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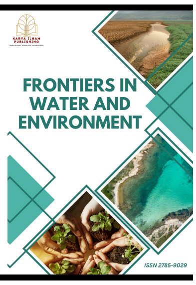
Frontiers in Water and Environment

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



Heat Distribution Analysis in Seawater Desalination Prototype using ANSYS Simulation: Comparison of Natural and Plate Heating Systems

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ARTICLE INFO

Article history:
Received 30 March 2026
Received in revised form 20 May 2026
Accepted 10 June 2026
Available online 6 July 2026

ABSTRACT

The increasing demand for clean water due to population growth and environmental degradation has intensified the need for efficient desalination technologies. Solar still systems offer a simple and low-cost solution; however, their performance is limited by low thermal efficiency and uneven heat distribution. Therefore, this study aims to analyze the heat distribution characteristics of a seawater desalination prototype by comparing natural solar heating and a system assisted by a heating plate. The methodology employed in this study involves numerical simulation using ANSYS Fluent to model heat transfer phenomena within the desalination system. A three-dimensional model of a box-type solar still was developed, consisting of fluid and solid domains, including seawater, air, glass cover, structural frame, and heating plate. Two simulation conditions were applied, namely natural heating (solar-based) and assisted heating using a heating plate, under steady-state conditions. The analysis focuses on temperature distribution and heat flux behavior within the system. The results indicate that the addition of a heating plate significantly enhances the thermal performance of the system. The temperature distribution becomes more uniform and reaches higher values compared to the natural heating condition. Moreover, the heat flux distribution shows increased intensity and improved heat transfer from the heat source to the fluid domain, which contributes to a higher evaporation potential. In conclusion, the integration of a heating plate into the solar desalination system improves heat distribution and thermal efficiency, thereby enhancing the overall performance of the desalination process. This approach provides a promising solution for improving solar still productivity, especially in conditions with limited solar radiation.

Keywords:

Solar still; heat distribution; ANSYS Fluent; desalination system; heating plate; heat flux

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1. Introduction
1.1 Background

The first sentence should start here. The increasing global population and industrial development have significantly intensified the demand for clean water, leading to a widening gap between freshwater availability and consumption [1]. Although approximately 97.5% of water on Earth is saline, only a very small fraction is accessible for human use, making desalination an essential solution to overcome water scarcity challenges. Solar still desalination is one of the simplest and most cost-effective methods for converting saline water into potable water, especially in remote areas [1]. Solar still systems are widely utilized due to their low operational cost and simple design, although their productivity remains relatively low [2]. Furthermore, the efficiency of solar still systems is strongly influenced by fluctuating solar radiation and significant thermal losses, which limit overall system performance [3].

To address these limitations, various studies have focused on enhancing the thermal performance of solar desalination systems through system modification and additional heat sources. Optimization of thermal design parameters plays a crucial role in improving desalination efficiency, particularly in systems utilizing low-grade heat sources such as solar energy [4]. In addition, the integration between thermal energy sources and desalination processes significantly affects system performance, especially in terms of temperature distribution and heat utilization [5]. Previous studies have also explored different enhancement techniques, such as the use of auxiliary heating systems, thermal storage materials, and reflectors, to increase evaporation rates and freshwater yield. However, despite these advancements, a comprehensive understanding of heat distribution within the system remains limited.

In recent years, Computational Fluid Dynamics (CFD) has emerged as a powerful tool for analyzing heat transfer phenomena in solar still systems. CFD simulations using ANSYS can accurately predict temperature distribution and distillate output when validated with experimental data [6]. Moreover, CFD enables detailed visualization of thermal behavior, including heat flux, fluid flow, and evaporation-condensation processes within the system [7]. CFD modeling has evolved significantly, allowing researchers to simulate complex physical processes such as radiation, convection, and phase change with high accuracy [8]. These capabilities make CFD an effective approach for optimizing system design and improving performance without extensive experimental trials.

Based on the literature review, it can be identified that although many studies have investigated performance enhancement techniques and numerical modeling of solar still systems, limited research has focused on the integration of additional heating components, such as heating plates, combined with detailed thermal distribution analysis using CFD. Therefore, this study aims to investigate the effect of a heating plate on the thermal performance of a solar still system and to analyze the heat distribution within the system using numerical simulation. This approach is expected to provide a deeper understanding of heat transfer mechanisms and contribute to the development of more efficient and sustainable desalination systems.

1.2 Literature Review

Solar still has been widely recognized as a simple, cost-effective, and sustainable desalination technology, particularly suitable for remote and energy-limited regions. Despite these advantages, its practical implementation remains constrained by relatively low freshwater productivity and non-uniform thermal distribution within the system. Previous studies consistently report that the performance of conventional solar stills is strongly influenced by heat transfer mechanisms, basin design, and the availability of thermal energy. In many cases, limited heat input and significant thermal losses result in low evaporation rates, which ultimately reduce overall system efficiency.

To overcome these limitations, numerous enhancement strategies have been proposed from a design perspective. These include the use of high thermal conductivity materials, thermal energy storage, solar reflectors, and modified basin geometries such as stepped or multi-effect configurations. Several studies demonstrated that increasing heat absorption capacity and improving energy retention within the basin can significantly elevate water temperature and enhance evaporation potential. Furthermore, recent developments have shifted focus toward achieving not only higher productivity but also improved thermal uniformity and stability throughout the desalination chamber.

In terms of methodology, solar still investigations can be broadly categorized into experimental, theoretical, and numerical approaches. Experimental studies provide direct measurement of distillate yield and system performance under real operating conditions; however, they are often limited in capturing detailed internal heat transfer behavior. Consequently, Computational Fluid Dynamics (CFD) has emerged as a powerful alternative, enabling in-depth analysis of temperature distribution, heat flux intensity, and buoyancy-driven flow within the enclosure. CFD simulations, particularly using ANSYS Fluent, allow detailed visualization of thermal interactions between fluid and solid domains, making them highly effective for studying complex heat transfer phenomena that are difficult to observe experimentally.

Several numerical studies have confirmed the capability of CFD in predicting solar still performance and optimizing system design. Most existing works focus on conventional basin-type configurations, modified geometries, or general enhancement techniques under steady-state or transient conditions. These studies commonly emphasize temperature distribution and natural convection as key parameters influencing system performance. While transient simulations have been shown to provide better insight into time-dependent thermal behavior, many studies still rely on simplified approaches or do not fully explore the detailed interaction between heat sources and fluid domains.

Despite these advancements, several research gaps remain evident. First, a significant portion of the literature emphasizes productivity improvement without thoroughly analyzing the spatial distribution of heat and its impact on thermal uniformity within the system. Second, although auxiliary heat sources have been introduced in some studies, their integration is often not optimized in terms of positioning and direct interaction with the basin, which limits their effectiveness in enhancing heat transfer. Third, comparative transient analyses that simultaneously evaluate temperature distribution and heat flux behavior between conventional solar heating and assisted heating systems are still relatively limited. To address these limitations, the present study proposes a modified solar still configuration by integrating a heating plate directly beneath the basin as an auxiliary heat source. This configuration enhances conductive heat transfer from the bottom of the basin while simultaneously intensifying natural convection within the fluid domain. In contrast to previous studies, this work employs a transient CFD approach to analyze both temperature distribution and heat flux evolution over time, providing a more comprehensive understanding of heat propagation and thermal interaction within the system. Therefore, this study offers a more detailed and physically representative evaluation of solar still performance, highlighting the advantage of the proposed system in achieving higher thermal intensity, improved temperature uniformity, and enhanced evaporation potential compared to conventional designs.

1.3 Research Gap

The summary of previous studies related to solar still enhancement and CFD-based thermal analysis is presented in Table 1. The table highlights the methods, research focus, and key findings of each study to identify the existing research gaps.

Tabel 1
Summary of previous studies on solar still enhancement and CFD-based thermal analysis

No	(Approach / Methods)	Research Focus	Main Findings
[1]	Review of CFD-based performance assessment of solar still systems	Evaluation of solar still performance using numerical simulation	CFD is effective in analyzing temperature distribution, evaporation, and heat transfer behavior in solar desalination systems
[2]	Review of solar still enhancement techniques	Improvement of distillate productivity using fins, PCM, and design modification	Various enhancement methods significantly improve water production, but focus mainly on output performance
[3]	CFD and AI-based analysis for solar still optimization	Investigation of thermal performance and efficiency improvement	CFD provides insights into thermal behavior, but challenges remain in detailed heat transfer analysis
[4]	Experimental study using heat localization materials	Enhancement of basin temperature and evaporation rate	High thermal conductivity materials improve system performance by increasing temperature
[11]	Experimental and CFD modeling using heat pipe integration	Performance enhancement of solar still using auxiliary heating system	Integration of heat pipe increases evaporation rate, but heat distribution behavior is not deeply analyzed
[12]	Review of CFD applications in solar still design	Development and optimization of solar still systems using CFD	CFD is widely used for system analysis, but mostly limited to temperature and efficiency evaluation
[13]	3D CFD simulation with experimental validation	Effect of baffle configuration on solar still performance	Modification of internal geometry improves heat transfer, but does not include auxiliary heating comparison
[14]	CFD-based analysis of double-basin solar still	Performance evaluation using numerical simulation	CFD can accurately predict system behavior, but lacks detailed heat flux analysis
[22]	CFD simulation of evaporation–condensation process	Energy and exergy analysis of modified solar still system	CFD effectively models thermal processes, but comparative heating configurations are not explored
[28]	CFD modeling for performance enhancement	Optimization of solar still performance using simulation	Numerical modeling improves design, but internal thermal distribution analysis is still limited

Based on Table 1, it can be observed that previous studies have extensively explored solar still systems through various approaches, including experimental methods, design modifications, and numerical simulations using CFD. These studies consistently demonstrate that improving temperature levels and heat transfer can enhance evaporation performance and freshwater productivity. However, most of these studies primarily focus on overall system performance, such as productivity and efficiency, rather than providing a detailed analysis of internal thermal behavior. In particular, several studies have introduced auxiliary heating systems, such as heat pipes or modified basin designs, to enhance thermal performance. Although these approaches improve evaporation rates, they often do not thoroughly investigate the internal heat transfer mechanisms, especially temperature distribution and heat flux behavior within the system. Additionally, many CFD-based studies are limited to evaluating temperature levels without deeply analyzing the spatial distribution of heat or comparing different heating configurations.

Furthermore, existing designs, including more complex configurations such as multi-stage systems, tend to emphasize productivity improvement through structural complexity rather than simplifying the system for detailed thermal analysis. This makes it difficult to clearly understand how heat is distributed and utilized within the system. In contrast, the present study proposes a simplified box-type solar still integrated with a heating plate, focusing not only on performance improvement but also on a detailed investigation of thermal characteristics. Unlike previous studies, this research provides a comparative analysis between natural solar heating and heating plate-assisted systems, enabling a clearer understanding of the role of auxiliary heating in enhancing temperature distribution and heat flux. Therefore, this study offers a more comprehensive thermal analysis and contributes to addressing the limitations identified in previous research.

2. Methodology

2.1 Research Method

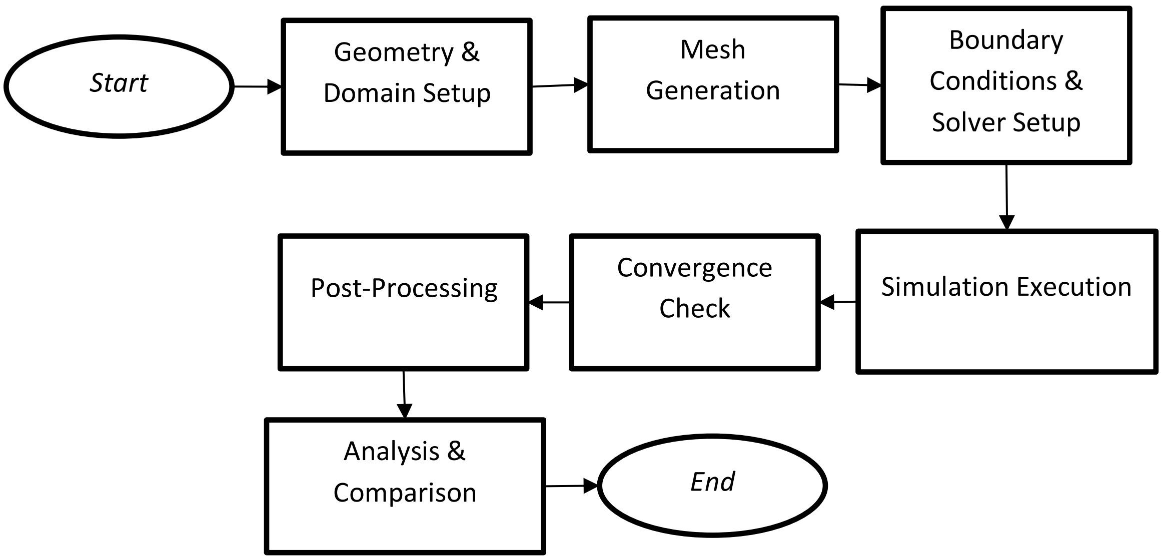


Fig. 1. Research methodology flowchart for the numerical analysis of solar desalination system using ANSYS Fluent

This study adopts a computational approach to critically evaluate heat transfer behavior in a solar desalination system by integrating conventional solar heating with an auxiliary heating plate. The use of Computational Fluid Dynamics (CFD) enables detailed examination of thermal interactions, allowing not only visualization of temperature and heat flux distribution but also identification of dominant heat transfer mechanisms within the system[9]. This approach is particularly relevant for addressing limitations in conventional solar stills, where heat losses and non-uniform thermal fields reduce overall efficiency. The methodological framework is structured to systematically capture the coupling between fluid flow and heat transfer processes. The system is represented in a three-dimensional (3D) computational domain to accurately resolve spatial variations across fluid and solid regions. The modeling strategy considers the interaction between seawater, air, and structural components, ensuring that conductive and convective heat transfer processes are simultaneously resolved. Such representation is essential to avoid oversimplification, which is commonly observed in two-dimensional analyses and may lead to inaccurate thermal predictions [10]. Two distinct operating configurations are investigated to quantify the impact of additional thermal input. The baseline configuration represents a conventional solar still driven solely by solar radiation, which typically exhibits limited and uneven heat distribution. The enhanced configuration incorporates a heating plate positioned beneath the basin to introduce a controlled heat source. This comparative approach allows a direct assessment of how supplementary energy input modifies thermal gradients, heat transfer intensity, and overall system behavior [11].

The governing equations of mass, momentum, and energy are solved to simulate the coupled fluid flow and thermal processes. Heat transfer is modeled through conduction within solid components and natural convection within fluid domains, with buoyancy effects incorporated to capture temperature-induced density variations. This formulation enables the identification of key mechanisms responsible for heat propagation and energy distribution within the enclosure[12]. In contrast to steady-state simplifications, this study employs transient analysis to capture the temporal evolution of thermal behavior. The simulation is performed over a 2-hour period with multiple observation intervals, allowing detailed evaluation of how heat is accumulated, distributed, and stabilized over time. This time-dependent approach provides deeper insight into system performance, particularly in distinguishing between initial heating response and long-term thermal stability [13]. Furthermore, the analysis focuses on temperature distribution, heat flux intensity, and heat transfer characteristics as primary indicators of system performance. These parameters are selected to establish a direct relationship between energy input and evaporation potential. By integrating comparative analysis with detailed thermal evaluation, the methodology provides a robust framework for assessing the effectiveness of heating plate integration in enhancing desalination performance [14].

2.2 Desalination System Design

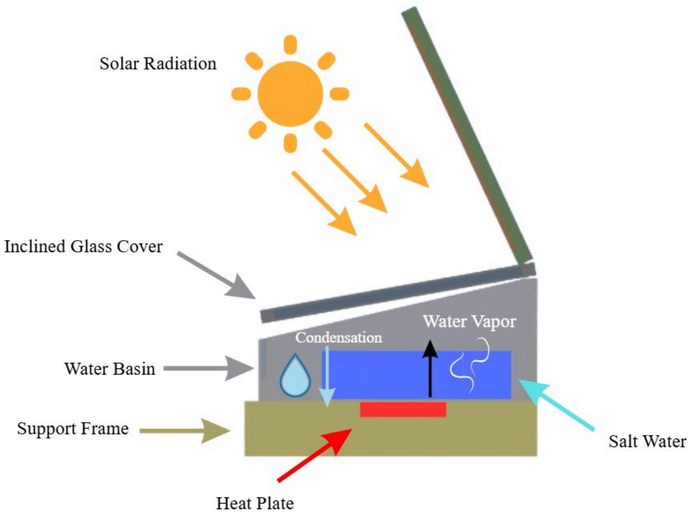


Fig. 2. Schematic diagram of solar desalination system with heating plate

The desalination system investigated in this study is a box-type solar still prototype designed to represent a simple and low-cost desalination unit, as illustrated in Fig. 2. Solar still systems are widely used due to their simple construction and ability to directly utilize solar energy for freshwater production. As shown in Fig. 2, the prototype consists of a closed chamber structure that enables evaporation and condensation processes to occur within a controlled environment.The system adopts a basin-type configuration, which is commonly used in solar desalination studies due to its effectiveness in absorbing solar radiation and facilitating heat transfer processes within the system [15]. he main components of the system include a water basin, an inclined transparent glass cover, a structural support frame, and an additional heating plate. The basin acts as the primary container for seawater and plays a crucial role in absorbing heat, which directly influences the evaporation rate. As depicted in Fig. 2, solar radiation enters through the inclined glass cover and heats the water in the basin, leading to the formation of water vapor [16]. The transparent glass cover is installed at an inclined angle to maximize solar radiation absorption and to facilitate condensation on its inner surface. The generated water vapor rises and condenses on the cooler glass surface, forming droplets that flow downward due to gravity. The structural frame supports the system and provides insulation to minimize heat losses to the surrounding environment. The temperature difference between the basin water and the glass cover is a critical parameter that significantly affects the efficiency of the desalination process

To enhance the thermal performance of the system, a heating plate is introduced as an auxiliary heat source, as shown in Fig. 2. The integration of additional heat sources has been reported to improve desalination efficiency by increasing water temperature and evaporation rate [17]. In this configuration, the heating plate is positioned beneath the basin to provide direct heat transfer to the seawater, thereby increasing the thermal energy within the system. Two different operating conditions are considered to evaluate the effect of the heating plate. The first condition represents a conventional solar still system that relies solely on solar radiation, while the second condition incorporates the heating plate as an additional heat source. This comparison allows for a more detailed investigation of temperature distribution and heat flux within the system. The use of numerical simulation for this analysis is essential, as CFD-based approaches enable detailed visualization of heat transfer mechanisms, including evaporation and condensation processes, as well as the overall thermal behavior of the system [18].

2.3 Geometric Modeling (ANSYS)

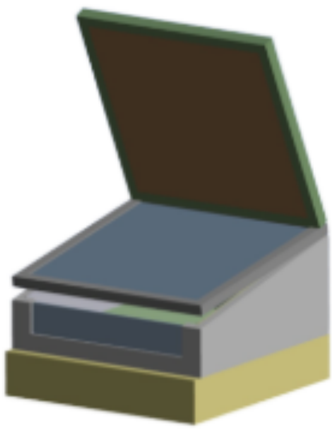


Fig. 3. Geometry model of desalination system in ANSYS

The geometric model of the desalination system is developed in a three-dimensional (3D) domain to accurately represent the physical configuration of the prototype, as illustrated in Fig. 3. The model consists of fluid, air, and solid regions that interact thermally during the desalination process [19]. The use of a 3D approach enables a more accurate representation of spatial temperature distribution and heat transfer behavior within the system. As shown in Fig. 3, the fluid domain represents seawater contained within the basin, while the air domain is located above the water surface to simulate vapor movement and natural convection. The solid domain includes the inclined glass cover, the structural frame, and the heating plate positioned beneath the basin. The interaction between these domains is essential for capturing both conduction through solid materials and convection within the fluid regions inside the enclosure [20]. The dimensions of the system are defined based on a small-scale prototype configuration. The basin has a length of 500 mm, a width of 500 mm, and a height of 150 mm, with a water depth of approximately 50 mm. The air gap between the water surface and the inclined glass cover is set to 120 mm, allowing sufficient space for vapor circulation and condensation processes. As depicted in Fig. 3, the glass cover is inclined at an angle of 30°, which facilitates the flow of condensed water toward the collection area.

The heating plate is modeled as a solid layer located beneath the basin with a thickness of 10 mm, ensuring effective heat transfer to the seawater. The thickness of the glass cover is set to 5 mm, while the structural frame is modeled with an average thickness of 20 mm to represent an insulating layer that minimizes heat loss to the surroundings. The total computational domain volume is approximately 0.015 m^3, including both fluid and air regions, which is sufficient to capture the thermal interaction within the system without introducing excessive computational cost. The geometry is created using ANSYS DesignModeler and subsequently prepared for mesh generation prior to simulation. The simplified yet representative geometry, as shown in Fig. 3**,** allows efficient numerical computation while maintaining the essential physical characteristics of the desalination system.

2.4 Mesh Generation

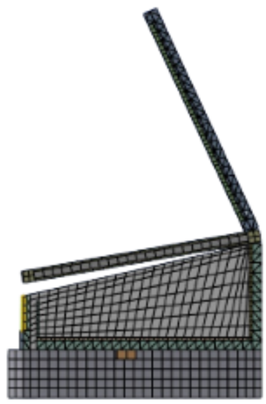


Fig. 4. Mesh distribution of the computational domain

The computational domain was discretized using an unstructured tetrahedral mesh to accurately represent the geometry of the solar desalination system, as illustrated in Fig. 4. The overall domain dimensions are 500 mm × 500 mm × 150 mm. This meshing approach was selected due to its flexibility in handling complex geometrical features, particularly at the interfaces between fluid and solid regions within the system. As shown in Fig. 4, a non-uniform meshing strategy was applied to improve numerical accuracy in regions with high thermal gradients. Local mesh refinement is clearly observed near the basin surface, heating plate, and air–water interface, where heat transfer and evaporation processes are most significant. In contrast, relatively coarser mesh elements are used in regions with lower thermal variation, such as the upper air domain, to reduce computational cost without compromising solution accuracy [21]. The total number of elements in the medium mesh configuration is approximately 180,000 cells, providing a balance between computational efficiency and numerical accuracy. Mesh quality was evaluated using skewness and orthogonal quality metrics. The maximum skewness value was maintained below 0.85, with an average value of approximately 0.25, while the orthogonal quality remained above 0.25, ensuring stable and reliable numerical computation. To further enhance the resolution near solid–fluid interfaces, inflation layers were applied along the basin surface and heating plate, as indicated in Fig. 4. This treatment is essential for accurately capturing boundary layer effects and resolving steep temperature gradients near the walls [22].

Overall, the mesh configuration, as presented in Fig. 4, was designed to provide an accurate representation of heat transfer behavior within the desalination system while maintaining a reasonable computational cost. The independence of the numerical solution from mesh size was subsequently verified through a grid independence test, as discussed in the following section [23].

2.5 Grid Independence Test

The grid independence test was conducted to ensure that the numerical results are not significantly affected by mesh size. The comparison of temperature and heat flux distributions for different mesh sizes (20 mm, 50 mm, and 100 mm) is presented in Fig. 5. [24].

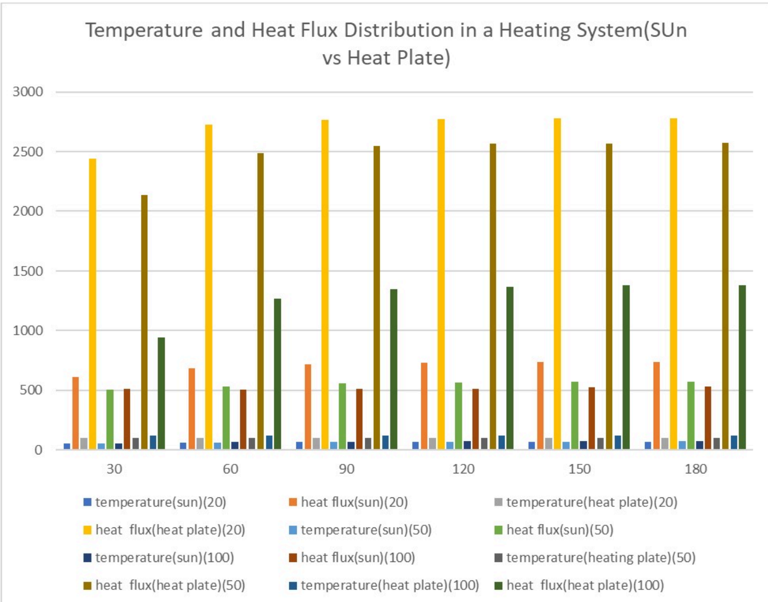


Fig. 5 Temperature and feat flux distribution in a heating system (Sun vs Heat Plate)

As shown in Fig. 5, both temperature and heat flux increase with simulation time for all mesh configurations, indicating consistent thermal behavior of the system. However, noticeable differences are observed between coarse and refined meshes. The 100 mm mesh generally produces lower temperature and heat flux values compared to the finer meshes, indicating reduced numerical accuracy due to insufficient resolution. In contrast, the results obtained using the 50 mm and 20 mm meshes show very similar trends, particularly for both temperature and heat flux distributions. The variation between these two mesh sizes becomes minimal after approximately 90 minutes of simulation time, where the curves begin to converge and exhibit nearly identical behavior. This indicates that further mesh refinement beyond 50 mm provides only a negligible improvement in the solution.For the heating plate-assisted system, a similar pattern is observed. Although the heat flux values are significantly higher compared to the solar-only system, the difference between the 50 mm and 20 mm meshes remains relatively small, confirming the stability of the numerical solution. Meanwhile, the coarse mesh (100 mm) shows a noticeable deviation, especially at earlier simulation times, further highlighting the importance of mesh refinement.

Overall, the graphical comparison in Fig. 5 clearly demonstrates that the numerical results become mesh-independent when using finer mesh configurations. The similarity between the 50 mm and 20 mm mesh results indicates that the solution has reached convergence. Therefore, the 50 mm mesh is considered sufficient to provide accurate results while maintaining computational efficiency, whereas the 20 mm mesh can be used as a reference for validation.

The grid independence test was evaluated using the error percentage formulation, as expressed in Eq. (1):

$$Error(\%) = \frac{T_{mesh} - T_{fine}}{T_{fine}} \times 100$$

where T_{mesh}represents the maximum temperature obtained from a given mesh size, and T_{fine}represents the temperature obtained from the finest mesh. This formulation is based on the relative error concept commonly used in CFD mesh convergence analysis.

The calculated error values for different mesh sizes are summarized in Table 1 and Table 2. Table 1 presents the results for the system without a heating plate, while Table 2 shows the results for the heating plate-assisted system. As shown in Table 1, the error percentage for the 100 mm mesh is 3.20%, indicating a noticeable deviation from the reference solution. However, the error significantly decreases to 0.01% when the mesh size is refined to 50 mm, compared to the finest mesh (20 mm). This very small error value indicates that the solution has reached excellent numerical convergence and is practically mesh-independent for the system without heating plate.

Similarly, for the heating plate-assisted configuration presented in Table 2, the error for the 100 mm mesh is relatively high at 18.84%, indicating that the coarse mesh is not sufficiently accurate. When the mesh is refined to 50 mm, the error decreases to 1.47%, showing a substantial improvement in accuracy. Although this value is slightly higher than the case without heating plate, it remains within an acceptable range for CFD simulations. Based on these results, the application of the error formulation in Eq. (1) clearly demonstrates that mesh refinement significantly improves numerical accuracy. The results in Tables 1 and Tables 2 confirm that the solution becomes less sensitive to mesh size as the mesh is refined. Therefore, the 50 mm mesh is considered sufficient for achieving a balance between computational efficiency and accuracy, while the finest mesh (20 mm) is used as a reference for validation.

Table 1
Grid independence test results for the system without heating plate

Mesh Size (mm)	$T_{\max}$	Error (%)
100	74.915	3.20
50	72,596	0.01
20	72,592	-

Table 2
Grid independence test results for the system with heating plate

Mesh Size (mm)	$T_{\max}$	Error (%)
100	119.8	18.84
50	102,29	1.47
20	100,81	-

2.6 Material Properties

The material properties used in this study are defined to represent the thermal characteristics of each solid component in the desalination system. The selected materials include wood, glass, copper, and zinc, which are commonly used in thermal systems due to their different heat transfer capabilities. The variation in thermal conductivity among these materials plays a significant role in determining heat distribution within the system [25].

Wood is used as the structural frame material due to its insulating properties. With relatively low thermal conductivity, wood minimizes heat loss to the surroundings and helps retain thermal energy within the system. Glass is utilized as the cover material, allowing solar radiation to penetrate into the system while facilitating condensation on its inner surface. Its moderate thermal conductivity enables heat transfer while maintaining structural transparency [26].

Copper and zinc are considered as metallic materials with high thermal conductivity, making them suitable for components that require efficient heat transfer, such as the heating plate. Copper, in particular, has a very high thermal conductivity, allowing rapid heat distribution to the fluid domain. Zinc, although slightly lower in conductivity than copper, still provides effective thermal transfer and can be used as an alternative material depending on system design and cost considerations [27].

The thermophysical properties of the materials used in the simulation are summarized in Table 3. These properties include density, thermal conductivity, and specific heat capacity, which are essential parameters for solving the energy equation and analyzing heat transfer behavior within the system.

Table 3
Thermophysical properties of materials used in the simulation

Material	Density (kg/m³)	Thermal Conductivity (W/m·K)	Specific Heat (J/kg·K)
Wood	7850	0,25	434
Glass	2500	1,4	750
Copper	8933	400	385
Zinc	7140	115,5	389

2.7 Boundary Condition

The boundary conditions applied in this study are defined to represent realistic operating conditions of the solar desalination system under tropical environments. Proper specification of these conditions is essential to ensure accurate prediction of temperature distribution and heat transfer behavior within the system[28]. Solar radiation is applied as the primary heat source entering the system through the inclined glass cover. In tropical regions such as Indonesia, solar irradiance typically ranges between 600–1000 W/m², depending on weather conditions and time of day. In this study, a representative average value of 800 W/m² is used to simulate steady solar heating. This heat flux is absorbed by the basin water and contributes directly to the evaporation process. In the enhanced configuration, an additional heat source is introduced in the form of a heating plate located beneath the basin. The heating plate is modeled as a constant heat flux boundary condition with a value of 500 W/m², providing supplementary thermal energy to improve temperature distribution and evaporation efficiency.

The ambient temperature is set to 300 K, representing typical environmental conditions in tropical climates. Heat losses from the outer surfaces of the system are modeled through natural convection to the surrounding air. The operating pressure is defined as atmospheric pressure (101325 Pa) and applied uniformly throughout the computational domain. Natural convection is considered in both air and water domains by activating gravity and applying the Boussinesq approximation. This allows the simulation to capture buoyancy-driven flow caused by temperature differences, which plays an important role in heat transfer and vapor transport within the system[29]. Overall, these boundary conditions are selected to simulate both natural solar heating and assisted heating scenarios under realistic operating conditions, enabling a comprehensive comparison of system performance.

Table 4
Boundary conditions used in the simulation

Parameter	**Value**
Solar radiation	800 W/m²
Heating plate	500 W/m²
Ambient temperature	300 K
Pressure	101325 Pa

2.8 Simulation Method

The numerical simulation was performed using ANSYS Fluent to analyze heat transfer behavior within the solar desalination system. The simulation setup was carefully defined to ensure accurate representation of thermal and fluid flow phenomena under the specified boundary conditions[30]. A pressure-based solver was employed due to its suitability for incompressible flow conditions commonly found in solar still systems. The flow regime inside the enclosure was modeled as laminar, as the fluid motion is primarily driven by buoyancy forces with relatively low velocity and no significant turbulence effects [31]. The energy equation was activated (ON) to enable the calculation of temperature distribution throughout both fluid and solid domains. This is essential for capturing heat transfer processes such as conduction in solid materials and convection in fluid regions.

To account for buoyancy-driven flow, gravity was activated (ON) in the vertical direction with a value of −9.81 m/s². The Boussinesq approximation was applied to model density variations as a function of temperature, allowing accurate simulation of natural convection within the enclosure while maintaining computational efficiency. The pressure–velocity coupling was handled using the SIMPLE algorithm, and the discretization scheme for the governing equations was set to second-order upwind to improve numerical accuracy. The convergence criteria for residuals were defined as 10^{-6} for the energy equation and 10^{-4} for continuity and momentum equations, ensuring stable and reliable simulation results. The simulation was conducted under transient conditions to capture the time-dependent behavior of temperature and heat transfer. The total simulation time was set to 180 minutes, with data recorded at intervals of 30 minutes to analyze the evolution of thermal distribution over time.

Two simulation scenarios were evaluated:

1. Without heating plate, representing a conventional solar still system driven solely by solar radiation.
2. With heating plate, incorporating an additional heat source to enhance thermal performance.

This simulation setup enables a comprehensive analysis of heat transfer mechanisms and allows direct comparison between natural and assisted heating conditions.

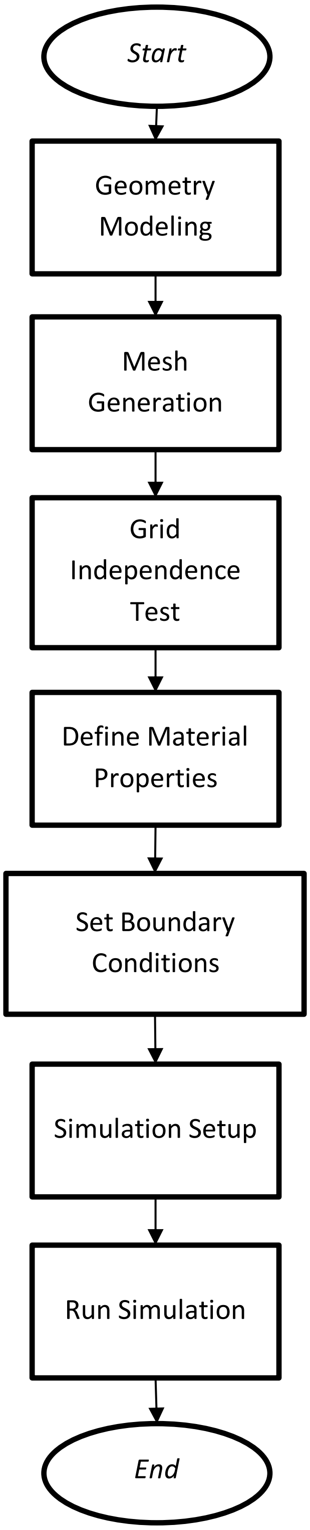


Fig. 6. Flowchart of the numerical simulation process for the desalination system

2.9 Numerical Scheme and Convergence

The numerical solution of the governing equations was performed using appropriate discretization schemes to ensure accuracy and stability of the simulation. The spatial discretization of momentum, energy, and other transport equations was carried out using a second-order upwind scheme, which provides higher accuracy compared to first-order methods, particularly in capturing temperature gradients and heat transfer behavior within the system [32].

The pressure–velocity coupling was handled using the SIMPLE algorithm, which is widely applied in pressure-based solvers for incompressible flow simulations. This method ensures stable coupling between pressure and velocity fields during the iterative solution process [33].

To ensure numerical accuracy, strict convergence criteria were applied. The residuals for the governing equations were monitored throughout the simulation, and convergence was considered achieved when the residual values dropped below the specified limits. The convergence criteria were set as follows:

- Energy equation: 10^{-6}
- Continuity equation: 10^{-4}
- Momentum equations: 10^{-4}

In addition to residual monitoring, solution stability was verified by observing the stabilization of key physical parameters, such as temperature distribution and heat flux within the domain. This ensures that the obtained results are not only numerically converged but also physically consistent. The use of second-order discretization combined with strict convergence criteria ensures that the simulation results accurately represent the heat transfer behavior within the solar desalination system.

2.10 Analysis parameters

The analysis parameters in this study were defined to evaluate the thermal performance of the solar desalination system under different heating conditions. The simulation was conducted using ANSYS Fluent with a focus on heat transfer behavior within the system [34]. The simulation was performed under transient conditions to capture the time-dependent evolution of temperature and heat transfer. The total simulation time was set from 30 to 180 minutes, with data recorded at intervals of 30 minutes (30, 60, 90, 120, 150, and 180 minutes). This time variation allows detailed observation of heat distribution and system response over the operating period.

The primary parameters analyzed in this study include:

- Temperature distribution
  Temperature contours were used to evaluate the spatial distribution of heat within the fluid and solid domains. This parameter is essential in determining the effectiveness of heat transfer from the heat source to the seawater and its impact on the evaporation process.
- Heat flux distribution
  Heat flux contours were analyzed to quantify the rate and direction of heat transfer within the system. This parameter provides insight into how thermal energy is distributed from the solar radiation and heating plate to the fluid domain.

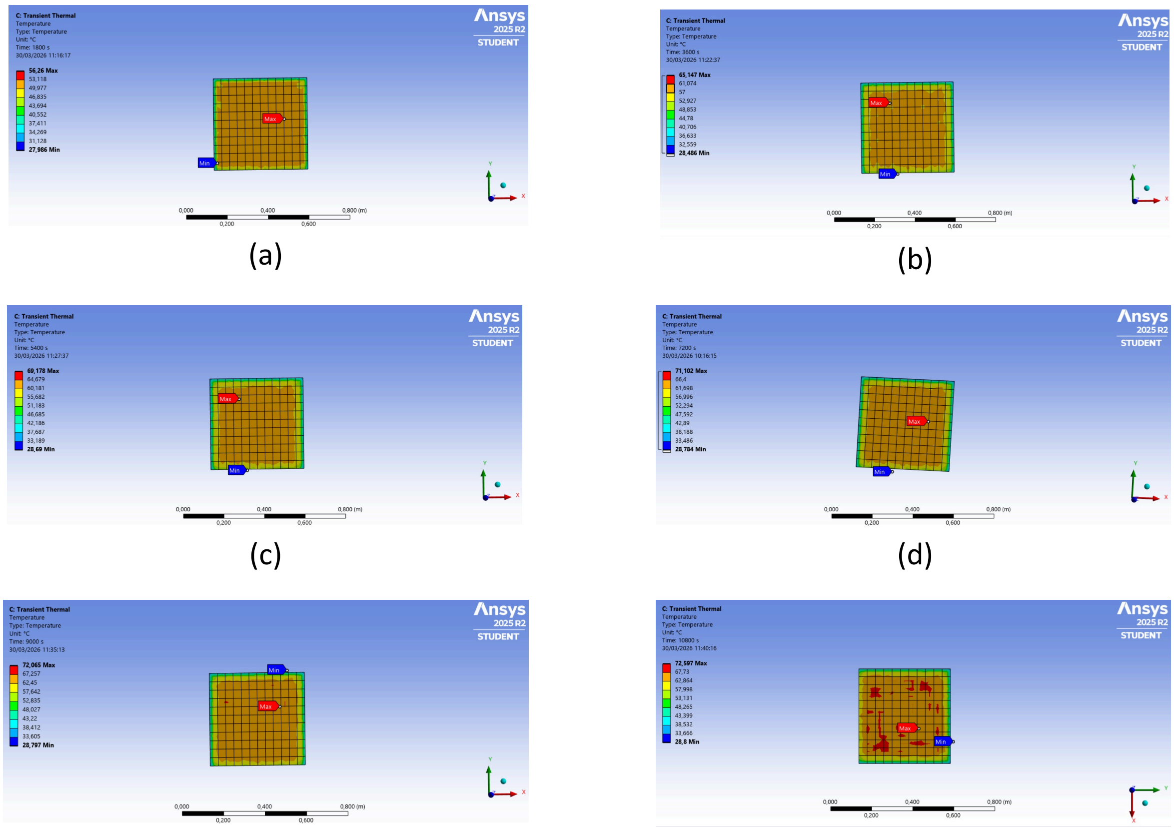
In addition to these parameters, a comparative analysis was conducted between two operating conditions, namely without heating plate and with heating plate, to evaluate the effect of the additional heat source on temperature uniformity and overall heat transfer performance. Overall, these analysis parameters enable a comprehensive assessment of heat transfer mechanisms and provide a clear basis for evaluating the performance improvement of the desalination system.

Table 5
Analysis parameters

Parameter	Description
Simulation time	30–180 minutes
Time interval	30 minutes
Temperature	Thermal distribution analysis
Heat flux	Heat transfer intensity

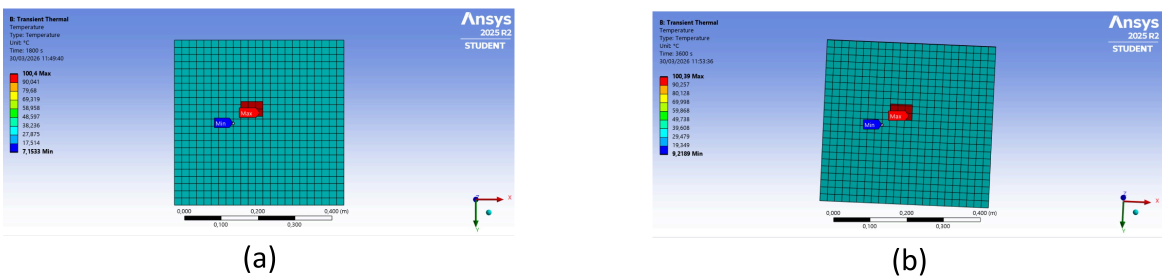
3. Result and Discussion

3.1 Temperature Distribution



(a) (b) (c) (d) (e) (f)

Fig. 7. Temperature distribution without heating plate: (a) 30 minute (b) 60 minute (c) 90 minute (d) 120 minute (e) 150 minute (f) 180 minute



(a) (b)

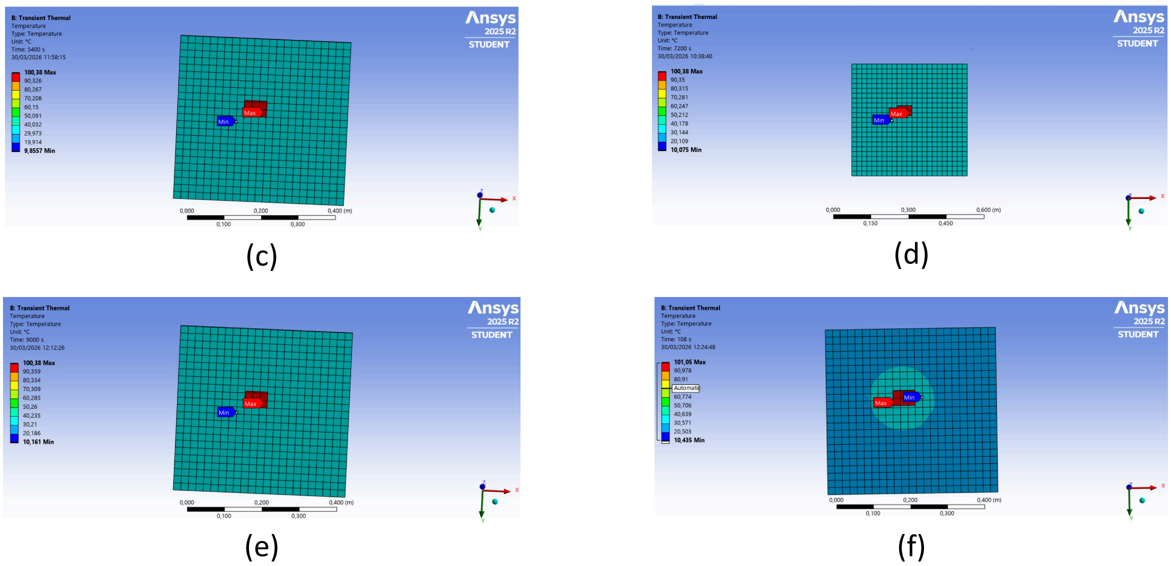


Fig. 8. Temperature distribution with heating plate: (a) 30 minute (b) 60 minute (c) 90 minute (d) 120 minute (e) 150 minute (f) 180 minute

The temperature distribution within the solar desalination system was analyzed to evaluate the thermal behavior under transient conditions over a simulation period of 30 to 180 minutes. The results are presented in Figure 7 and Figure 8, which illustrate the temperature contours for the system without heating plate and with heating plate, respectively.

3.1.1 Temporal evolution of temperature

The simulation results indicate that temperature increases progressively over time due to continuous heat input from solar radiation and the heating plate. At the early stage (30 minutes), the temperature distribution is relatively low and localized, indicating limited heat absorption within the system. As the simulation progresses to 60 and 90 minutes, the temperature begins to increase gradually. However, in the system without heating plate, the temperature distribution remains uneven and concentrated near specific regions, indicating limited heat propagation. At 120 minutes, the temperature starts to spread more widely across the domain, although the overall thermal intensity remains moderate. At 150 and 180 minutes, the system approaches a more stable thermal condition. The temperature distribution becomes more uniform compared to earlier stages, indicating that heat transfer processes have reached a quasi-steady state. This behavior highlights the importance of transient analysis in capturing the temporal evolution of thermal behavior within the desalination system.

3.1.2 Effect of heating plate on temperature distribution

A significant difference in temperature distribution is observed between the two configurations. The system without heating plate reaches a maximum temperature of approximately 74.915°C, whereas the system with heating plate achieves a significantly higher temperature of 119.8°C. The presence of the heating plate accelerates the rate of temperature increase and enhances heat distribution within the system. At 30 minutes, the heating-assisted system already exhibits higher temperature levels compared to the conventional system. As time progresses, the temperature spreads more uniformly across the domain due to additional heat input from the bottom of the basin.

In contrast, the system without heating plate shows clear temperature stratification, with lower temperature regions persisting throughout the simulation. This indicates that heat transfer is less effective when relying solely on solar radiation.

The improved temperature uniformity in the heating-assisted system is attributed to enhanced heat transfer mechanisms, particularly conduction from the heating plate and increased natural convection within the fluid domain. This results in a more homogeneous thermal field, which is essential for efficient evaporation. Overall, the results demonstrate that the integration of a heating plate significantly enhances both the magnitude and distribution of temperature within the desalination system, leading to improved thermal performance.

3.2 Heat Flux Distribution

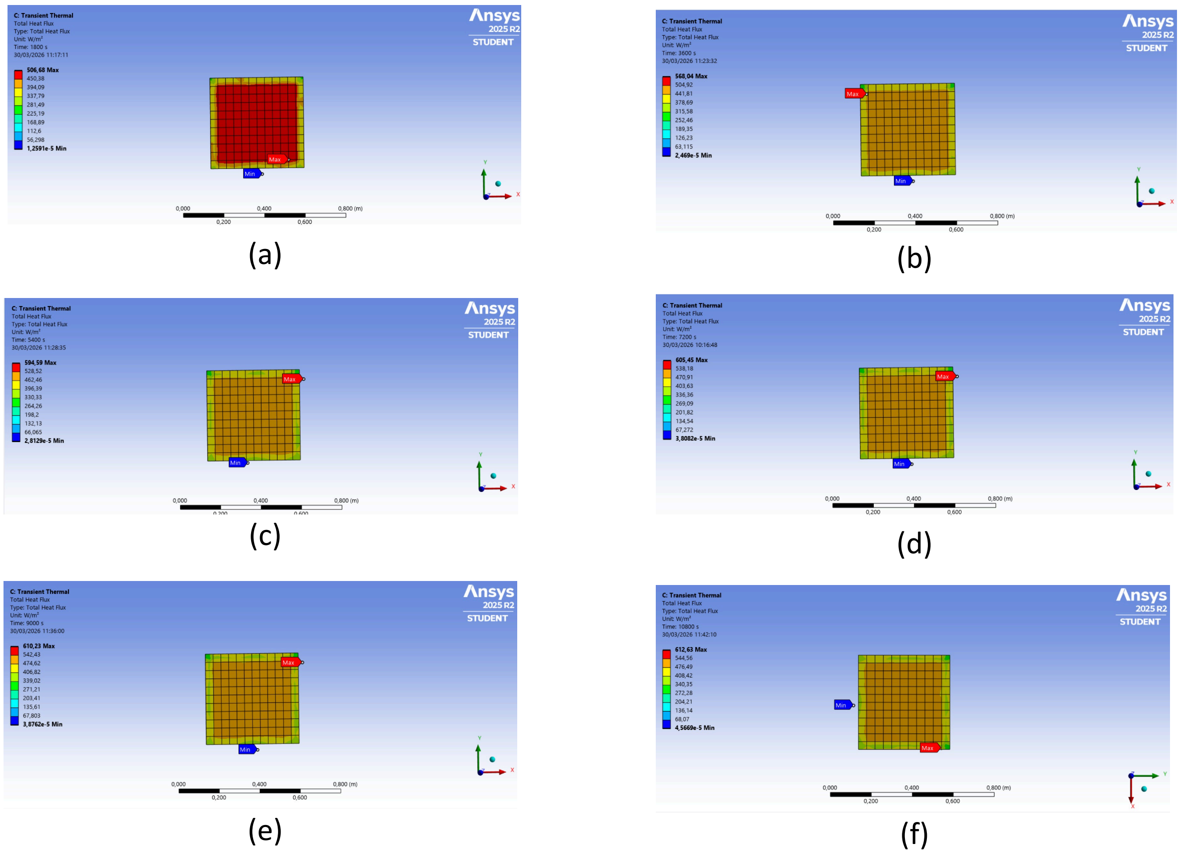
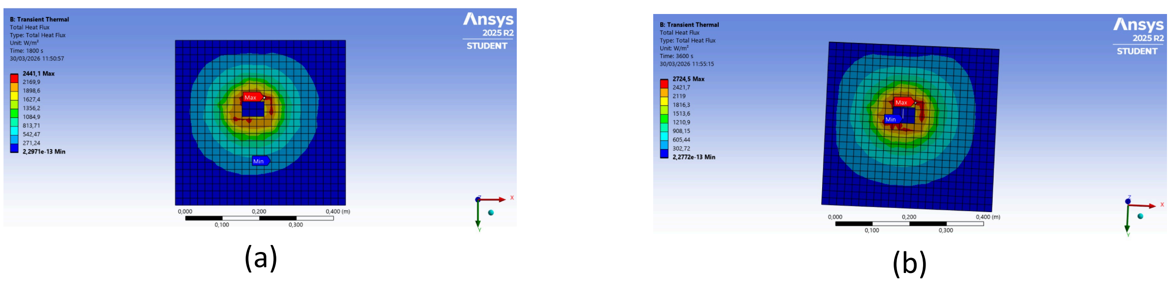


Fig. 9. Heat flux distribution without heating plate at different time intervals: (a) 30 minute (b) 60 minute (c) 90 minute (d) 120 minute (e) 150 minute (f) 180 minute



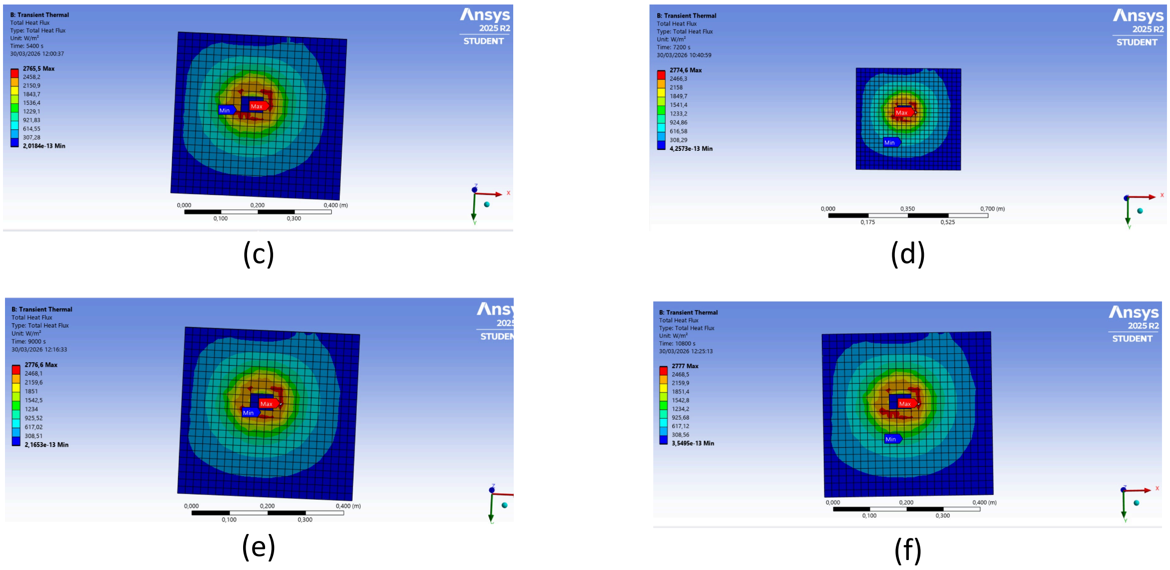


Fig. 10. Heat flux distribution with heating plate at different time intervals: (a) 30 minute (b) 60 minute (c) 90 minute (d) 120 minute (e) 150 minute (f) 180 minute

The heat flux distribution within the desalination system was analyzed to evaluate the intensity and effectiveness of heat transfer under transient conditions. The results are presented in Figure 9 and Figure 10, which illustrate the heat flux contours for the system without heating plate and with heating plate at different time intervals ranging from 30 to 180 minutes.

3.2.1 Heat flux evolution over time

The simulation results show that heat flux evolves significantly over time as thermal energy is continuously supplied to the system. At 30 minutes, the heat flux distribution is relatively low and localized, indicating that heat transfer is still limited to regions close to the heat source. As time progresses to 60 and 90 minutes, the heat flux begins to increase gradually and spreads across a wider area of the domain. At 120 minutes, the heat flux becomes more distributed, indicating improved heat transfer throughout the system. By 150 and 180 minutes, the heat flux distribution reaches a more stable condition, where the pattern of heat transfer remains relatively consistent over time. This behavior suggests that the system approaches a quasi-steady thermal state under continuous heating. However, in the configuration without heating plate, the heat flux distribution remains uneven and relatively weak throughout the simulation. The heat transfer is primarily driven by solar radiation, resulting in limited energy propagation and slower thermal response.

3.2.2 Effect of heating plate on heat transfer intensity

A clear difference is observed between the two configurations in terms of heat flux magnitude and distribution. The system with heating plate exhibits significantly higher heat flux intensity compared to the system without heating plate. At early stages (30 minutes), the heating-assisted system already shows stronger heat flux near the basin region due to direct heat input from the heating plate. As time increases, the heat flux spreads more uniformly across the domain, indicating enhanced heat transfer efficiency. In contrast, the system without heating plate shows localized heat flux patterns with lower intensity, indicating inefficient heat distribution. The absence of an auxiliary heat source limits the ability of the system to transfer thermal energy effectively.

The presence of the heating plate enhances conductive heat transfer from the bottom of the basin and promotes stronger natural convection within the fluid domain. This results in improved heat circulation and more uniform energy distribution. Furthermore, the increased heat flux intensity in the heating-assisted system directly contributes to higher thermal energy availability, which supports the findings in Section 3.1 where higher temperature levels were observed. This synergy between temperature and heat flux indicates a more efficient heat transfer mechanism. Overall, the integration of a heating plate significantly improves heat transfer intensity, spatial distribution, and thermal efficiency within the desalination system.

3.3 System Performance Comparison

The overall performance of the desalination system was evaluated by comparing the temperature and heat flux distributions under two operating conditions, namely without heating plate and with heating plate. This comparison provides a comprehensive understanding of how additional heat input influences thermal behavior and evaporation potential. The results show that the system with heating plate achieves a significantly higher temperature compared to the conventional system. The maximum temperature increases from 74.915°C (without heating plate) to 119.8°C (with heating plate), indicating a substantial enhancement in thermal intensity. This increase in temperature demonstrates that the heating plate effectively supplies additional energy to the system. In terms of heat distribution, the heating-assisted system exhibits a more uniform temperature field and heat flux distribution. The presence of the heating plate reduces temperature stratification and minimizes localized cold regions within the domain. In contrast, the system without heating plate shows uneven heat distribution, with thermal energy concentrated only in specific areas.

The improvement in both temperature magnitude and heat flux distribution directly affects the evaporation process. Higher temperatures increase the rate of water evaporation, while more uniform heat distribution ensures that evaporation occurs more consistently across the entire water surface. As a result, the heating-assisted system provides a more stable and continuous evaporation process compared to the conventional system. Overall, the integration of a heating plate significantly enhances system performance by increasing thermal intensity, improving heat distribution uniformity, and promoting more effective evaporation. These results confirm that the addition of an auxiliary heat source is an effective approach to improve the efficiency of solar desalination systems.

3.4 Heat Transfer Analysis

The heat transfer mechanisms within the desalination system are governed by the combined effects of conduction and natural convection, which significantly influence the overall thermal performance and evaporation process. Heat conduction occurs predominantly through the solid components, including the heating plate, basin, and glass cover. In the heating-assisted system, the heating plate acts as a direct thermal source, transferring heat efficiently to the basin through conduction. This bottom-up heat transfer mechanism reduces thermal resistance and accelerates the increase in seawater temperature. In contrast, the conventional system relies mainly on solar radiation, where heat transfer to the basin occurs indirectly, resulting in slower and less effective conductive heat transfer.

Natural convection plays a dominant role within the fluid domains, particularly in the seawater and air regions inside the enclosure. As the seawater is heated, its density decreases, causing upward fluid motion, while cooler fluid descends to replace it. This buoyancy-driven flow enhances heat circulation and promotes more effective heat distribution. The presence of the heating plate intensifies this convective motion by increasing the temperature gradient within the system. As a result, stronger circulation patterns are formed, leading to improved heat transfer from the basin to the upper regions of the enclosure. The interaction between conduction and convection results in a more efficient thermal transport process in the heating-assisted system. The continuous heat supply from the heating plate ensures that thermal energy is not only increased but also distributed more evenly throughout the system. This reduces temperature stratification and minimizes thermal losses. Furthermore, the enhanced heat transfer mechanisms directly impact the evaporation process. Higher thermal energy and improved heat distribution increase the rate of water evaporation, while stable thermal conditions support continuous vapor generation over time. In contrast, the conventional system experiences weaker heat transfer mechanisms, leading to lower evaporation rates and less efficient thermal utilization. Overall, the analysis confirms that the integration of a heating plate significantly improves heat transfer performance by strengthening conductive heat transfer, enhancing natural convection, and promoting more uniform energy distribution. These combined effects contribute to improved thermal efficiency and higher desalination performance.

4. Conclusions

This study presents a comprehensive numerical analysis of heat distribution in a solar desalination system by comparing conventional solar heating and a heating-assisted configuration using a heating plate. The findings clearly demonstrate that the integration of an auxiliary heating plate significantly enhances the thermal performance of the system. The heating-assisted system exhibits higher temperature levels, faster thermal response, and more uniform heat distribution compared to the conventional system. The improved heat flux intensity and spatial uniformity indicate a more efficient transfer of thermal energy from the heat source to the seawater. These enhancements lead to a stronger and more stable temperature gradient within the system, which is essential for driving the evaporation process. Furthermore, the transient analysis over a 2-hour period reveals that the heating plate accelerates heat propagation and maintains thermal stability over time. This results in a more consistent and continuous evaporation process, in contrast to the conventional system, which shows slower and less uniform thermal development.

Overall, the addition of a heating plate improves conduction, strengthens natural convection, and enhances overall heat transfer efficiency within the desalination system. These improvements contribute to increased evaporation potential and better system performance. Therefore, the use of an auxiliary heating plate is a promising approach to overcome the limitations of conventional solar still systems, particularly under conditions of low or fluctuating solar radiation.

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