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Characteristics of heat exchange in the energy-efficient exterior wall of a passive house

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Abstract: This research thoroughly examines the unique characteristics of heat exchange in the energy-efficient external wall of a passive house. With a growing emphasis on sustainability and energy-efficient construction, passive houses have gained significant attention. The external wall, specifically in the form of a Trombe wall, plays a crucial role in maintaining thermal comfort while minimizing energy consumption. This article explores the intricacies of heat exchange in the Trombe Wall, considering factors such as solar radiation influence and modeling strategies. Through physical modeling and analytical investigations, the study delves into how these factors impact heat exchange and overall energy efficiency. The conclusions drawn provide valuable insights to architects, engineers, and construction professionals engaged in designing and implementing energy-efficient building envelopes. Understanding the nuances of heat exchange within the context of passive houses is vital for achieving optimal thermal efficiency and enhancing sustainable development in modern construction practices.

Keywords: Trombe wall, passive house, energy-efficient external wall, energy efficiency

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Introduction

Innovative passive energy-saving technologies based on the use of Trombe walls are a relevant and interesting approach to energy-efficient construction, especially in the context of energy conservation and carbon emissions reduction. Such technologies are quite effective as they can harness solar energy to maintain thermal comfort in buildings and provide ventilation while reducing the consumption of traditional fossil fuels. Trombe wall technologies are highly effective for regions with different

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climatic conditions and are suitable for various types of buildings, making them an attractive alternative for sustainable construction.

Regarding the use of solar energy as an alternative to traditional fuel sources, there are currently numerous proposals, including the utilization of various types and designs of solar collectors. For the efficient utilization of equipment of this type, a series of scientific studies have been conducted, presenting a comprehensive comparative analysis of different types of solar collectors to assess their performance and efficiency for various applications (Zhang & Zhu, 2022).

The presented results are from in-depth parametric studies and comparisons of flat, vacuum tube, and concentrating collectors. Key parameters such as thermal efficiency, cost, and environmental impact were considered. To obtain reliable results, a modern methodology was employed, based on experimental research, numerical modeling, and analysis of the collected data. This allowed the authors to draw quantitative conclusions about the performance of each collector type in various weather conditions and climatic zones. Furthermore, attention was given to the design, structural materials, and manufacturing processes of each collector type to evaluate their advantages and disadvantages. Research of this kind contributes to a deeper understanding of the pros and cons of each collector type, facilitating well-informed decisions regarding the design and implementation of solar energy systems, taking into account their technical and economic characteristics (Elsaid et al., 2023; Guo et al., 2023; Ibrahim et al., 2023; Li et al., 2022a). This enables the selection of the most suitable solar collector technologies based on specific application requirements and regional conditions.

A significant body of scientific work is dedicated to the accumulation of solar energy and its subsequent utilization. Special attention is given to the Trombe wall research, as an effective method for energy storage and its use in maintaining indoor microclimate parameters. Various types of thermal energy storage systems were considered, including those with phase-change materials, as well as photovoltaic panels (Borah et al., 2023; Chen et al., 2022; He et al., 2022).

To ensure the credibility of the results in evaluating the efficiency of various thermal storage structures, numerical models and experimental research were employed. Of particular note is the combination of heat energy utilization and electricity generation technologies. Such studies aim to determine optimal combinations of technological schemes for the effective utilization of the Trombe wall (Alqaed, 2022; Ataş et al. 2023; Delač et al., 2022; Li et al., 2022b; Xu et al., 2023; Yadav et al., 2023; Zhou et al., 2023).

Modern passive technologies widely employ the multifunctionality of the Trombe wall. Several scientific publications focus on showcasing the results of research that not only address heating but also delve into the purification of incoming air in energy-efficient buildings (Li et al., 2023). A characteristic feature of such systems is the provision of optimal comfort and the improvement of indoor air quality, reducing dependence on traditional energy sources and pollutants. The authors thoroughly investigate the design and construction features of multifunctional Trombe walls, allowing for the absorption of solar energy and its efficient utilization for space heating.

Special emphasis is placed on the use of various types of filters in the Trombe wall system to purify incoming air from dust, allergens, and other contaminants, thereby improving indoor air quality. The characteristics of the purification mechanism and its impact on the health and comfort of occupants are highlighted.

The multifunctionality of the Trombe wall is also explored in scientific papers dedicated to an innovative approach that goes beyond heating and ventilation by incorporating air conditioning systems (Bai et al., 2022; Bevilacqua et al., 2022; Guan et al., 2023; Huang et al., 2023; Liang et al., 2022; Long et al., 2022; Teodosiu et al., 2022; Wu et al., 2023; Xiao et al., 2023; Zhou et al., 2023). The application of this energy-efficient solution allows for an integrated system that optimizes indoor climate conditions, providing a comfortable and healthy environment for occupants. The authors present research demonstrating the effectiveness of using the Trombe wall to facilitate air exchange within buildings and maintain optimal microclimate parameters. Positive impacts on air quality and indoor comfort conditions are highlighted. The research results presented in the publications underscore the promising nature of this technology in the context of sustainable construction and energy efficiency, contributing to a comfortable and environmentally friendly living environment for occupants.

Despite the wide parametric application of the Trombe wall as an energy-efficient solar energy utilization technology, passive heating systems remain the most promising for widespread use. Therefore, further scientific research on such systems with the aim of enhancing their efficiency remains highly relevant (Luo et al., 2023; Mokni et al., 2022; Shapoval et al., 2017; 2019; 2021; Szuba, 2023; Ulewicz et al., 2022; Venhryn et al., 2023; Wang et al., 2023; Xiao et al., 2022; Zhelykh et al., 2016; 2020; 2021; 2022). The presented series of scientific publications provide practical recommendations for the implementation of the Trombe wall in construction projects to ensure optimal heating conditions. The benefits of this solution, such as reduced heating costs, energy conservation, and reduced carbon dioxide emissions into the environment, are analyzed. The conclusions presented in scientific articles emphasize the importance of using the Trombe wall for building heating, which significantly reduces dependence on traditional energy sources and promotes resource conservation. The research results provide a basis for the implementation of this technological solution in construction practice to stimulate sustainable development and reduce the impact on climate change.

1. Methodology

The aim of this research is to determine the thermal efficiency of an energy-efficient wall designed in the form of a Trombe wall and used as an external envelope for passive houses. Passive houses are designed in such a way as to provide the necessary thermal comfort inside the building through effective thermal insulation of external structures, ventilation systems, and other engineering technologies, primarily based on the use of alternative energy sources. Special attention is given to heating and air ventilation systems as they are the most energy-intensive components.

The paper proposes an original design of an energy-efficient external enclosure based on the use of a Trombe wall as a passive heating system (Fig. 1).

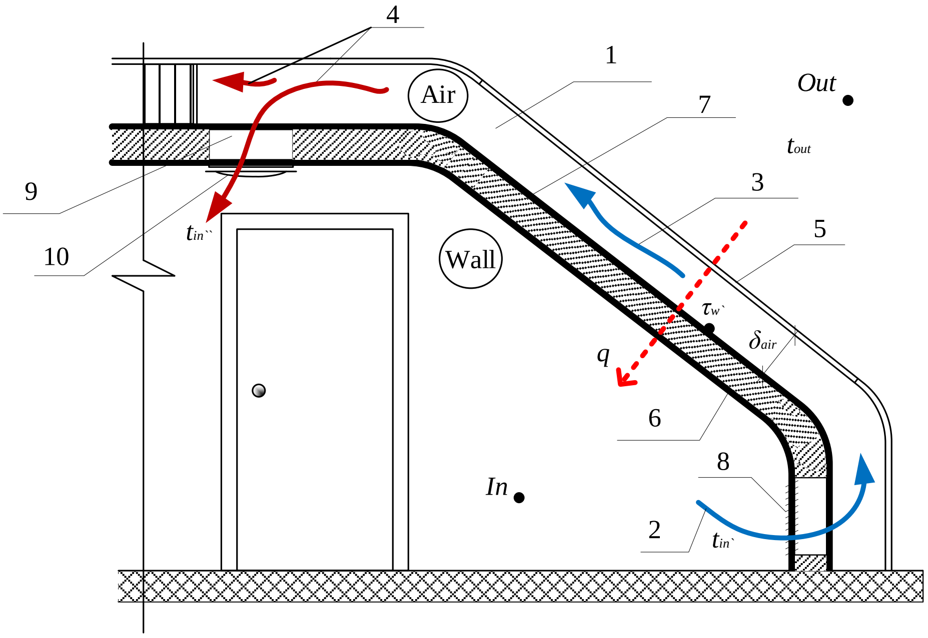

Fig. 1. Diagram of the energy-efficient wall operation during the cold season: 1 – air duct; 2 – cold air; 3 – heated air; 4 – warmed air; 5 – transparent enclosure; 6 – load-bearing protective structure; 7 – black surface; 8 – exhaust opening; 9 – intake opening; 10 – air distribution device; Wall – thermal capacity "Wall"; Air – thermal capacity "Air"; *q* – heat flow; *In* – indoor air; *Out* – outdoor air (*own research*)

During the cold season or transitional periods such as spring or autumn, when heating is needed during daylight hours, solar radiation penetrates through the transparent enclosure 5 and heats the black surface 7 on the load-bearing protective structure 6. This results in convective heat exchange between the heated black surface and the cold air 2, which enters the air duct 1 through the exhaust opening 8. Due to free air convection, the heated air 3 moves towards the intake opening 9 and through the air distribution device 10, the already warmed air 4 enters the room. This passive heating of the room occurs without the use of additional energy sources, by heating the indoor air from temperature $t_{\mathrm{in}`}$ to temperature $t_{\mathrm{in}``}$.

To assess the heat exchange processes that occur in the energy-efficient wall, a computational heat exchange scheme has been developed. In this scheme, heat flows between the elements of the external protective structure are to some extent considered, and for the convenience of modeling and identifying these processes, graph theory is proposed to be used. The arrows on the edges of the directed graph indicate the direction of heat flow. This approach allows for the efficient solution of direct and inverse heat transfer problems in the modeling, identification, and optimization of heat transfer processes. It is based on a systematic approach to solving complex heat transfer problems.

The structure of the energy-efficient wall is presented as a system of thermal capacities, between which heat exchange occurs and which interacts with heat sources (Fig. 2).

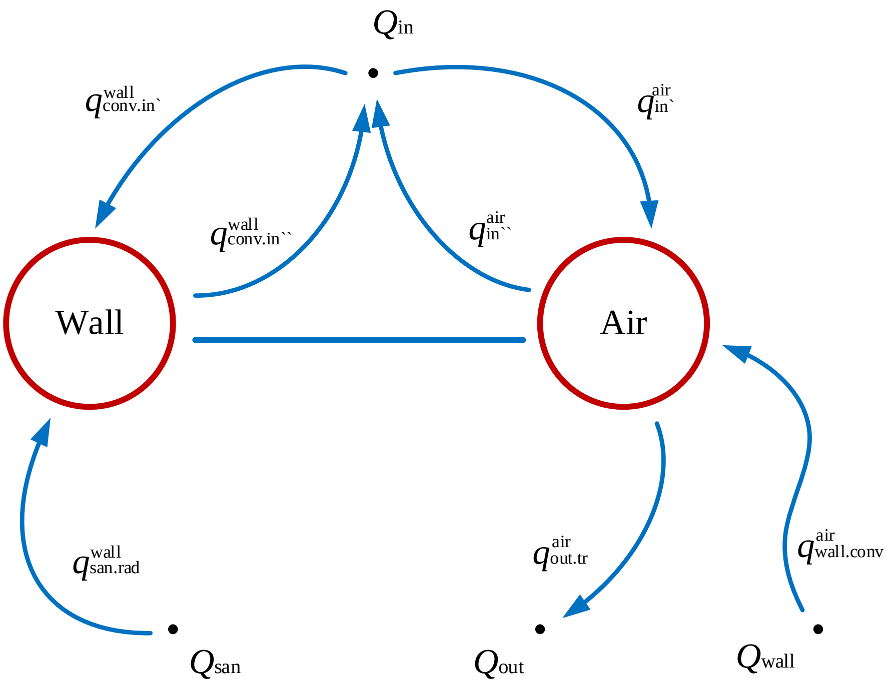

Fig. 2. Directed graph of heat flows in the energy-efficient wall.
Thermal Capacities: "Wall" – the structure of the energy-efficient wall; "Air" – the air layer.
Heat Sources: Q_{in} – indoor air; Q_{san} – solar radiation; Q_{out} – external environment.
Heat Flux: $q^{\text{wall}}_{\text{san.rad}}$ – solar radiation on the wall surface; $q^{\text{wall}}_{\text{conv.in`}}$ – convective heat exchange between cold air and the wall surface; $q^{\text{wall}}_{\text{conv.in``}}$ – heat flux during convective heat exchange between heated air and the wall surface; $q^{\text{air}}_{\text{in`}}$ – heat flux during heat exchange between indoor air and air in the air layer; $q^{\text{air}}_{\text{in``}}$ – heat flux during heat exchange between inflowing air and indoor air; $q^{\text{air}}_{\text{wall.conv}}$ – heat flux during convective heat exchange between the wall surface and air in the air layer; $q^{\text{air}}_{\text{out.tr}}$ – heat flux due to transmission heat loss from the wall surface (*own research*)

The design features two thermal capacities, or nodes of the graph: the load-bearing wall structure – thermal capacity "Wall"; the air in the air channel – thermal capacity "Air". The thermal interaction between the capacities, as well as with the heat sources, is represented as directed edges connecting the nodes. Accordingly, an extended matrix of isolated thermal capacities has been formed:

	Wall	Air	
Wall	0	ΔQ_{wall}	$\pm Q^{\text{wall}}_{\text{san.rad}} \pm Q^{\text{wall}}_{\text{in`.conv}} \pm Q^{\text{wall}}_{\text{in``.conv}}$
Air	ΔQ_{air}	0	$\pm Q^{\text{air}}_{\text{in``}} \pm Q^{\text{air}}_{\text{in`}} \pm Q^{\text{air}}_{\text{wall.conv}} \pm Q^{\text{air}}_{\text{out.tr}}$

The heat balance for the thermal capacity "Wall" can be expressed as follows:

$$\Delta Q_{\text{wall}} = \pm Q_{\text{san.rad}}^{\text{wall}} \pm Q_{\text{in`.conv}}^{\text{wall}} \pm Q_{\text{in``.conv}}^{\text{wall}} = 0, \qquad (1)$$

where: $Q_{\text{san.rad}}^{\text{wall}}$ – the solar radiation [W]; $Q_{\text{in`.conv}}^{\text{wall}}$ – the convective heat exchange between the exhaust air and the heated surface [W]; $Q_{\text{in``.conv}}^{\text{wall}}$ – the convective heat exchange between the heated surface and the incoming air [W].

The system of balance equations for the thermal capacity "Wall" can be expressed as follows:

$$\begin{cases} Q_{\text{san.rad}}^{\text{wall}} = A * F * G \\ Q_{\text{in`.conv}}^{\text{wall}} = \alpha_{\text{air}} \times A \times (\tau_{\text{wall}} - t_{\text{in`}}) \\ Q_{\text{c.in}}^{\text{wall}} = \alpha_{\text{air}} \times A \times (\tau_{\text{wall}} - t_{\text{in``}}) \end{cases} \qquad (2)$$

where: A – the surface area of the wall [m^2]; F – the surface absorption coefficient (a dimensionless quantity that reflects how much of the solar radiation the surface absorbs), since the heat-absorbing surface of the energy-efficient wall construction is black, the absorption coefficient can be approximately estimated at 0.9-0.95; G – the intensity of solar radiation on the wall surface [W/m^2]; α_{air} – the heat transfer coefficient from the black surface of the wall construction to the air [W/(m^2·°C)]; τ_{wall} – the temperature on the black surface of the wall construction [°C]; $t_{\text{in`}}$ – the temperature of the air inside the room [°C]; $t_{\text{in``}}$ – the temperature of the incoming air [°C].

The heat balance for the thermal capacity "Air" can be expressed as:

$$\Delta Q_{\text{air}} = \pm Q_{\text{in``}}^{\text{air}} \pm Q_{\text{in`}}^{\text{air}} \pm Q_{\text{wall.conv}}^{\text{air}} \pm Q_{\text{out.tr}}^{\text{air}} = 0, \qquad (3)$$

In this equation: $Q_{\text{in``}}^{\text{air}}$ – the heat carried away from the energy-efficient wall structure with incoming air [W]; $Q_{\text{in`}}^{\text{air}}$ – the heat introduced into the air layer with cold air [W]; $Q_{\text{wall.conv}}^{\text{air}}$ – the convective heat exchange between the heated black surface and the air in the air layer [W]; $Q_{\text{out.tr}}^{\text{air}}$ – the transmission heat losses from the air layer [W].

The system of balance equations for the thermal capacity "Air" is as follows:

$$\begin{cases} Q_{\text{in``}}^{\text{air}} = G_{\text{in}} \times c_{\text{p}} \times (-t_{\text{in``}}) \\ Q_{\text{in`}}^{\text{air}} = G_{\text{in}} \times c_{\text{p}} \times \left(\overline{t_{\text{air}}} - t_{\text{in`}}\right) \\ Q_{\text{wall.conv}}^{\text{air}} = \alpha_{\text{air}} \times A \times (\tau_{\text{wall}} - \overline{t_{\text{air}}}) \\ Q_{\text{out.tr}}^{\text{air}} = k \times A \times \left(\overline{t_{\text{air}}} - t_{\text{out}}\right) \end{cases}, \qquad (4)$$

where: G_{in} – the air flow rate in the air layer [kg/s]; c_{p} – the specific heat capacity of air [J/(kg·°C)]; $\overline{t_{\text{air}}}$ – the average temperature of the air in the air layer [°C], which is determined from the equation:

$$\overline{t_{\text{air}}} = \frac{t_{\text{in}`} + t_{\text{in}``}}{2}, \tag{5}$$

α_{air} – the heat transfer coefficient from the heated wall surface to the air [J/(m^2·°C)]; τ_{wall} – the temperature of the heated wall surface [°C]; k – the heat transfer coefficient through the transparent shield [W/(m·°C)]; t_{out} – the temperature of the external air [°C].

2. Results and discussion

To ensure the uniqueness of the balance equations' solution for the purpose of determining the temperature of the inflow air $t_{\text{in}``}$, which, after heating in the air gap of the wall structure, enters the room, a series of assumptions and simplifications were made. In particular, the heat exchange process in the energy-efficient wall structure was assumed to be stationary; the wall surface area was assumed to be multiple of 2 m^2 and varied from 2 to 12 m^2. The intensity of solar radiation on the wall surface was taken for regions with a moderate climate during the transitional periods of the year, i.e., spring and autumn when heating is needed. The intensity value was considered in the range of 400-1000 W/m^2. The solution of the system of balance equations to obtain the dependence between the main parameters that determine the degree of heating of the inflow air $t_{\text{in}``}$ [°C], the wall surface area A [m^2], and the intensity of solar radiation G [W/m^2] was performed using the Mathcad software package.

The systems of balance equations were solved with respect to the surface area of the wall A and the solar radiation intensity G. Since the systems of equations contained a significant number of significant factors, the "simplify" operator was used to obtain an algebraic expression. It allowed improving the presented calculation results and making them more understandable and easier to analyze. To obtain parametric solutions, the "solve" operator was used, as the temperature of incoming air $t_{\text{in}``}$ was expressed in terms of other parameters.

The calculation results are presented in Figure 3.

The dependency clearly shows that this wall construction, based on the Trombe wall, is quite effective. Even with a small surface area, specifically 2 m^2, the temperature of the incoming air supplied to the passive house for heat loss compensation remains within the range of 35 to 37°C. With such a degree of air heating and sufficient airflow during the transitional seasons, it is possible to establish air heating to maintain a warm environment inside the rooms. Additionally, it should be noted that for a relatively large wall construction area within the range of 10 to 12 m^2, the temperature of the incoming air does not exceed 50°C. This temperature does not exceed the comfort and safety thresholds for human health. However, temperatures exceeding 50°C can lead to the decomposition of microorganisms present in the air. High temperatures can affect bacteria, viruses, and other microorganisms, resulting in unpleasant odors and negatively impacting air quality.

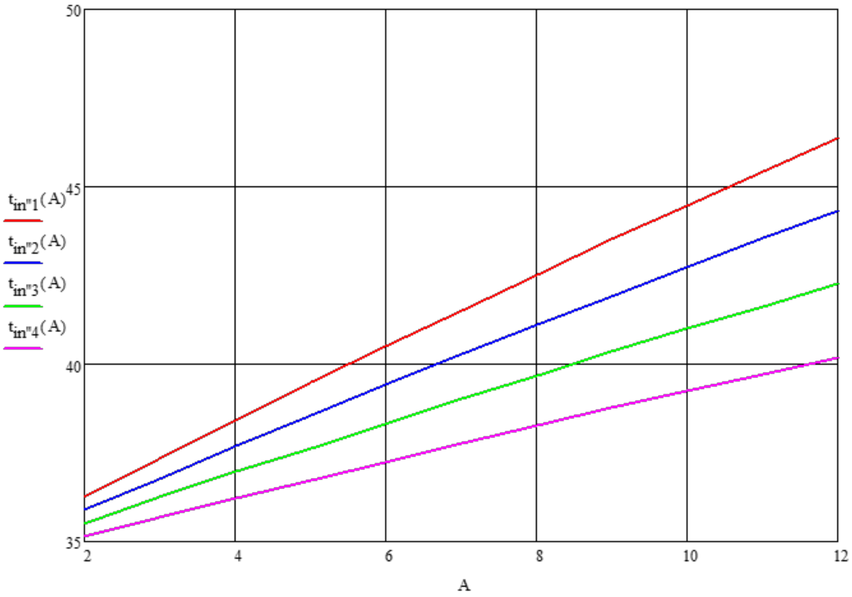

Fig. 3. The graphical dependence of the incoming air temperature $t_{in``}$ on the surface area of the energy-efficient wall $A$, at different values of solar radiation intensity $G$ is shown (*own research*): $t_{in``1}(A) \rightarrow G$ = 1000 W/m^2; $t_{in``2}(A) \rightarrow G$ = 800 W/m$^2$; $t_{in``3}(A) \rightarrow G$ = 600 W/m^2; $t_{in``4}(A) \rightarrow G$ = 400 W/m^2

Conclusions

Thus, the methodological approach presented in the article for analyzing heat exchange processes using graph theory has facilitated a broad parametric assessment of factors influencing the performance of the external wall construction of a passive house based on the Trombe Wall. This approach allowed for visualizing the structure and relationships between different elements of the heat exchange system, thus simplifying the understanding of the processes involved. It contributed to the analysis of a complex system with many interdependent components. Graphs clearly delineated the components of the system and their connections, including the thermal capacities of "Wall" and "Air." This helped analyze how different heat sources within the system interact and affect heat exchange.

The obtained graphical physical model was used for mathematical modeling of heat exchange processes and predicting the performance efficiency of the wall construction in the Mathcad software package. One of the results was the graphical dependence of the incoming air temperature $t_{in``}$ [°C] on the surface area of the energy-efficient wall A [m^2] at different values of solar radiation intensity G [W/m^2] for regions with a moderate climate.

The obtained graphical dependency has practical value as it can be used by architects and engineers in the design of passive houses with an efficient passive heating system based on Trombe wall technologies. This dependency allows for determining the required wall area and building orientation to maximize the utilization of solar energy and reduce energy consumption. Additionally, an assessment was conducted on how solar radiation affects the incoming air temperature. For instance, with a solar radiation intensity of G = 400 W/m^2, increasing the area of the energy-efficient wall by 2 m^2 results in a 1°C increase in the incoming air temperature with a constant airflow rate in the air duct. This helps determine how effectively the system can utilize solar energy for regulating the temperature in a passive house.

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