[1.] Snežana DRAGIĆEVIĆ

THERMODYNAMIC ANALYSIS OF A SOLAR WALL SYSTEM FOR AIR HEATING AND ENERGY STORAGE

[1.] University of Kragujevac, Faculty of Technical Sciences in Čačak, SERBIA

Abstract: In this paper, the thermodynamic analysis of a solar wall air heating system featuring a central duct filled with heat storage material is presented. The analyzed system comprises a double–glazing structure and a substantial wall incorporating an opening with a central duct, which is filled with heat storage material. To enhance its operational efficiency, a fan is positioned at the lower vent of the wall. A one–dimensional steady–state mathematical model is developed to simplify the analytical assessment of the air heating system's effectiveness within the active solar wall. This model accounts for the simultaneous heating of the air in the room and energy accumulation. Subsequently, the acquired data are analyzed to forecast the potential impacts of operational and environmental parameters on the thermal efficiency of the system.
Keywords: solar wall, thermodynamic model, air heating, energy storage

1. INTRODUCTION

Energy is the primary driver of technological advancement. Historically, humanity's utilization of energy sources evolved slowly over thousands of years. In the last century, primarily due to industrialization and population growth, the demand for energy has exponentially increased year by year. In the past few decades, at the beginning of the new millennium, renewable energy sources, especially solar energy, have played an increasingly significant role in global energy production.

In the era of increasing environmental awareness and the pursuit of sustainable energy solutions, the utilization of solar energy for indoor air heating has gained prominence as a subject of significant scholarly interest and practical relevance. This paradigm shift underscores the recognition of the advantages offered by solar–based heating systems, particularly in their capacity to reduce environmental impact and enhance energy efficiency within confined spaces. The application of solar energy to meet the indoor heating demands of residential, commercial, and industrial spaces represents a pivotal convergence of renewable energy utilization and improved indoor environmental quality.

Solar space heating systems rely on the use of massive solar walls covered with transparent coatings, whose radiated surface has good absorption characteristics and the wall mass possesses significant heat storage capacity. The massive active solar wall could be constructed with a central duct within the wall [1–3]. This construction allows for a faster and more efficient transfer of heat from the receiving space, where significant heat losses occur, to the central part of the wall, which can be constructed with or without fill material. The circulation of heated air from the receiving space to the central duct can be natural (thermosiphon) or forced, requiring the installation of fans in the wall opening.

Solar walls have been the subject of extensive experimentation and research investigations. Numerous theoretical and empirical studies have substantiated the enhancement of indoor comfort attributed to well–designed solar walls [4–6]. Given the increasing prominence of massive solar walls in the context of space heating applications, it becomes imperative to undertake precise testing procedures aimed at evaluating the optimal wall parameters conducive to achieving energy efficiency operating conditions. In this paper, a thermodynamic analysis has been performed on a solar wall featuring a central duct filled with energy–storing material. Analyzed configuration of the solar wall is employed for both concurrent air space heating and energy storage within the wall.

2. MATERIAL AND METHODS

Heat transfer analysis

The analyzed model of a solar wall for space heating, with simultaneous heat accumulation in the inner layers of the wall and the filling material of the central duct, is illustrated in Figure 1. The material used to fill the central duct of the wall can be in the form of solid pieces, homogeneous material, or a combination of both. It is important for the surface of the filling material in contact with heated air to be as large as possible, as this results in a greater contact surface area for heat exchange within the given volume. By using smaller–sized granules, a more even distribution of hot air contact is ensured throughout the filling, accommodating a larger mass within a specific volume. After a certain period of heat accumulation, there is also a more even temperature distribution of the filling material. If homogeneous material is used for filling, it results in a smaller contact surface area for heat exchange, and it takes more time to heat these pieces to their depth.

The utilization of this solar wall model facilitates enhanced heat accumulation within the inner wall layers and a more even temperature distribution along the wall. Thermodynamic analysis was carried out for the wall exposed to global solar radiation G, while the room air temperature is maintained at T_p.

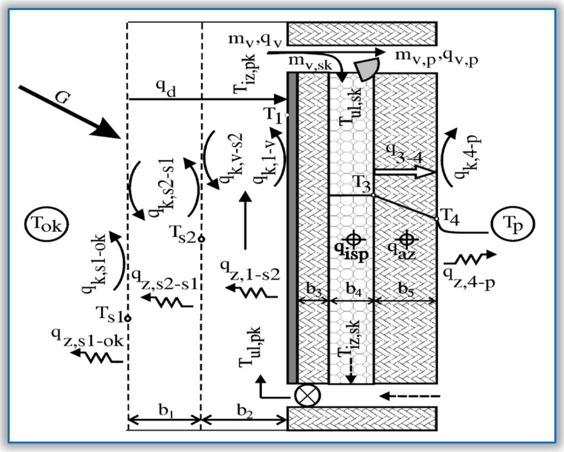

Figure 1. Active solar wall with a filled duct space – simultaneous airflow to the central duct and the heated room

The characteristic temperatures, given in Figure 1, are as follows:

- T_{ok} – ambient air temperature
- T_1 – absorber temperature
- T_3 and T_4 – temperatures of the boundary surfaces inside the wall
- T_{s1} and T_{s2} – glass cover temperatures
- $T_{ul,pk}$ and $T_{iz,pk}$ – temperatures at the inlet and outlet of the receiving duct of the wall
- $T_{ul,sk}$= $T_{iz,pk}$ and $T_{iz,sk}$ – temperatures at the inlet and outlet of the central duct of the wall.

Heat exchange between structural elements of the wall occurs through conduction, convection and radiation. When considering the heat effects of solar radiation during the heating phase of the wall, the amount of heat carried by the heated air from the receiving duct to the central duct of the wall is distributed as follows:

- q_{isp} – a portion of the heat is absorbed by the material in the central duct
- q_{az} – a portion is absorbed within the inner part of the solar wall
- q_{3-4} – some of the heat is conducted through the inner wall towards the heated room
- The remaining heat is returned from the central to the receiving duct of the solar wall. The energy potential of the return air stream from the heated room is negligible compared to the potential of the air flowing through the receiving duct. Therefore, the heat flux of the return air stream can be disregarded in energy balances.

Thermodynamic model

A thermodynamic model is established for cases where the temperature within the heated room falls below a specified level, prompting the need for the circulation of warm air into the room. The geometrical, thermo–physical and operational parameters of the system are:

- Double glass glazing unit: b_1=b_2=10 cm
- Solar wall parameters: ρ_z=2400 kg/m^3, ρ_{isp}=1840 kg/m^3, c_{isp}=800 J/kgK, H=2.7m, Y=3m, λ_z=0.9 W/mK, b_3=b_4=5 cm, b_5=10 cm
- Ambient conditions: t_{ok}=0°C, w_v=0 m/s.

The mass and energy balance equations for the solar wall model shown from Figure 1 are as follows:

$$\mathrm{m_v = m_{v,p} + m_{v,sk}} \quad (1)$$

$$\mathrm{m_v = \frac{2}{3} w_o \rho_v b_2 Y} \quad (2)$$

$$\mathrm{q_v = q_{v,p} + q_{isp}} \quad (3)$$

where are:

$\mathrm{m_v}$[kg/m^3] mass flow rate of air through the receiving duct of the wall;

$\mathrm{m_{v,p} = \xi m_v}$ [kg/m^3] mass flow rate of air flowing from the receiving duct of the wall into the heated room;

$\mathrm{w_o}$ [m/s] the air velocity at the inlet of the entrance duct;

$\xi \in (0 \div 1)$ the coefficient that defines the mass flow rate of air from the receiving duct to heated room;
$m_{v,sk} = (1-\xi)m_v$ [kg/m^3] mass flow rate of air flowing from the receiving duct to the central duct of wall;
q_v [W/m^2] heat flux carried by the heated air from the receiving duct;
$q_{v,p} = \xi q_v$ [W/m^2] heat flux that the heated air from the receiving duct transfers to the air in heated room;
$q_{isp} = (1-\xi)q_v$ [W/m^2] heat flux that the heated air carries from the receiving duct to the accumulating material in the central duct of the wall.
The heat flux that heated air carries from receiving duct can be calculated from the following equation:

$$q_v = h_{p,k}(T_1 + T_{s2} - T_{ul,pk} - T_{iz,pk}) = h_{p,k}\left\{\left[\frac{1}{2}(T_1 + T_{s2}) - T_{ul,pk}\right]\left(1 + e^{-\frac{3h_{p,k}H}{c_p\rho_v w_o b_2}}\right)\right\} \quad (4)$$

$$h_{p,k} = 2.27\,\left(\frac{w_o}{b_2}\right)^{0.5} \quad (5)$$

$$T_{iz,pk} = \frac{1}{2}(T_1 + T_{s2})(1 - e^{-\theta}) + T_{ul,pk}e^{-\theta} \quad \theta = \frac{6.81H}{c_p\,\rho_v\,w_o^{0.5}b_2^{1.5}} \quad (6)$$

where $h_{p,k}$ [W/m^{2}K] represents heat transfer coefficient in the receiving duct of the wall.
In the analyzed solar wall model, heat can accumulate in the inner part of the wall and in the material filling the central duct because it is assumed that the external part of the wall is of small thickness and does not have significant energy storage capacity. The energy balance for the air flowing through the central duct of the wall is as follows:

$$q_{sk} = q_{isp} + q_{az} + q_{3-4} \quad (7)$$

$$(1-\xi)\frac{2}{3}\rho_v w_o b_2 Y c_p (T_{ul,sk} - T_{iz,sk})\tau = \rho_{isp} b_4 YZ\zeta c_{isp}(T_{isp,\tau} - T_{isp,o}) + \\ +\rho_z b_4 YZ c_z (T_{z,\tau} - T_{z,o}) + \frac{\lambda_z}{b_5}(T_3 - T_4)YZ\tau \quad (8)$$

where are $T_{isp,\tau}$ respresents temperature of the material fills up after the observed time of heat transfer.
Simplifications of the mathematical model are:

- The initial average temperature of the filling material, as well as that of the inner wall section, is presumed to be equal to the air temperature in the room: $T_{isp,o} = T_{z,o} = T_p$;
- The average temperature of the filling material, following the observed time period of heat transfer, is identical to the temperature of the exterior surface of the inner wall section $T_{isp,\tau} = T_3$;
- The average temperature of the inner part of the wall after the observed time period of heat transfer is calculated as $T_{z,\tau} = (T_3 + T_4)/2.$

The thermal efficiency of the system, which represented the ratio of the useful heat gain to the global solar power received by the wall, can be expressed using next equation:

$$\eta = \frac{q_{v,p} + q_{4-p}}{q_G + \varepsilon_v} \quad (9)$$

where are:
$q_G = \tau\alpha G$ [W/m^2] the heat flux incident upon the absorber due to solar radiation;
q_G transmittance–absorptance product for the glass cover–absorber system;
ε_v [W/m^2] electrical energy consumed for the fan operation;
q_{4-p} [W/m^2] heat flux transferred through the inner part of the wall to the room air, through radiation and convection, can be calculated using the following equation:

$$\frac{\lambda_z}{b_5}(T_3 - T_4) = 11.24\frac{(T_4 - T_p)^{1.33}}{T_p^{0.33}} + \varepsilon_z\sigma(T_4^4 - T_p^4) \quad (10)$$

where $\varepsilon_z = 0.95$ is emissivity coefficient of the wall material, and $\sigma = 5.67 \cdot 10^{-8}$ [W/m^{2}K^4] Stefan–Boltzmann constant.
Following the development of the mathematical model for the solar air heating system designed for simultaneously air heating and energy storage within the interior section of the wall, a series of numerical simulations has been carried out to evaluate the efficiency of the proposed air solar heating system.

3. RESULTS AND DISCUSSION

The thermal analysis of such a system presents a significant complexity due to the potential variations in construction, operational, and environmental parameters. Consequently, in the efficiency studies conducted on the presented solar wall system, certain parameters are held constant, while the impact of two specific parameters is subject to accurate analysis [7].

The influence of global solar radiation intensity on the efficiency of the system for different mass flow rates of air flowing from the receiving space to the heating room is depicted in Figure 2. As the global solar radiation increases, the heat flux leaving the receiving duct and heating the air in the heating room also increases, leading to a higher thermal efficiency of the heating system. The figure also illustrates that with an increase in the flow coefficient of the heated air from the receiving duct to the room, the thermal efficiency of the analyzed heating system increases. The thermal efficiency of the wall increased with a mass flow rate up to 57 %. The impact of these parameters on the system efficiency is more pronounced for global solar radiation values up to 600 W/m^2, as the efficiency of the system remains approximately constant for higher values of solar radiation for the analyzed parameters.

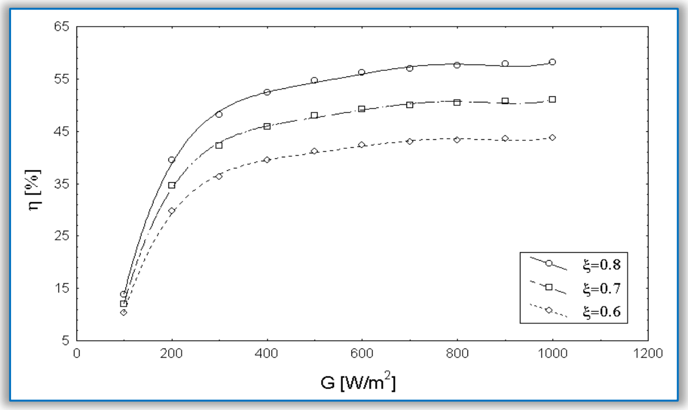

Figure 2. Variation in the thermal efficiency of the solar wall with a global solar radiation for different air mass flow rate coefficient ξ, $w_o = 1\frac{m}{s}, \tau = 15$ min

The influence of the width of the central duct of the wall on the intensity of heat flux that the heated air carries from the receiving duct to the accumulating material in the central duct of the wall, for different values of global solar radiation is shown in Figure 3. The simulation results of the system operation indicate an increase in the heat flux accumulated in the filling material as global solar radiation increases. For a specific intensity of global solar radiation, the heat flux is greater when the width of the central duct of the wall is larger.

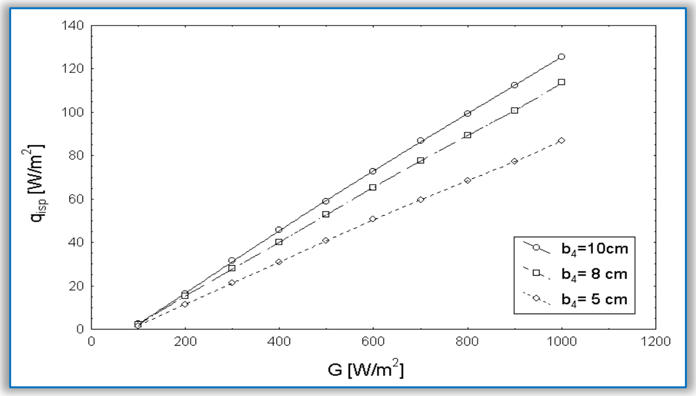

Figure 3. Variation in the heat flux accumulated in the filling material in the central duct with a global solar radiation, for different width of the central duct b_4, $w_o = 1\frac{m}{s}, \tau = 15$ min, $\xi = 0.6$

The influence of the time period of heat transfer on the thermal efficiency is depicted in the diagram shown in Figure 4. The figure illustrates that for a longer time period of heat transfer, the thermal efficiency is higher, and vice versa. The thermal efficiency of the system increases with the increase in the air flow rate at the inlet of the receiving duct up to a velocity of 6 m/s, after which it slightly decreases. The results show that the maximum thermal efficiency of the system for the analyzed parameters is 52%.

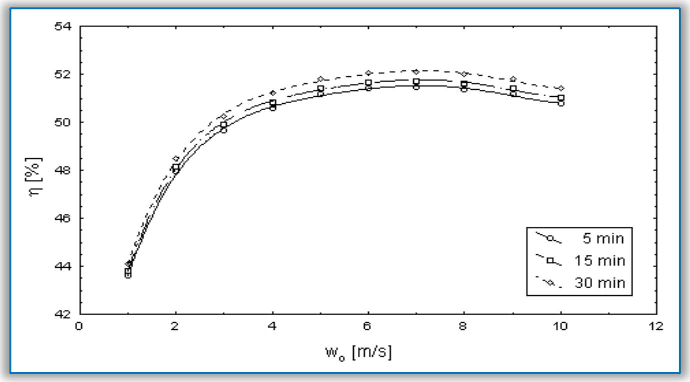

Figure 4. Variation in the thermal efficiency with the air velocity at the inlet of the entrance duct, for different time of heat transfer, $G = 1000 \frac{W}{m^2}, \xi = 0.6$

ISSN 1584 – 2665 (printed version); ISSN 2601 – 2332 (online); ISSN-L 1584 – 2665

4. CONCLUSION

The findings from this study provide valuable insights into the effectiveness of air heating using an active solar wall featuring a central duct, under various operating and environmental conditions. The active solar wall model under analysis serves the dual purpose of heating the room and storing energy when exposed to sunlight. The optimization results for this active solar wall model were obtained while maintaining the room's air temperature at 20 °C.

The findings presented in this study reveal a trend in thermal efficiency concerning the impact of solar radiation levels and inlet air velocity on a solar wall system designed for air heating in enclosed spaces. Notably, there is a substantial increase in thermal efficiency as solar radiation levels elevate from 100 to 600 W/m^2. Additionally, increase in inlet air velocity at the entrance duct correlates with improved thermal efficiency. It is observed that for the analyzed duration of heat transfer, air velocities of up to 4 m/s result in a significant efficiency boost, after which the efficiency remains relatively stable. The examined solar wall model, engineered for space heating purposes, incorporates a central channel filled with an accumulating material. Notably, the width of this central channel exhibits a linear relationship with the heat flux accumulated within the filling material, elucidating an important parameter for system optimization.

This analysis provides users with the means to evaluate the thermal efficiency and heat fluxes of the solar wall air heating system. Results show comparative analyses and predictive modeling of the thermal performance of the presented solar wall under diverse operational conditions.

Acknowledgements

This study was supported by the Ministry of Education, Science and Technological Development of the Republic of Serbia, and these results are parts of the Grant No. 451–03–68/2023–14/200132 with University of Kragujevac – Faculty of Technical Sciences Čačak, Serbia.

References

[1] Szyszka, J., Bevilacqua, P., Bruno, R., An Innovative Trombe Wall for Winter Use: The Thermo–Diode Trombe Wall, Energies,, 13, 2188; doi:10.3390/en13092188, 2020.
[2] Yuewei Zhu, Y., Zhang, T. Ma, Q., Fukuda, H., Thermal Performance and Optimizing of Composite Trombe Wall with Temperature–Controlled DC Fan in Winter, Sustainability, 14, 3080. https://doi.org/10.3390/su14053080, 2022.
[3] Abbas, E., Al–abady, A., Raja, V., AL–bonsrulah, H., Al–Bahrani, M., Effect of air gap depth on Trombe wall system using computational fluid dynamics, International Journal of Low–Carbon Technologies, Vol. 17, pp. 941–949, 2022.
[4] Briga–Sa, A., Boaventura–Cunha, J.,Lanzinha, J.C., Paiva, A., Experimental and analytical approach on the Trombe wall thermal performance parameters characterization, Energy and Buildings, Vol. 150, pp. 262–280, 2017.
[5] Kunelbayev, M., Bigaliyeva, Z., Tuleshov, Y., Ibekeyev, S., Kerimkulov, D., Thermodynamic Analysis of an Experimental Model of a Solar–Heat Supply System, Processes, Vol. 11, No. 2, 451, 2023.
[6] Shen, X., Li, N., Lu, J., Yongga, A., Heating Performance of Solar Building Integrated Wall under Natural Circulation, Energies, Vol. 13, 6288, 2020.
[7] Mokni, A., Lashin, A., Ammar, M., Mhiri, H., Thermal analysis of a Trombe wall in various climatic conditions: An experimental study, Solar Energy, Vol. 243, No. 1, pp. 247–263, 2022.

Note: This paper was presented at IIZS 2023 – The XIII International Conference on Industrial Engineering and Environmental Protection, organized by Department of Mechanical Engineering and Department of Environmental Protection of the Technical Faculty “Mihajlo Pupin” Zrenjanin, from the University of Novi Sad, in cooperation with partners – University Politehnica Timisoara, Faculty of Engineering, Hunedoara (ROMANIA), University "St. Kliment Ohridski", Technical Faculty, Bitola (MACEDONIA), "Aurel Vlaicu" University of Arad, Faculty Of Engineering, Arad (ROMANIA), University of East Sarajevo, Faculty of Mechanical Engineering East Sarajevo, Sarajevo (BOSNIA & HERZEGOVINA) and University of Giresun, Faculty of Engineering, Giresun (TURKEY) – in Zrenjanin, SERBIA, in 05–06 October, 2023.

ISSN 1584 – 2665 (printed version); ISSN 2601 – 2332 (online); ISSN-L 1584 – 2665