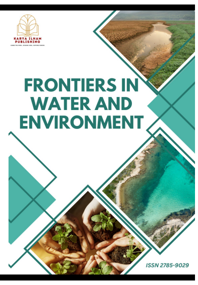
KARYA ILHAM PUBLISHING
CONNECTING MINDS, BRIDGING IDEAS, INSPIRING READERS

Frontiers in Water and Environment

Journal homepage:
https://karyailham.com.my/index.php/fwe/index
ISSN: 2785-9029



Thermal Performance Assessment of a Greenhouse-Assisted Solar Water Heater with Sand Thermal Storage

Ega Alfaizin Saputro[1], Panorama Gravyn Augusta[1], Abdillah Harits Ash-Shidiqi[1], Zelda Amanda Putri[1], Singgih Dwi Prasetyo[1,*]

[1] Power Plant Engineering Technology, Faculty of Vocational Studies, State University of Malang, Malang 65145, Indonesia

ARTICLE INFO

Article history:
Received 11 April 2026
Received in revised form 20 May 2026
Accepted 10 June 2026
Available online 6 July 2026

Keywords:

Hydropower performance; power plant efficiency; water discharge analysis; operational hours; energy conversion

ABSTRACT

The increasing demand for domestic water heating, coupled with the environmental impact of fossil fuel-based systems, has driven the need for sustainable and low-carbon thermal technologies. This study presents a thermal performance assessment of a greenhouse-assisted solar water heater integrated with sand-based thermal energy storage. A three-dimensional steady-state numerical model was developed using ANSYS Fluent to analyze the coupled heat transfer mechanisms, including conduction, convection, and radiation within the system. The system consists of a transparent cover to induce the greenhouse effect, a black absorber surface, a sand thermal storage medium, and a spiral coil heat exchanger for water heating. The results show that the absorber region reaches a maximum temperature of approximately 127°C, while the inlet water temperature of around 72°C increases to about 93°C at the outlet, indicating a temperature rise of over 20°C. The sand storage medium demonstrates effective heat retention, contributing to a more uniform temperature distribution and prolonged thermal energy release. Heat flux analysis reveals that the highest heat transfer occurs at the absorber surface, while heat losses are primarily observed at the outer wall. The integration of sand-based thermal storage and greenhouse effect significantly enhances the thermal performance of the system, improving energy utilization and stability. The system operates passively without additional energy input, making it an environmentally friendly and low-carbon solution for residential water heating. However, its performance remains dependent on solar radiation intensity, suggesting the need for further optimization under varying environmental conditions.

1. Introduction

The increasing demand for domestic hot water, driven by population growth and improved living standards, has significantly contributed to global energy consumption and carbon emissions, particularly from conventional systems based on electricity and fossil fuels [1]. This situation

* *Corresponding author.*
E-mail address: singgih.prasetyo.fv@um.ac.id

highlights the urgent need for sustainable and low-carbon heating technologies. Among various renewable energy solutions, solar water heating systems have attracted considerable attention due to their ability to utilize abundant solar energy and reduce environmental impact [2]. These systems are widely recognized for their efficiency and economic feasibility in residential applications, although their performance is strongly influenced by system design and operational conditions [3], [4]. One of the main challenges in solar water heating systems is the intermittent nature of solar radiation, which leads to fluctuations in thermal performance and limits system reliability [5]. To overcome this issue, thermal energy storage (TES) has been introduced to store excess heat during peak solar radiation and release it during low or no solar input [6]. Various storage materials have been investigated, including phase change materials (PCMs) and sensible heat storage media. Although PCMs offer high energy storage density, their high cost and stability issues restrict widespread application [7]. In contrast, sensible heat storage materials such as sand have emerged as a promising alternative due to their low cost, high thermal stability, and availability [8,9].

In addition to thermal storage, improving heat retention within the solar collector is essential for enhancing system efficiency [10]. The application of the greenhouse effect mechanism, achieved through the use of transparent covers, allows solar radiation to enter while reducing heat losses to the environment [11,12]. Previous studies have demonstrated that this mechanism can significantly improve thermal performance by maintaining higher internal temperatures [13]. Furthermore, computational fluid dynamics (CFD) has been widely used as an effective tool to analyze heat transfer and fluid flow in solar thermal systems, enabling detailed investigation of temperature distribution and system performance under varying conditions [14,15].

Despite the extensive research on solar water heaters and thermal energy storage systems, which have been widely studied for improving energy efficiency and system performance [16], limited studies have investigated the integrated performance of sand-based thermal storage combined with a greenhouse effect mechanism using numerical simulation approaches. Most existing works tend to focus either on storage materials or on collector enhancements separately, leaving a gap in understanding the coupled heat transfer behavior within such integrated systems. Therefore, this study aims to conduct a numerical investigation of a solar water heating system incorporating sand as a thermal energy storage medium and a greenhouse effect mechanism using ANSYS Fluent. The objective is to evaluate the thermal performance, temperature distribution, and energy storage characteristics of the system, as well as to assess its potential as a sustainable and low-carbon solution for residential water heating applications.

2. Methodology

2.1 Research Approach

This research was conducted through a systematic sequence of stages as illustrated in **Figure 1**, beginning with a literature study to establish a theoretical foundation on solar water heating systems, heat transfer mechanisms (conduction, convection, and radiation), thermal energy storage, and the greenhouse effect in solar collectors. The next stage involved modelling and simulation using Computational Fluid Dynamics (CFD), which is widely recognized as an effective tool for analyzing heat transfer and fluid flow in thermal systems [17]. A geometric model of the solar water heater system consisting of the collector, water domain, and sand as a thermal energy storage medium was developed and meshed to ensure accurate numerical results. The simulation parameters were then defined by incorporating conduction in solid materials, convection between fluid and surfaces, and radiation from solar energy to represent real operating conditions [18]. Subsequently, simulations were conducted under specified boundary conditions such as solar radiation intensity, ambient temperature, and initial water temperature. The results were analyzed by observing temperature distribution, heat flux, and temperature profiles using probes to evaluate heat absorption, storage, and transfer characteristics within the system. Finally, all findings were comprehensively evaluated to draw conclusions regarding the effectiveness of the solar water heater integrated with sand-based thermal energy storage in improving thermal efficiency and supporting low-carbon energy utilization.

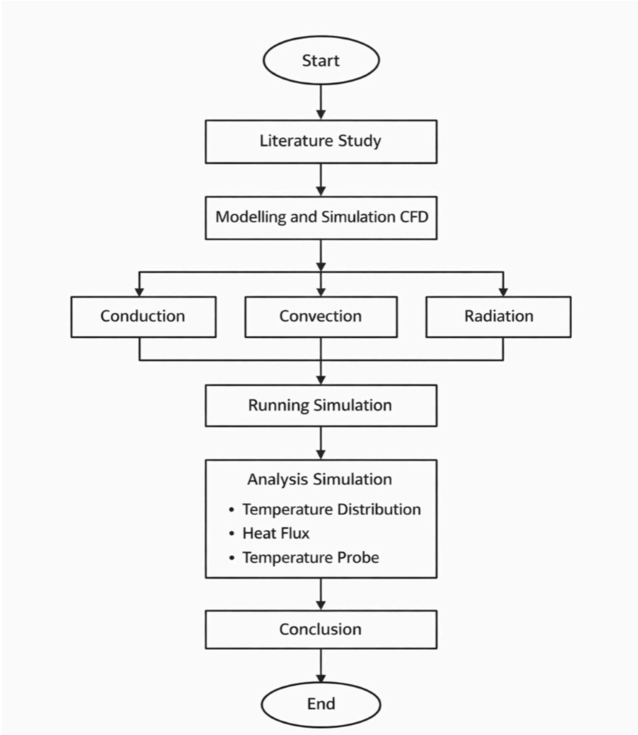


Fig. 1. Flowchart the research

2.2 System Desian

The system design in this study is developed in the form of a solar water heater integrated with sand as a thermal energy storage medium, as illustrated in **Figure 2.** The system consists of a solar collector, a heating chamber, a water flow channel, and a sand storage layer, where the collector functions to absorb solar radiation and convert it into thermal energy that is subsequently transferred to the water and surrounding materials. The model includes an inlet for water entry and an outlet for heated water discharge to ensure continuous flow within the system. The collector is equipped with a transparent cover to create a greenhouse effect, allowing solar radiation to enter and be trapped inside, thereby increasing the internal temperature. Sand is utilized as a thermal storage medium due to its ability to absorb, store, and gradually release heat, which helps maintain temperature stability. The geometry of the system is created using CAD software and then imported into ANSYS Fluent for simulation, with internal surfaces assumed to be smooth to simplify the analysis and focus on heat transfer behavior rather than surface roughness effects. With this design, the temperature distribution, heat transfer characteristics, and overall system performance can be analyzed more realistically, representing practical applications in solar water heating systems.

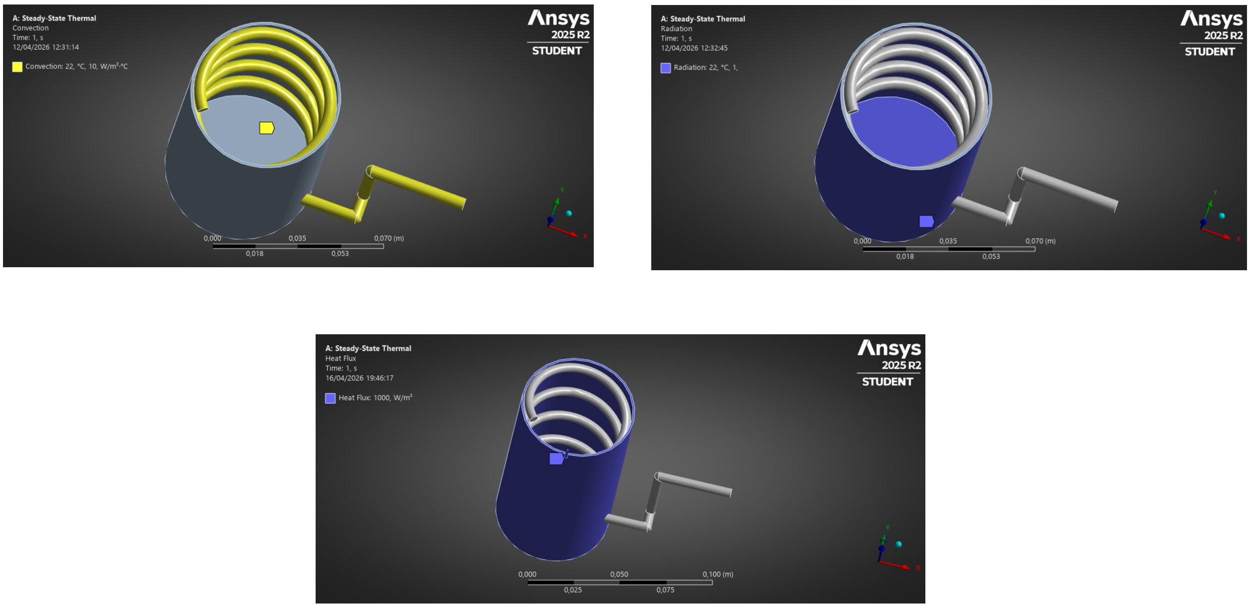


Fig. 2. Geometry and boundary conditions of the solar water heater system

2.3 Equation

a. Governing Equations

The thermal behavior of the proposed solar water heating system was governed by heat conduction in solid domains, internal heat generation within the thermal storage region, and boundary heat transfer through convection and radiation [19]. The general transient heat conduction equation with internal heat generation can be expressed as:

$$\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot (k\nabla T) + \dot{q} \tag{1}$$

Where:
ρ= density (kg/m^3)
c_p= specific heat capacity (J/(kg.K)
t= time(s)
k= thermal conductivity (W/(m.K))
$\dot{q}$= volumetric heat generation rate (W/ m^3)
For steady-state thermal analysis, the time-dependent term becomes zero, and the governing equation is reduced to:

$$\nabla \cdot (k\nabla T) + \dot{q} = 0 \tag{2}$$

This equation describes the temperature distribution inside the system and forms the basis for generating the temperature contour used to identify hotspot and coldspot regions.

b. Internal Heat Generation or Surface Heat Flux

$$\dot{q} = \frac{Q}{V} \tag{3}$$

Where:
Q= total thermal power input (W)
V= volume of the heated domain (m^3)

If the heat source is applied as a surface heat flux, the boundary condition becomes:

$$q'' = \frac{Q}{A} \quad (4)$$

Where:
q''= applied heat flux (W/m^2)
Q= total thermal power input (W)
A= heated surface area (m^2)
These equations define the thermal energy entering the system from the low-carbon heating source or solar absorber surface.
c. Fourier's Law of Heat Conduction

$$q = -k\nabla T \quad (5)$$

or in one-dimensional form:

$$q_x = -k\frac{dT}{dx} \quad (6)$$

where q is the heat flux vector (W/m^2) This equation is essential for determining the magnitude and direction of heat transfer within the system and is directly related to the total heat flux vector plot.

d. Convective Heat Transfer Boundary Condition [20].

$$q_{conv} = h(T_s - T_\infty) \quad (7)$$

Where:
q_{conv}= convective heat flux (W/m^2)
h= convective heat transfer coefficient (W/(m^2.K))
T_s= surface temperature (K)
T_∞= ambient tenmperature (K)
In boundary form, this can also be written as:

$$-k\frac{\partial T}{\partial n} = h(T_s - T_\infty) \quad (8)$$

Where $\frac{\partial T}{\partial n}$ is the temperature gradient normal to the surface. This equation describes the heat loss from the outer walls of the system to the surrounding environment.

e. Radiative Heat Transfer Boundary Condition
When the system operates at elevated temperature and radiation effects become significant, surface radiation is modeled using the Stefan-Boltzmann law:

$$q_{rad} = \varepsilon\sigma(T_s^4 - T_{sur}^4) \quad (9)$$

Where:
q_{rad}= radiative heat flux (W/ m^2)
ε= survace emissivity
σ = stefan Boltzmann constan $\left(5.67 \times 10 - 8W/(m2 \cdot K4)\right)$
T_s= surface temperature (K)
T_{sur}^4= surrounding temperature (K)
If convection and radiation occur simultaneously on the same external surface, the combined boundary condition can be expressed as:

$$-k\frac{\partial T}{\partial n} = h(Ts - T\infty) + \varepsilon\sigma(T_s^4 - T_{sur}^4) \quad (10)$$

This equation is particularly important for solar heating systems because thermal losses to the surroundings occur through both convection and radiation.

f. Adiabatic or Perfectly Insulated Boundary Condition

For surfaces assumed to be perfectly insulated, no heat transfer occurs through the boundary. Therefore, the normal heat flux is set to zero:

$$q_n = -k\frac{\partial T}{\partial n} = 0 \quad (11)$$

This boundary condition ensures that thermal energy remains within the system and is commonly applied to insulated side walls and bottom walls.

g. Heat Transfer Rate

$$Q = \int_A q \cdot n \, dA \quad (12)$$

where :
Q = total heat transfer rate (W),
q = heat flux vector, and
n = outward normal vector.
This expression is used to evaluate the total heat loss or useful heat transfer in the system.

h. Point Temperature Evaluation
To evaluate the thermal response at specific locations, the temperature at selected monitoring points can be extracted as:

$$T_p = T(x, y, z, t) \quad (13)$$

Where T_p is the temperature at a probe point. This formulation corresponds to the reaction probe or temperature probe used in post-processing to monitor the temperature at targeted heating points.

i. Thermal Performance Indicator

$$Q_u = \dot{m}c_p(T_{out} - T_{in}) \quad (14)$$

Where:
Q_u= useful heat gain (W)
$\dot{m}$= mass flow rate (kg/s)
$T_{out}T_{in}$= outlet and inlet water temperatures
The thermal efficiency of the solar water heating system can then be calculated as:

$$\eta = \frac{Q_u}{IA} \quad (15)$$

Where:
η= thermal efficiency
I= solar radiation intensity (W/m^2)
A= collector area (m^2)

3. Results

3.1 Temperature Distribution

Figure 3 presents the temperature distribution of the greenhouse-assisted solar water heater system obtained from steady-state thermal simulation using ANSYS 2025 R2 Student, showing a temperature range from approximately 69°C to 127°C as indicated by the color gradient from blue (low temperature) to red (high temperature). The highest temperature is observed at the absorber surface and central region of the sand storage, reaching up to 127.2°C, which confirms their role as the primary heat absorption and storage zones due to direct solar radiation and thermal accumulation. The sand storage region exhibits a relatively uniform temperature distribution ranging from 85.2°C to 127.2°C, indicating effective heat retention and stable thermal energy storage. A significant temperature drop is observed at the coil inlet, with values between 69.2°C and 75.0°C, caused by the inlet of cooler working fluid into the system; however, as the fluid flows through the coil, the temperature gradually increases to a range of 80.5°C to 95.8°C at the outlet, demonstrating efficient heat transfer from the surrounding sand medium to the fluid. Meanwhile, the outer wall temperature ranges from 82.0°C to 100.3°C, which is lower than the internal regions, indicating heat loss to the surrounding environment despite the presence of the greenhouse effect. Overall, the temperature distribution reveals a clear thermal gradient from the absorber and storage region toward the outer boundaries, highlighting the combined influence of conduction within the sand, convection in the fluid flow, and partial heat loss to the environment, thereby confirming the effectiveness of the integrated sand thermal storage and greenhouse-assisted heating mechanism in enhancing system thermal performance.

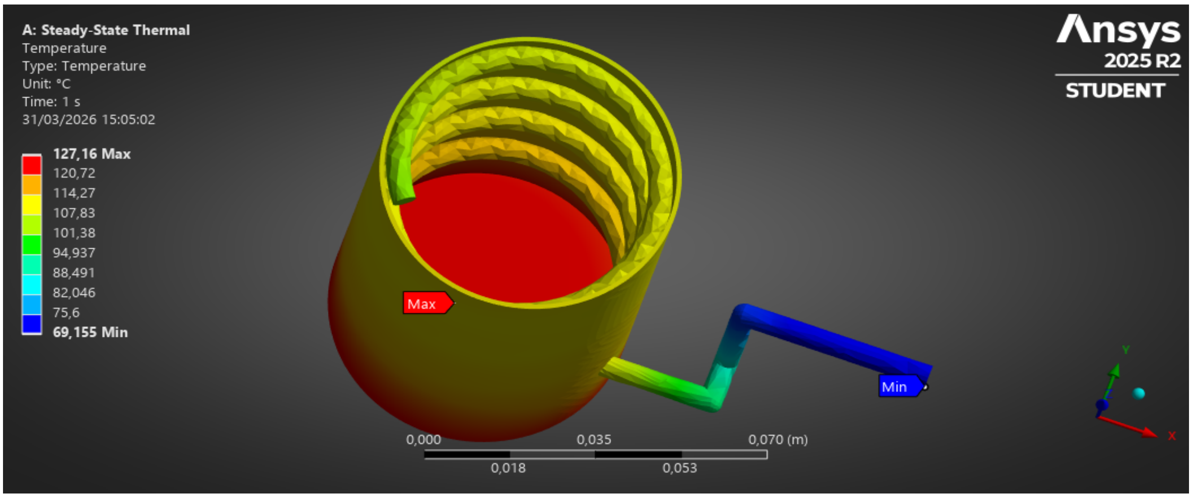


Fig. 3. Temperature distribution simulation results

3.2 Heat Flux

Figure 4 illustrates the overall heat flux spread of the greenhouse-enhanced solar water heater system, derived from steady-state thermal simulations conducted with ANSYS 2025 R2 Student, showing values between roughly 167 W/m² and 62,614 W/m², represented by a color gradient from blue (indicating lower heat flux) to red (indicating higher heat flux). The peak heat flux is detected at the entrance of the coil that is linked to the absorber, where the red area signifies substantial heat transfer resulting from direct exposure to the main heat source. As heat moves through the system, the flux progressively diminishes along the coil and nearby structures, shifting into green and blue areas that mark a decrease in heat transfer effectiveness along the flow route. The sand storage area shows a fairly lower and consistent heat flux distribution, implying that heat is being absorbed and retained instead of being quickly dispersed. In contrast, the outer wall records the minimal heat flux levels, indicating some heat loss to the surrounding environment, though this is relatively constrained owing to the greenhouse effect. In summary, the heat flux distribution indicates that most thermal energy transfer is concentrated close to the absorber and inlet area, whereas the regions downstream are subject to decreased heat intensity, underscoring the interplay of conduction in the storage medium, convection in the fluid movement, and gradual thermal leakage to the surroundings.

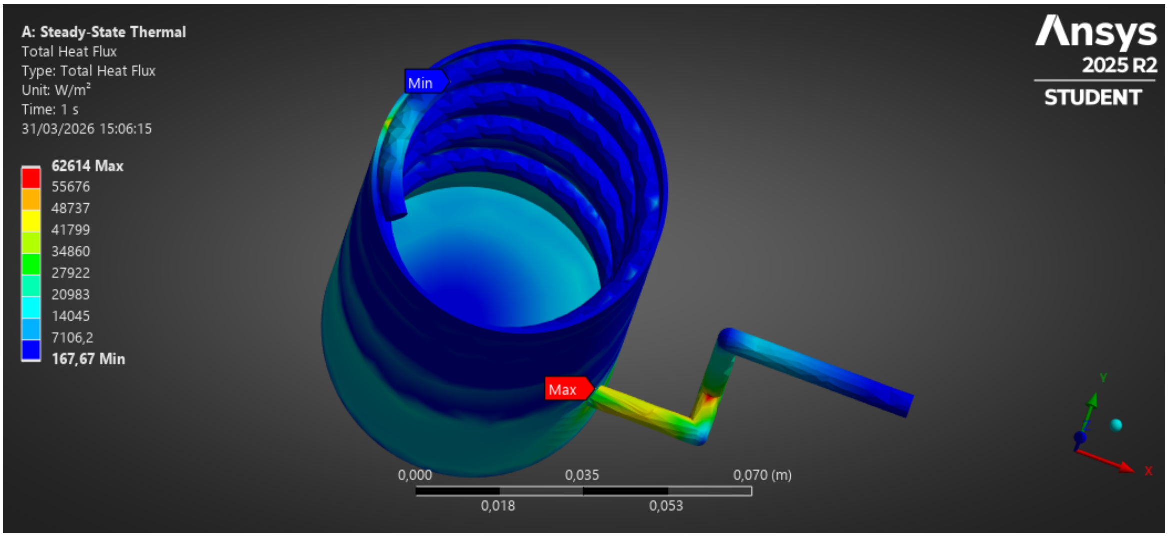


Fig. 4. Heat flux simulation result

3.3 Temperature Probe

Figure 5 presents the temperature probe location used to evaluate the thermal performance of the greenhouse-assisted solar water heater system, particularly along the fluid flow path within the coil. The probe is positioned near the outlet region to capture the representative temperature of the heated fluid after undergoing heat exchange with the surrounding sand thermal storage medium. The results indicate that the outlet temperature reaches approximately 93°C, significantly higher than the inlet temperature of around 72°C, resulting in a temperature increase of about 21°C. This substantial temperature rise confirms the effectiveness of the heat transfer process within the system, where thermal energy stored in the sand is efficiently transferred to the working fluid through conduction and convection mechanisms. The stable and elevated outlet temperature also demonstrates the capability of the sand medium to maintain thermal energy and provide continuous heating. Furthermore, the probe analysis validates the overall system performance by confirming that the combination of the greenhouse effect and sand-based thermal storage enhances heat retention and utilization. These findings highlight the potential of the proposed system as an energy-efficient and low-carbon solution for domestic water heating applications, although its performance remains dependent on operating conditions such as solar radiation intensity and flow rate.

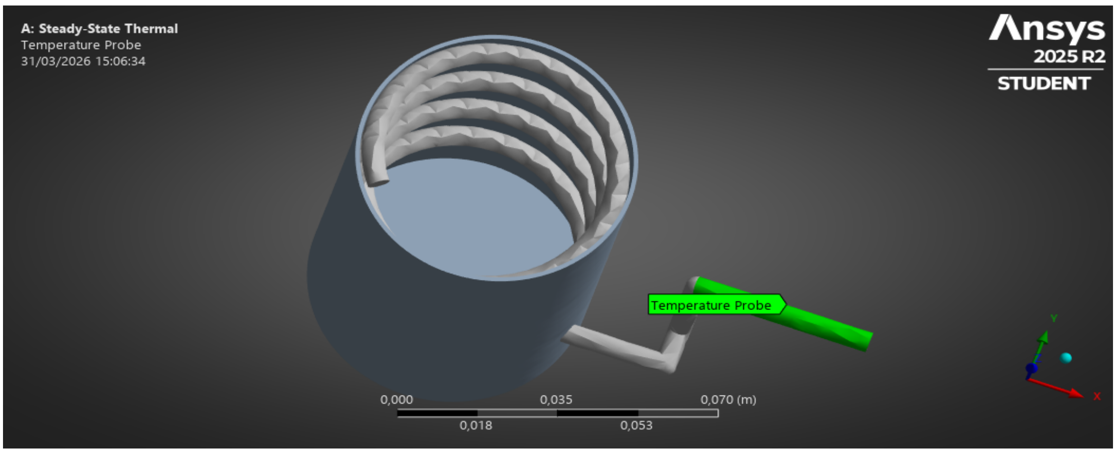


Fig. 4. Probe temperature simulation result

3.4 Thermal Analysis Result

The results summarized in **Table 1** present the temperature distribution across the main components of the greenhouse-assisted solar water heater system, including the sand storage region, absorber surface, coil inlet, coil outlet, and outer wall. The highest temperatures are observed at the absorber surface and sand storage region, reaching a maximum of 127.2°C, confirming their roles as the primary heat absorption and storage zones. The average temperatures of 112.3°C and 105.6°C, respectively, indicate effective heat retention and relatively uniform thermal distribution. In contrast, the coil inlet exhibits the lowest temperature range (69.2°C–75.0°C) due to the inlet of cooler working fluid, while the coil outlet temperature increases significantly to an average of 88.6°C, demonstrating efficient heat transfer from the surrounding sand medium to the fluid. The outer wall shows intermediate temperature values (82.0°C–100.3°C), indicating the presence of heat loss to the environment despite the greenhouse effect mechanism. These findings are further supported by the temperature probe results in Table 3, which show a consistent increase in fluid temperature from 72.3°C at the inlet to 93.4°C at the outlet, resulting in a temperature rise of approximately 21.1°C, confirming the effectiveness of the heat exchange process.

The heat flux distribution presented in **Table 2** further explains the thermal behavior within the system, where the absorber surface exhibits high heat flux values with an average of 38,300 W/m², indicating intense heat transfer at the primary heating region. The coil outlet shows the highest average heat flux of 52,100 W/m², highlighting its critical role in transferring thermal energy to the fluid, while the sand storage region maintains moderate values, acting as a thermal buffer that absorbs and redistributes heat. The outer wall demonstrates lower heat flux, confirming heat dissipation to the surroundings. The overall system performance, as shown in **Table 4**, indicates that at a mass flow rate of 0.02 kg/s, the system achieves a useful heat gain of 1765 W and a thermal efficiency of 0.62. These results demonstrate that the integration of sand-based thermal storage and the greenhouse effect significantly enhances heat retention, transfer efficiency, and overall thermal performance, making the system a promising low-carbon solution for residential water heating applications.

Table 1
Temperature distribution acroos system components

Location	Min Temperature (°C)	Max Temperature (°C)	Average Temperature (°C)
Sand Storage Region	85.2	127.2	105.6
Absorber Surface	95.4	127.2	112.3
Coil Inlet	69.2	75.0	72.1
Coil Outlet	80.5	95.8	88.6
Outer Wall	82.0	100.3	91.4

Table 2
Heat flux distribution acroos system components

Location	Min Heat Flux (W/m²)	Max Heat Flux (W/m²)	Average Heat Flux (W/m²)
Sand Storage Region	167.67	27922	14045
Absorber Surface	27922	48737	38300
Coil Inlet	7106.2	20983	14045
Coil Outlet	41799	462614	52100
Outer Wall	14045	34860	24450

Table 3
Temperature at selected probe locations

Probe Location	Temperature (°C)
Coil Inlet	72.3
Mid Coil	85.7
Coil Outlet	93.4
Sand Center	118.5
Absorber Surface	127.2

Table 4
Thermal performance parameters of the system

Parameter	Value	Unit
Mass flow rate	0.02	kg/s
Inlet temperature	72.3	°C
Outlet temperature	93.4	°C
Temperature rise	21.1	°C
Useful heat gain (Q_u)	1765	W
Thermal efficiency (η)	0.62	-

3.5 Temperature and Heat Flux Distribution Line Graph

The temperature and heat flux line graphs **Figure 5** provide important insight into the thermal performance and energy utilization efficiency of the system beyond simple distribution analysis. The temperature graph shows a sharp increase from the sand region to the absorber, followed by a significant drop at the coil inlet and a gradual recovery toward the outlet. This behavior indicates that while the system is capable of storing high thermal energy in the absorber and sand regions, there is a strong thermal gradient when the working fluid enters the system. The subsequent temperature increase along the coil suggests that heat transfer is effective, but not fully optimized, as the outlet temperature remains significantly lower than the peak temperature at the absorber. This implies that a portion of the stored thermal energy is not fully utilized, indicating moderate thermal transfer efficiency rather than optimal performance.

The heat flux graph further supports this interpretation by showing that the highest heat transfer intensity is concentrated at the absorber region, followed by a rapid decrease toward the coil and outer wall. This uneven distribution of heat flux indicates that the system experiences localized heat concentration rather than uniform heat utilization, which can reduce overall system efficiency.

Ideally, a more uniform heat flux distribution would lead to better energy transfer to the fluid. The significant drop in heat flux toward the outer wall also suggests the presence of thermal losses, which negatively affect system performance. From an engineering standpoint, these results indicate that while the system demonstrates effective heat absorption and storage, there is still room for improvement in terms of heat transfer uniformity, insulation, and fluid interaction. Enhancing these aspects could lead to improved thermal efficiency, reduced energy loss, and more effective utilization of the stored thermal energy.

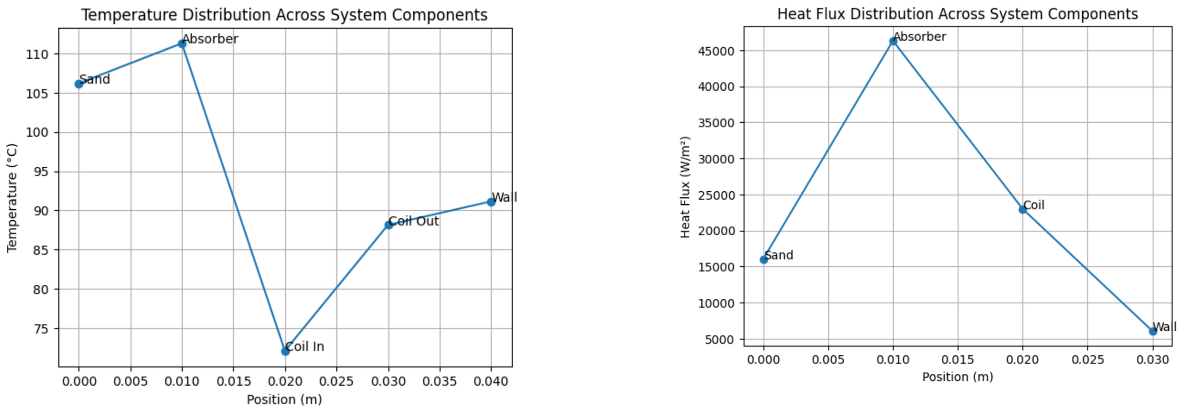


Fig. 5. Temperature and heatflux distibution

4. Conclusions

Based on the findings from numerical simulations conducted using ANSYS Fluent, the greenhouse-assisted solar water heater integrated with sand-based thermal energy storage demonstrates strong thermal performance in terms of heat absorption, storage, and transfer. The system is capable of reaching a maximum temperature of approximately 127.2°C at the absorber surface and sand storage region, indicating effective solar energy capture and thermal accumulation. The temperature of the working fluid increases significantly from 72.3°C at the inlet to 93.4°C at the outlet, resulting in a temperature rise of 21.1°C. This improvement confirms that the heat exchange process between the sand storage medium and the fluid flowing through the coil is effective. The relatively uniform temperature distribution within the sand region further indicates its capability to act as a stable thermal storage medium, allowing gradual heat release and maintaining system performance over time.

From a heat transfer perspective, the heat flux distribution reveals that the highest heat transfer intensity occurs at the absorber and coil regions, where thermal energy is actively transferred to the fluid. In contrast, lower heat flux values at the outer wall indicate the presence of heat loss to the surrounding environment, although this is partially minimized by the greenhouse effect mechanism. The system achieves a useful heat gain of 1765 W and a thermal efficiency of 0.62, demonstrating that a significant portion of the absorbed solar energy is successfully converted into useful thermal energy. However, the non-uniform distribution of heat flux and the noticeable temperature difference between the absorber and fluid outlet suggest that not all stored thermal energy is fully utilized. This indicates that while the system performs well, there is still potential for improving heat transfer uniformity and reducing thermal losses.

Physically, the observed thermal behavior can be explained through the combined mechanisms of conduction, convection, and radiation within the system. Heat is initially absorbed by the absorber surface through solar radiation, then conducted into the sand storage medium, which acts as a thermal buffer. The stored heat is subsequently transferred to the working fluid via convection as it flows through the coil. The gradual increase in fluid temperature along the flow path confirms the effectiveness of this mechanism. However, thermal resistance between the sand and coil surface, as well as heat dissipation through the outer wall, contributes to energy losses that reduce overall system efficiency. This highlights the importance of optimizing thermal contact, material properties, and insulation in order to maximize energy transfer efficiency.

In general, the results of this study demonstrate that the integration of sand-based thermal energy storage with a greenhouse effect mechanism provides a promising approach for enhancing the performance of solar water heating systems. The system shows stable thermal behavior, effective heat storage, and satisfactory efficiency under the given operating conditions. Nevertheless, further improvements can be achieved by optimizing system design parameters such as coil configuration, insulation thickness, and flow rate to reduce heat loss and improve heat transfer distribution. Future research should focus on transient analysis to evaluate the long-term thermal storage capability, as well as experimental validation to verify the accuracy of the simulation results. Additionally, investigating the effects of varying solar radiation intensity, material properties, and flow conditions will provide a more comprehensive understanding of system performance and support the development of more efficient and reliable low-carbon water heating technologies.

References

[1] SV, Vimal, and Surya SS. "Performance Analysis of Solar Water Heater with Various Working Fluids." *Journal of Mines, Metals & Fuels* 70 (2022). https://doi.org/10.18311/jmmf/2022/32028

[2] Tukhtabaev, Jamshid, Jakhongir Tursunov, Abdurahmon Abduvohidov, Bakhriddin Khasanov, Islom Kadirov, and Mirolim Nurillaev. "CFD Analysis of Thermal Performance in a U-Tube Solar Collector." In *EPJ Web of Conferences*, vol. 355, p. 04006. EDP Sciences, 2026. https://doi.org/10.1051/epjconf/202635504006

[3] Znaczko, Pawel, Norbert Chamier-Gliszczynski, and Kazimierz Kaminski. "Experimental Study of Solar Hot Water Heating System with Adaptive Control Strategy." *Energies* 18, no. 15 (2025): 3904. https://doi.org/10.3390/en18153904

[4] Shamsul Azha, Nurril Ikmal, Hilmi Hussin, Mohammad Shakir Nasif, and Tanweer Hussain. "Thermal performance enhancement in flat plate solar collector solar water heater: a review." *Processes* 8, no. 7 (2020): 756. https://doi.org/10.3390/pr8070756

[5] Alwan, Naseer T., Milia H. Majeed, Ihsan M. Khudhur, S. E. Shcheklein, Obed M. Ali, Salam J. Yaqoob, and Reza Alayi. "Assessment of the performance of solar water heater: an experimental and theoretical investigation." *International Journal of Low-Carbon Technologies* 17 (2022): 528-539. https://doi.org/10.1093/ijlct/ctac032

[6] Arévalo, Paul, Danny Ochoa-Correa, and Edisson Villa-Ávila. "Advances in thermal energy storage systems for renewable energy: a review of recent developments." *Processes* 12, no. 9 (2024): 1844. https://doi.org/10.3390/pr12091844

[7] Sivanathan, Amende, Xi Guo, Ziyan Fu, and Mizi Fan. "Advances in phase change building materials: An overview." *Nanotechnology Reviews* 12, no. 1 (2023): 20220554. https://doi.org/10.1515/ntrev-2022-0554

[8] Bagre, Boubou, Ibrahim Kolawole Muritala, Tizane Daho, Makinta Boukar, Yomi Woro Gounkaou, Babajide Epe Shari, Aissatou Ndiaye, Antoine Bere, and Adamou Rabani. "Development of sensible heat storage materials using sand, clay and coal bottom ash." *Materials Sciences and Applications* 13, no. 12 (2022): 603-626. https://doi.org/10.4236/msa.2022.1312038

[9] Niksiar, Paniz, Claire Rogillio, Hamid Torab, and Saeed Tiari. "Experimental study of a silica sand sensible heat storage system enhanced by fins." *Energies* 17, no. 21 (2024): 5402. https://doi.org/10.3390/en17215402

[10] J. Pelemo and K. T. Akindeji, "A Study to Evaluate Heat Loss Phenomenon in A Flat Plate Solar Collector System," *IRE J.*, vol. 7, no. 12, 2024.

[11] Elmnifi, Monaem, Ammar M. Al-Tajer, Hasan A. Al-Asadi, Mohammed Al Saker, and Laith J. Habeeb. "Computational Fluid Dynamics Analysis of a Parabolic Trough Solar Collector for Enhanced Efficiency and Thermal Performance." *Mathematical Modelling of Engineering Problems* 10, no. 3 (2023). https://doi.org/10.18280/mmep.100339

[12] Al Kindi, Fatema, Talal Al-Shukaili, Pankaj B. Pathare, Farooq Al Jahwari, Nasser Al-Azri, and Ohood Al Ghadani. "Thermal Performance of a Flat-Plate Solar Collector for Drying Agricultural Crops." *AgriEngineering* 5, no. 4 (2023): 2349-2365. doi: 10.3390/agriengineering5040144.

[13] Zhuang, Yunfei, Shumei Zhao, Jieyu Cheng, Pingzhi Wang, Na Lu, Chengwei Ma, Wenxin Xing, and Kexin Zheng. "An air convection wall with a hollow structure in Chinese solar greenhouses: Thermal performance and effects on microclimate." *Agronomy* 12, no. 2 (2022): 520. https://doi.org/10.3390/agriengineering5040144

[14] M. Haidari and M. Dubey, "CFD Analysis of differently arranged Solar Water Heater," vol. 8, no. 5, 2022.

[15] Pérez Grajales, Sandro Guadalupe, Teresa Hernández Ortíz, Rogelio Martinez-Oropeza, Tabai Torres, López-Pérez Luis Adrián, Javier Delgado-Gonzaga, Armando Huicochea, and David Juárez-Romero. "Prediction of Heat Transfer in a Hybrid Solar–Thermal–Photovoltaic Heat Exchanger Using Computational Fluid Dynamics." *Processes* 12, no. 10 (2024): 2296. https://doi.org/10.3390/pr12102296

[16] Jaisankar, S., J. Ananth, and K. N. Sheeba. "Advances in thermal solar water systems for efficient and sustainable energy conversion: An extensive review of design, experimentation, simulation and optimization." *Renewable and Sustainable Energy Reviews* 226 (2026): 116449. https://doi.org/10.1016/j.rser.2025.116449

[17] Rifqi, Andi Muhammad, and Yusuf Al-Khalil. "Thermal Performance Analysis of Heat Exchanger Using Computational Fluid Dynamics." *RESWARA: Jurnal Riset Ilmu Teknik* 3, no. 2 (2025): 60-68. https://doi.org/10.70716/reswara.v3i2.416

[18] Thiao, Serigne, Omar Drame, Awa Mar, L. NDIAYE, and Issakha Youm. "Experimental and Numerical CFD Analysis of a Solar Dryer with Integration of Basalt Thermal Bed for Heat Storage." *International Journal* 14, no. 1 (2025): 20-31. https://doi.org/10.11648/j.ijsge.20251401.12

[19] Sánchez-Mora, Heriberto, Sergio Quezada-García, Marco Antonio Polo-Labarrios, Ricardo Isaac Cázares-Ramírez, and Alejandro Torres-Aldaco. "Dynamic mathematical heat transfer model for two-phase flow in solar collectors." *Case Studies in Thermal Engineering* 40 (2022): 102594. https://doi.org/10.1016/j.csite.2022.102594

[20] Assaye, Mebratu, Muluken Biadgelegn, and Birlie Fekadu. "Numerical investigation of convection heat transfer in solar air heater with semi-circular shape transverse rib." *Cogent Engineering* 9, no. 1 (2022): 2106930. https://doi.org/10.1080/23311916.2022.2106930