Enhanced convection

Lastly, Figure 8 highlights the Reynolds and Nusselt numbers within the channel under varying conditions. The stark differences observed between forced and natural convection modes clearly demonstrate that employing a fan to enhance airflow within the channel significantly improves system performance. Specifically, we observe a fivefold increase in the Reynolds number, accompanied by an approximate 5.5-fold increase in the Nusselt number. This substantial rise not only contributes to warming the room on colder days but also facilitates increased airflow, which effectively dissipates more heat from the surface of the photovoltaic panel. Ultimately, this leads to enhanced performance of the solar panel itself.

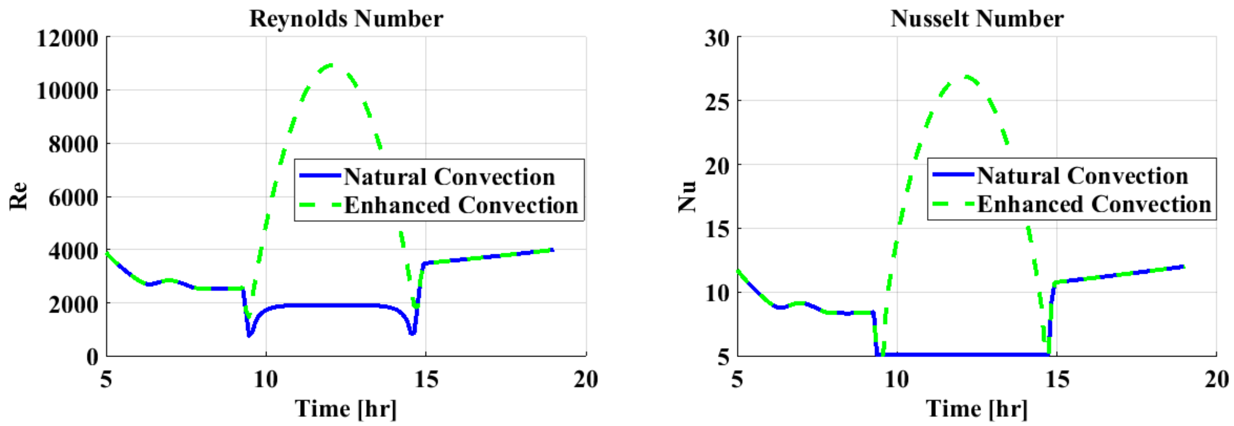

Figure 8. the variation of Re and Nu per whole day for Natural and Enhanced convection

In conclusion, this study emphasizes the importance of understanding thermal dynamics in optimizing solar energy systems, particularly in regions with stable temperature variations like Tehran. By leveraging forced convection through fan-assisted airflow, we can significantly improve both heat transfer efficiency and solar panel performance, thereby contributing to more effective energy utilization in architectural designs that incorporate Trombe walls and photovoltaic systems. The implications of these findings extend beyond mere academic interest; they highlight practical strategies for enhancing renewable energy systems in urban environments, promoting sustainability and energy efficiency in building designs across similar climatic conditions worldwide.

5. Conclusion

In conclusion, this study has provided valuable insights into the thermal dynamics of Trombe-photovoltaic wall systems, particularly in the context of Tehran's stable autumn climate. The findings underscore the critical interplay between solar radiation and ambient temperature, revealing that even modest temperature fluctuations can significantly influence the performance of solar energy systems. With maximum solar radiation levels peaking below 1200 watts per square meter and air temperatures ranging from 10 to 30 degrees Celsius for much of the year, it is imperative to optimize these systems to harness their full potential. The investigations focused on two modes of heat transfer: natural convection and forced convection. The results demonstrated that forced convection, facilitated by fan assistance, markedly enhances heat transfer efficiency. Specifically, the inner surface temperature of the wall in forced convection mode was found to be approximately 1.5 degrees Celsius higher than in natural convection mode during peak sunlight hours. This difference highlights the importance of active airflow in maximizing thermal performance.

Furthermore, our analysis revealed that heat transfer through the vent significantly exceeds that through the wall, accounting for only about 2% of total heat transfer under natural convection conditions. This finding strongly advocates for the integration of fans within Trombe-photovoltaic systems to optimize heat transfer and improve overall efficiency. The ability of a fan to induce forced convection not only enhances the thermal environment within the room but also contributes to more effective cooling strategies for solar panels. The study also explored the output power and efficiency of the photovoltaic panels used in conjunction with the Trombe wall. With an area of 1.8 square meters, the solar panels exhibited relatively low efficiency rates, underscoring the necessity for cooling interventions. Our results indicated that introducing a fan could increase panel efficiency by approximately 0.5% during peak solar radiation hours, translating to an additional output power of around 40 watts. This enhancement is particularly beneficial for operating the fan itself and further amplifying the overall efficiency of the Photovoltaic-Trombe Wall (PV-TW) system.

Additionally, we examined the Reynolds and Nusselt numbers within the channel under both forced and natural convection conditions. The substantial differences observed, specifically a fivefold increase in Reynolds number and a 5.5-fold increase in Nusselt number when employing forced convection, underscore the effectiveness of fan-assisted airflow in optimizing system performance. Such improvements not only facilitate enhanced heat dissipation from photovoltaic surfaces but also contribute to increased room temperatures during colder periods.

Overall, this research highlights the significant potential for integrating forced convection strategies into Trombe-photovoltaic wall systems, particularly in climates similar to Tehran's. By leveraging these findings, architects and engineers can design more efficient renewable energy systems that promote sustainability and energy efficiency in urban environments. Future studies should continue to explore innovative methods for optimizing thermal dynamics in solar energy applications, aiming to further enhance performance and reliability in diverse climatic conditions.

In summary, this study serves as a pivotal contribution to understanding how thermal dynamics can be effectively managed within solar energy systems. The implications extend beyond theoretical knowledge, offering practical solutions that can lead to more sustainable architectural designs and improved energy utilization in buildings worldwide. As we strive towards a greener future, such advancements will play a crucial role in harnessing renewable energy sources effectively while addressing the challenges posed by climate change and urbanization.

References

1. Abdullah, A. A., Atallah, F. S., Algburi, S., & Ahmed, O. K. (2022). Impact of a reflective mirrors on photovoltaic/Trombe wall performance: Experimental assessment. *Results in Engineering, 16*, 100706. https://doi.org/10.1016/j.rineng.2022.100706
2. Agrawal, B., & Tiwari, G. N. (2010). Optimizing the energy and exergy of building integrated photovoltaic thermal (BIPVT) systems under cold climatic conditions. *Applied Energy, 87*(2), 417–426. https://doi.org/10.1016/j.apenergy.2009.06.013
3. Ahmed, O. K., Hamada, K. I., & Salih, A. M. (2019). Enhancement of the performance of Photovoltaic/Trombe wall system using the porous medium: Experimental and theoretical study. *Energy, 171*, 14–26. https://doi.org/10.1016/j.energy.2019.01.016
4. Ali, M. M., Ahmed, O. K., & Abbas, E. F. (2020). Performance of solar pond integrated with photovoltaic/thermal collectors. *Energy Reports, 6*, 3200–3211. https://doi.org/10.1016/j.egyr.2020.11.134
5. Bergman, T. L., Lavine, A. S., Incropera, F. P., & DeWitt, D. P. (2011). *Introduction to heat transfer* (6th ed.). John Wiley & Sons.
6. Charqui, Z., Boukendil, M., El Moutaouakil, L., Hidki, R., Zrikem, Z., & Abdelbaki, A. (2023). Simulation and optimization of the thermal behavior of a Trombe wall under unsteady conditions. *Materials Today: Proceedings, 72*, 3780–3785. https://doi.org/10.1016/j.matpr.2023.03.157
7. Demirbas, M. F. (2006). Thermal energy storage and phase change materials: An overview. *Energy Sources, Part B: Economics, Planning, and Policy, 1*(1), 85–95. https://doi.org/10.1080/15567240500237057
8. Duffie, J. A., Beckman, W. A., & Blair, N. (2020). *Solar engineering of thermal processes, photovoltaics and wind* (5th ed.). John Wiley & Sons.
9. Ellis, P. G. (2003). *Development and validation of the unvented Trombe wall model in EnergyPlus* (Doctoral dissertation, University of Illinois at Urbana-Champaign). https://www.ideals.illinois.edu/handle/2142/85293
10. Holman, J. P. (2009). *Heat transfer* (10th ed.). McGraw-Hill Higher Education.
11. Hu, Z., He, W., Ji, J., Hu, D., Lv, S., Chen, H., & Shen, Z. (2017). Comparative study on the annual performance of three types of building integrated photovoltaic (BIPV) Trombe wall system. *Applied Energy, 194*, 81–93. https://doi.org/10.1016/j.apenergy.2017.03.021
12. Irshad, K., Habib, K., & Thirumalaiswamy, N. (2015). Performance evaluation of PV-Trombe wall for sustainable building development. *Procedia CIRP, 26*, 624–629. https://doi.org/10.1016/j.procir.2014.07.039
13. Irshad, K., Habib, K., & Thirumalaiswamy, N. (2014). Energy and cost analysis of photovoltaic-Trombe wall system

in tropical climate. *Energy Procedia, 50*, 71–78. https://doi.org/10.1016/j.egypro.2014.06.009

14. Irshad, K., Habib, K., Thirumalaiswamy, N., & Elmahdi, A. E. A. (2014). Performance analysis of photovoltaic Trombe wall for tropical climate. *Applied Mechanics and Materials, 465*, 211–215. https://doi.org/10.4028/www.scientific.net/AMM.465.211
15. Jaber, S., & Ajib, S. (2011). Optimum design of Trombe wall system in Mediterranean region. *Solar Energy, 85*(9), 1891–1898. https://doi.org/10.1016/j.solener.2011.04.023
16. Ji, J., Yi, H., He, W., & Pei, G. (2007). PV-Trombe wall design for buildings in composite climates. *Energy and Buildings, 39*(2), 212–220. https://doi.org/10.1016/j.enbuild.2006.07.003
17. Jie, J., Hua, Y., Gang, P., Bin, J., & Wei, H. (2007). Study of PV-Trombe wall assisted with DC fan. *Building and Environment, 42*(10), 3529–3535. https://doi.org/10.1016/j.buildenv.2006.10.041
18. Jin, X., Medina, M. A., & Zhang, X. (2013). On the importance of the location of PCMs in building walls for enhanced thermal performance. *Applied Energy, 106*, 72–78. https://doi.org/10.1016/j.apenergy.2013.01.032
19. Khatib, T., & Elmenreich, W. (2016). *Modeling of photovoltaic systems using Matlab: Simplified green codes*. John Wiley & Sons.
20. Koyunbaba, B. K., & Yilmaz, Z. (2012). The comparison of Trombe wall systems with single glass, double glass and PV panels. *Renewable Energy, 45*, 111–118. https://doi.org/10.1016/j.renene.2012.02.027
21. Koyunbaba, B. K., Yilmaz, Z., & Ulgen, K. (2013). An approach for energy modeling of a building integrated photovoltaic (BIPV) Trombe wall system. *Energy and Buildings, 67*, 680–688. https://doi.org/10.1016/j.enbuild.2013.08.002
22. Peng, J., Lu, L., Yang, H., & Han, J. (2013). Investigation on the annual thermal performance of a photovoltaic wall mounted on a multi-layer façade. *Applied Energy, 112*, 646–656. https://doi.org/10.1016/j.apenergy.2013.02.030
23. Pomianowski, M., Heiselberg, P., & Zhang, Y. (2013). Review of thermal energy storage technologies based on PCM application in buildings. *Energy and Buildings, 67*, 56–69. https://doi.org/10.1016/j.enbuild.2013.08.006
24. Saadatian, O. M., Haw, L. C., Sopian, K., Salleh, E., & Ludin, N. J. (2012). Solar walls: The neglected components of passive designs. *Advances in Environment, Biotechnology and Biomedicine*, *2012*, 120–126.
25. Stazi, F., Mastrucci, A., & Perna, C. (2012). The behaviour of solar walls in residential buildings with different insulation levels: An experimental and numerical study. *Energy and Buildings, 47*, 217–229. https://doi.org/10.1016/j.enbuild.2011.11.035
26. van Helden, W. G., van Zolingen, R. J. C., & Zondag, H. A. (2004). PV thermal systems: PV panels supplying renewable electricity and heat. *Progress in Photovoltaics: Research and Applications, 12*(6), 415–426. https://doi.org/10.1002/pip.541
27. Wang, D., Hu, L., Du, H., Liu, Y., Huang, J., Xu, Y., & Liu, J. (2020). Classification, experimental assessment, modeling methods and evaluation metrics of Trombe walls. *Renewable and Sustainable Energy Reviews, 124*, 109772. https://doi.org/10.1016/j.rser.2020.109772
28. Xiong, Q., Alshehri, H. M., Monfaredi, R., Tayebi, T., Majdoub, F., Hajjar, A., ... & Izadi, M. (2021). Application of phase change material in improving Trombe wall efficiency: An up-to-date and comprehensive overview. *Energy and Buildings*, 111824. https://doi.org/10.1016/j.enbuild.2021.111824