

## Research Article

# Numerical Simulation and Thermal Performance of a Novel Parabolic Solar Collector Panels

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## Abstract:

*This study investigates the design of a novel parabolic solar collector. It examines the effects of solar radiation on the collector panels and the flow characteristics of water through the system. The design incorporates two solar collector panels, each measuring  $2 \times 1.5$  meters, with 2-inch diameter water pipes extending 11 meters in total. The parabolic panels have a focal point positioned 0.25 meters above the collector surface. A computational fluid dynamics (CFD) analysis was performed for flow rates of 0.25, 0.50, 0.75 and 1.00 liters per minute. The computational domain consisted of 1,520,000 mesh elements for analyzing solar thermal energy and 130,000 elements for simulating heat transfer from the radiation panels to the water within the pipes. The optimal flow rate was found to be between 0.50 and 0.75 liters per minute. The results show that the designed parabolic heat collector achieves maximum thermal efficiencies of 36.03% and 41.57%, respectively.*

**Keywords:** Computational Fluid Dynamics, Numerical simulation, Parabolic solar collector panel, Thermal performance design

## 1. Introduction

Soil sterilization improves farming conditions by eliminating pathogens like weeds and pests, which hinder plant growth. It also boosts agricultural productivity and reduces long-term chemical use. Farmers can use several methods for soil sterilization, depending on the types of pathogens and their goals. Common methods include heat treatment, chemical application, biocontrol, physical conditioning, and soil amendments. Each method has its advantages and drawbacks, so choosing the right one for the specific situation is essential. Heat sterilization, based on soil pasteurization, is one of the most studied methods in previous research [1-6].

This method uses hot steam or hot water with temperatures ranging from 60 to 80 degrees Celsius to eliminate fungi, bacteria, and nematodes. It is commonly applied in nurseries [7-8]. Furthermore, several studies have explored the technique of soil solarization, which is another approach that uses solar energy to increase soil temperature [9]. This method involves covering the soil with transparent plastic for 4-6 weeks to effectively inhibit and eliminate soil pathogens. For the production of hot water used in soil sterilization, this can generally be achieved using water from solar panels, boiling water with fuel, electric heating, or steam from a boiler, among other methods. Particularly, the use of solar panels for hot water production is becoming increasingly popular due to its low-cost technology and the efficient and cost-effective use of renewable energy.

The maximum efficiency of hot water production using solar radiation panels depends on the design and development of equipment that can effectively convert solar energy for practical use. Parabolic solar radiation panels are devices used to capture solar radiation, with the function of reflecting sunlight to focus at the absorption tube, which is positioned at the focal point of the parabola [10]. To design a parabolic solar radiation panel for optimal performance,

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it is necessary to analyze the curvature of the parabola, as studied in the research of Surawattanawan, Limboonruang, and Dirk et al. [10, 11]. Recent research has focused on designing parabolic solar collectors using computational fluid dynamics (CFD). This method improves solar radiation capture by optimizing collector structures with fluid dynamics and physics. It allows collectors to capture sunlight from different directions, even in areas with little or uneven sunlight. For a research example, Ghasemi and Ranjbar studied the thermal performance of parabolic trough solar collectors using nanofluids [12]. Liu et al. [13], explored new design strategies to improve solar energy production. Akrami et al. [14], examined the best materials and concentration ratios for these collectors using CFD.

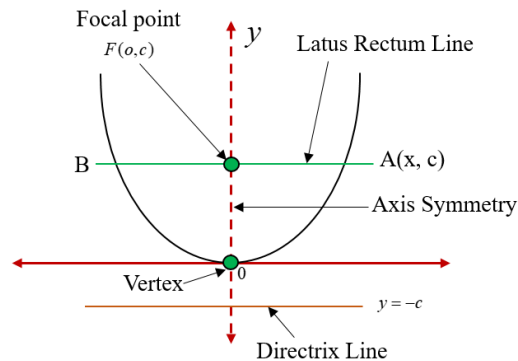
Additionally, many studies explore the relationship between parabolic radiation and solar energy using fluid dynamics analysis [15-19]. Renewable energy, especially solar hot water production, is crucial today. Researchers focus on improving thermal efficiency, developing solar energy use, and optimizing the design of parabolic radiation collectors. These studies also examine concentration ratios, focal point design for solar panels, and the geometry of parabolas to increase efficiency. The findings from this research can help develop new parabolic panel models. These models are suitable for areas with sufficient sunlight and can be used in applications that require thermal energy for hot water production, such as soil sterilization in Thailand.

This research examines the design process and analyzes how sunlight affects solar radiation collectors. It also investigates water flow through a high-efficiency parabolic solar collector, which is ideal for hot water production in soil sterilization. The goal is to provide guidelines for developing efficient renewable energy systems for widespread use in Thailand.

## 2. Related theories and research

### 2.1 Design principles of parabolic solar collector

Parabolic solar collectors possess a distinctive feature that enables them to reflect or capture radiation incident along a direction parallel to the axis of the parabola, thereby concentrating the radiation at the focal point [10]. The theoretical components of the parabolic radiation collector are illustrated in Fig. 1.



**Fig. 1.** Theoretical components of a parabolic radiation receiver [20].

Figure 1 illustrates that, when considering the equation of the upward-facing parabola, the vertex is located at the origin (0,0), as shown in Eq. (1).

$$y = \frac{x^2}{4f} \quad (1)$$

Equation (1) indicates that, when applied to the design of a parabolic solar radiation collector, the vertical distance or depth of the parabolic shape can be set equal to the focal length as a result of the mathematical properties of the parabola. Consequently, this relationship can be expressed in the form of Eq. (2).

$$\frac{f}{w} = 0.25 \quad (2)$$

where  $f$  is the desired design focus point,  $w$  is the width of the parabolic solar collector panel support collector.

## 2.2 Principles of parabola solar collector performance analysis

The steps of theoretical parabolic solar collector performance analysis in this research can be calculated from Eq. (3) [21].

$$\eta_{collector} = \frac{Q_u}{A_c I} \quad (3)$$

where  $\eta_{collector}$  is defined to represent the performance of the parabolic solar collector panel,  $Q_u$  is the heat value received from parabolic solar collectors (J),  $A_c$  is sunlight receiving area of parabolic solar collector ( $m^2$ ), and  $I$  is solar radiation intensity ( $W / m^2$ ).

The thermal variables of the parabolic solar radiation collector can be calculated using the relationship between the water flow rate, the specific heat capacity of water, and the inlet and outlet water temperatures, as shown in Eq. (4) [22-23].

$$Q_u = \dot{m} C_p (T_{Out} - T_{In}) \quad (4)$$

where  $\dot{m}$  represents the mass flow rate of water passing through the parabolic solar collector ( $kg / s$ ),  $C_p$  is specific heat of water ( $J / kg.^{\circ}C$ ),  $T_{in}$  is temperature of water flowing into the parabolic solar collector ( $^{\circ}C$ ), and  $T_{Out}$  is temperature of water flowing out of parabolic solar collector panel ( $^{\circ}C$ ).

## 2.3 Principles of sun movement

The movement of the sun is considered based on the declination angle, which represents the angular position of the sun at solar noon. This angle is compared with the angle of the equatorial plane, which can be determined from Eq. (5) and also calculated using Eq. (6) [24-25].

$$-23.45^{\circ} \leq \delta \leq 23.45^{\circ} \quad (5)$$

$$\delta = 23.45 \sin \left( 360 \times \frac{248 + n}{365} \right) \quad (6)$$

where  $n$  is the number of days considered.

Considering the angle, the earth must rotate so that the meridian of the plane is directly under the sun; this can be calculated from Eq. (7).

$$\omega_{Angle} = 15(12 - st) \quad (7)$$

where  $st$  is the local standard time is considered relative to the noontime in the test area, which can be calculated from Eq. (8).

$$st = \text{Standard time} + E-4(Long_{st} - Long_{Loc}) \quad (8)$$

where  $Long_{st}$  is the longitude lines used to draw through standard time periods, and  $Long_{Loc}$  is the longitude line used to draw through the local time period being tested.

## 2.4 Principles of computational fluid dynamics

The principle of computational fluid dynamics relies on the relationship of a system of three equations: the energy conservation equation, the mass conservation equation, and the momentum conservation equation. These relationships can be expressed in the form of a correlation equation, as shown in Eq. (9).

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \quad (9)$$

From Eq. (10), the variables  $x$ ,  $y$ , and  $z$  represent the motion in the Cartesian coordinate system, while the variables  $u$ ,  $v$ , and  $w$  represent the velocities along the  $x$ ,  $y$ , and  $z$  axes, respectively. The momentum conservation equation will be used to calculate the rate of change of pressure and frictional forces. The relationships of the momentum conservation equations along the different axes can be expressed as Eqs. (10-12).

$$\text{x-component: } \rho \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial v u}{\partial y} + \frac{\partial w u}{\partial z} \right) = -\frac{\partial P}{\partial x} + \mu \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right) \quad (10)$$

$$\text{y-component: } \rho \left( \frac{\partial u v}{\partial x} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial w v}{\partial z} \right) = -\frac{\partial P}{\partial y} + \mu \left( \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} \right) \quad (11)$$

$$\text{z-component: } \rho \left( \frac{\partial u w}{\partial x} + \frac{\partial w u}{\partial y} + \frac{\partial^2 w}{\partial z^2} \right) = -\frac{\partial P}{\partial z} + \mu \left( \frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} \right) + \rho g \quad (12)$$

where  $\rho$  is the fluid density ( $\text{kg} / \text{m}^3$ ),  $P$  is fluid pressure ( $\text{Pa}$ ),  $\mu$  is the viscosity of a fluid in the  $x$ ,  $y$  and  $z$  directions ( $\text{Pa.s}$ ).

When considering the changes in kinetic energy and thermal energy occurring in the water flow process, these relationships can be determined using the law of energy conservation. The corresponding equation can be expressed as shown below:

$$\rho c \frac{\partial T}{\partial t} - k \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) - Q = 0 \quad (13)$$

where  $c$  is the specific heat capacity of fluid ( $\text{J} / \text{kg.K}$ ),  $T$  is the temperature values at different positions of the fluid under consideration ( $^{\circ}\text{C}$ ), and  $Q$  is the water flow rate per unit volume in the  $x$ ,  $y$ , and  $z$  directions ( $\text{m}^3 / \text{s}$ ).

For the analysis of fluid dynamics in turbulent flow problems, calculations can be performed using the  $k$ - $\varepsilon$  turbulence model. This model consists of two key equations: the turbulent kinetic energy equation and the turbulence dissipation equation. The relationships and details of these equations are given in Eqs. (14) and (15).

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + (G_k + G_b) - (\rho \varepsilon + Y_M) + S_k \quad (14)$$

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_i}(\rho \varepsilon u_i) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + C_{\varepsilon 1} \frac{\varepsilon}{k} (G_k + C_{\varepsilon 3} G_b) - C_{\varepsilon 2} \rho \frac{\varepsilon^2}{k} + S_\varepsilon \quad (15)$$

where  $\mu_t$  represents the turbulent viscosity of the fluid, which can be calculated using Eq. (16). The variable  $G_k$  denotes the kinetic energy influencing the turbulent flow, generated by the velocity gradient in the flow field, and can be determined using Eq. (17). Additionally, the variable  $G_b$  represents the energy induced by buoyancy forces in the turbulent flow field, which can be computed using Eq. (18) [26].

$$\mu_t = f \left( \rho \frac{k^2}{\varepsilon} \right) = \rho C_\mu \frac{k^2}{\varepsilon} \quad (16)$$

$$G_k = 2\mu_t S_{ij} S_{ij} \quad (17)$$

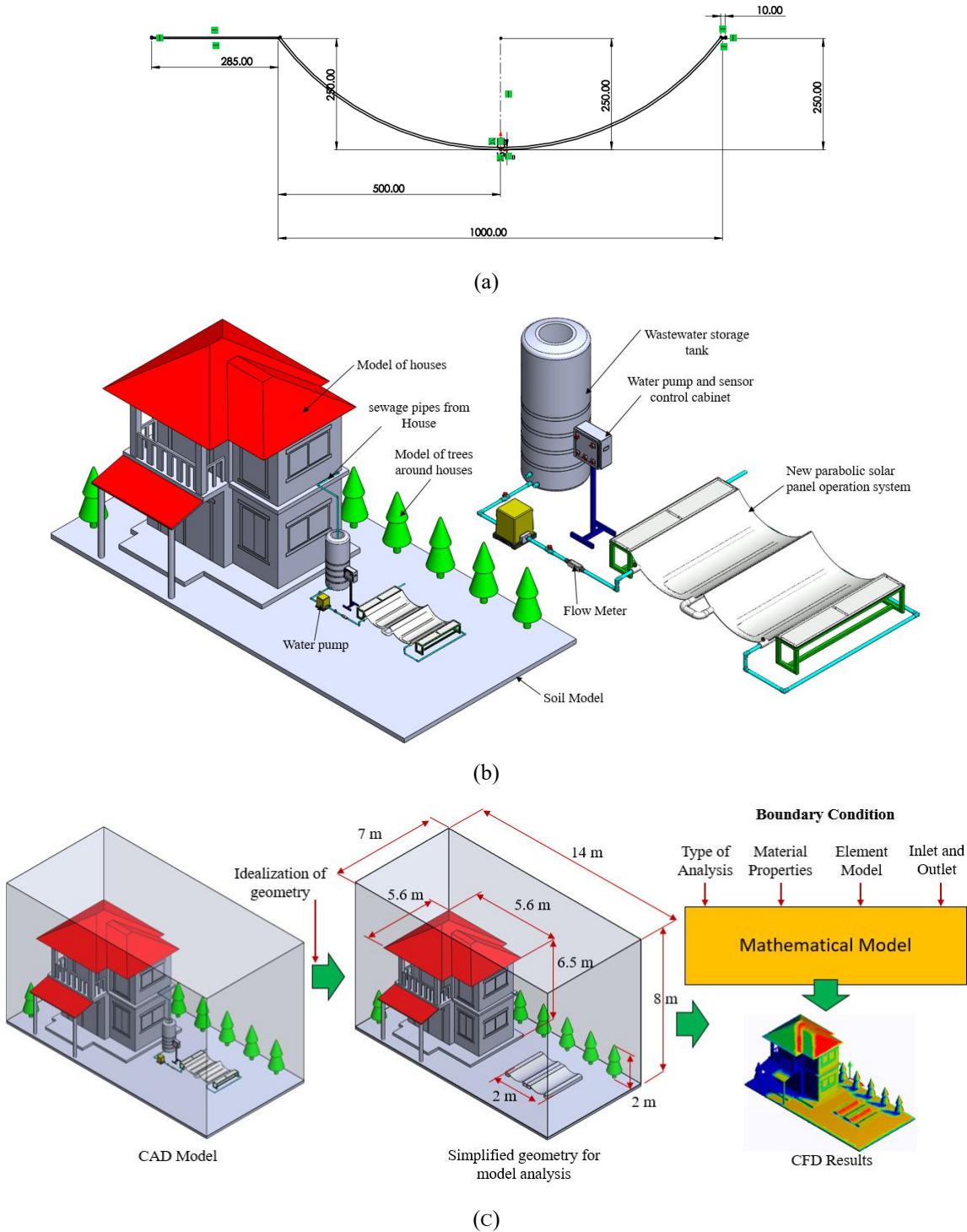
$$G_b = -g_i \frac{\mu_t}{\text{Pr}_t} \frac{\partial \rho}{\partial x_i} \quad (18)$$

### 3. Design and preparation steps for computational fluid dynamics

#### 3.1 Principles of parabolic solar collector design

Based on the relationship defined in Eq. (2), the appropriate width of the parabolic solar collector can be determined. Initially, the focal point and height were set at 0.25 meters, resulting in the design configuration shown in Fig. 2(a).

Subsequently, the components of the system were designed, as illustrated in Fig. 2(b). Furthermore, the idealization method was applied, simplifying complex analytical structures to create a more concise and manageable model for computational fluid dynamics (CFD) simulations. Accordingly, the dimensions and proportions of the problem domain, used to analyze the thermal effects of solar energy, are presented in Fig. 2(c).



**Fig. 2.** 3D model of the analysis components in this study: (a) the sketch for the fabrication of the parabolic solar collector derived from the calculations, (b) overall system components of the novel designed parabolic solar collector, and (c) the process of simplifying complex analytical structures for improved clarity.

3.2 Preparation steps for solar heat impact analysis

The analysis of the heat impact from solar energy in this study is conducted using fluid dynamics to investigate the positioning of solar radiation incident on a parabolic solar collector panel. The present study investigates fluid dynamic effects by means of numerical simulations implemented via the Transient Thermal Analysis module. It also includes the calculation of the heat generation rate from solar energy at the collector, which can be used to evaluate the performance of the parabolic solar collector system. This information is a critical variable for simulating the heat transfer process from the collector to the water flowing through the pipe. The simulation process for analyzing the heat impact of solar energy begins with the preparation of the analysis model, as shown in Fig. 1(c), followed by the definition of various properties of the model, as detailed in Table 1.

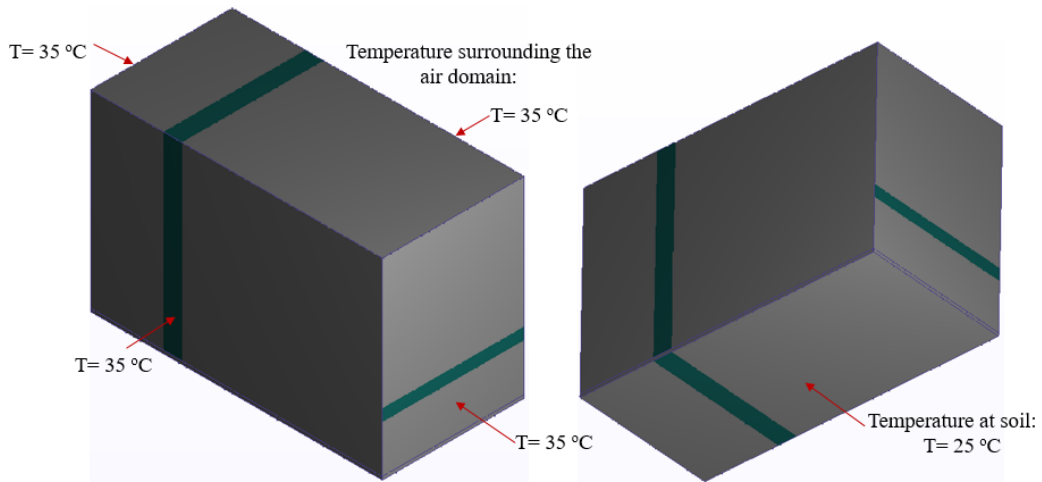
**Table 1:** Material properties for analytical modelling of solar heat effects [27].

| Materials       | Properties                |                         |                                 |                                   |                             |                        |
|-----------------|---------------------------|-------------------------|---------------------------------|-----------------------------------|-----------------------------|------------------------|
|                 | Density<br>( $kg / m^3$ ) | Viscosity<br>( $Pa.s$ ) | Conductivity<br>( $W / m - K$ ) | Specific Heat<br>( $J / kg - K$ ) | Compressibility<br>( $NA$ ) | Emissivity<br>( $NA$ ) |
| Air Domain      | 1.250                     | 1.817e-05               | 0.02563                         | 1,004                             | $C_p / C_v = 1.4$           | 1                      |
| House Domain    | 1,920                     | -                       | 0.72                            | 835                               | -                           | 0.94                   |
| Tree Domain     | 720                       | -                       | 0.16                            | 1,255                             | -                           | 0.80                   |
| Soil Domain     | 720                       | -                       | 10                              | 1,225                             | -                           | 0.30                   |
| Parabola Domain | 7,140                     | -                       | 116                             | 389                               | -                           | 0.50                   |

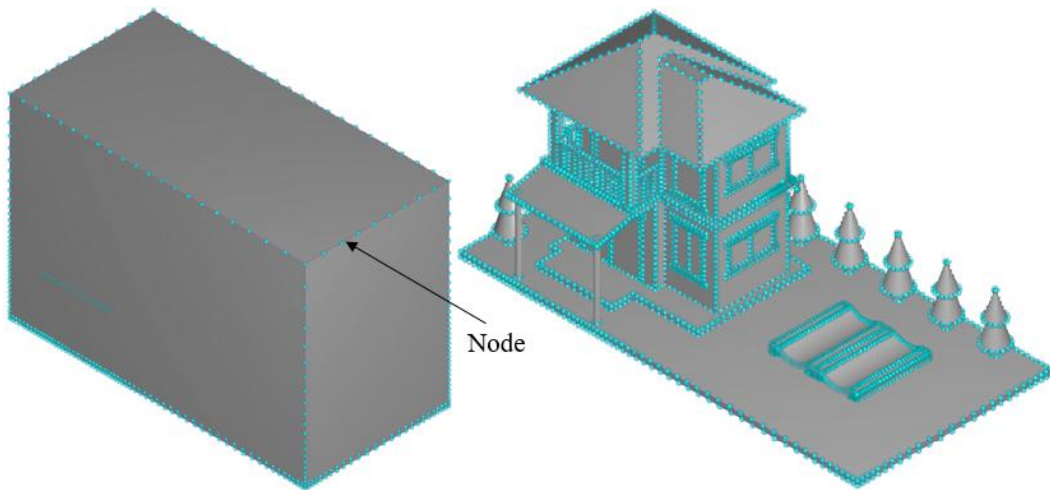
After assigning the material properties to the analysis model, the next step is to define the boundary conditions for the analysis within the air domain. The ambient temperature around the air domain is set to 35°C, and the soil layer temperature is set to 25°C, as shown in Fig. 3(a). Subsequently, mesh elements for the analysis model are generated with the following variable settings: a global resolution of 1, local stretching of 1.1, a minimum point/edge of 2, a point on the longest edge of 10, and a surface limiting aspect ratio of 20. This results in a total of 1,520,000 mesh elements, as shown in Fig. 3(b). Additionally, the pre-calculation properties are defined using the geographical data of Phitsanulok Province, Thailand, located at a latitude of 16°31'23" N and a longitude of 99°52'27" E [28]. The calculation process then proceeds to the next steps. This research establishes a set of analytical boundary conditions designed to reflect the temporal fluctuations in solar irradiance. We formulated a time-dependent curve using a hybridized methodological framework to accurately characterize the irradiance-time relationship. This framework integrates the ramp-step function—which synthesizes a linear ramp component with a constant step to capture both continuous and discrete transitions in irradiance intensity—with the exponential form of periodic boundary conditions, thereby enabling a more robust modeling of cyclic and temporally variant solar patterns.

3.3 Heat transfer analysis modeling process

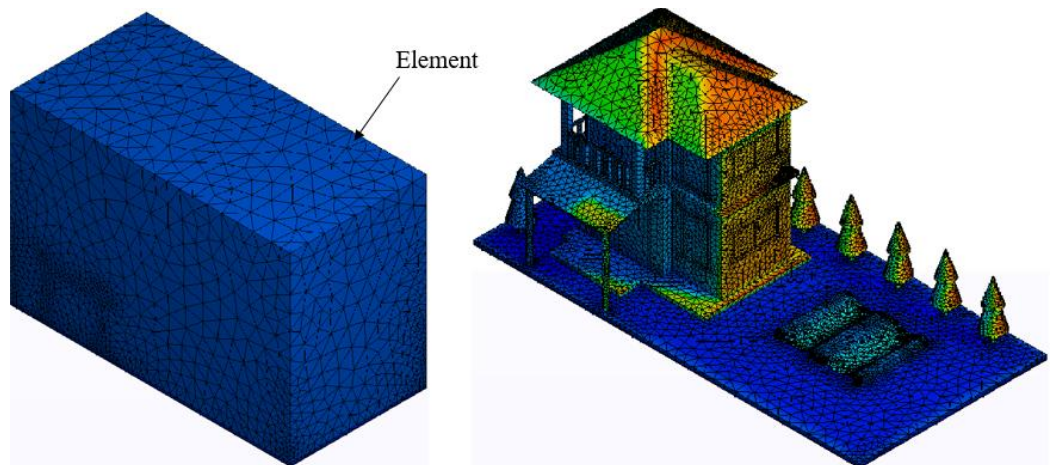
The heat transfer analysis from the parabolic solar collector to the water flowing inside the pipe in this case study is conducted as an internal flow analysis, a critical step in the final stage of the research. The heat impact assessment, based on previous calculations of the parabolic solar collector, is used to simulate and examine the temperature of the water at flow rates of 0.25, 0.50, 0.75, and 1 liter per minute. The study begins by creating an analysis model consisting of two main components: (1) the newly designed parabolic solar collector panel and (2) the water pipe flowing along its curve, as shown in Fig. 4. A 2-inch water pipe was selected for this design, which is mounted on the structurally enhanced parabolic solar collector panel. The pipe is halved and installed along the collector's curved section. Design results, shown in Fig. 4, demonstrate that the 2-meter-wide, 1.5-meter-long parabolic solar collector panel is suitable for installing the 2-inch water pipe. A total length of 11 meters, the pipe facilitates efficient heat transfer from the collector to the fluid within. Consequently, the total surface area of the parabolic solar collector employed in this study is 3 square meters.



(a)

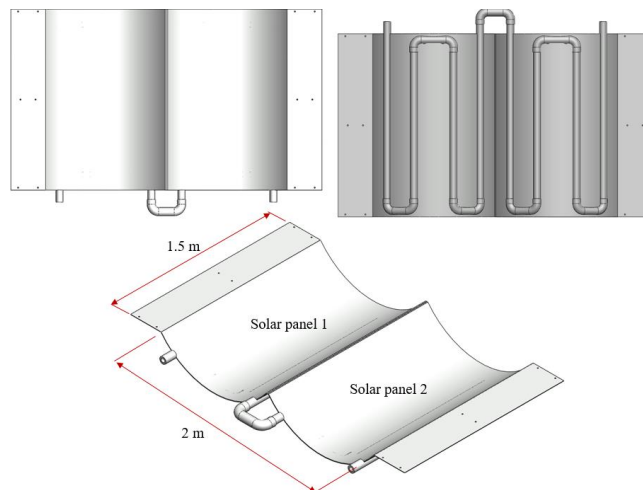


(b)



(c)

**Fig. 3.** Conceptual framework for analyzing the thermal impact of solar radiation: (a) Specification of temperature boundary conditions across atmospheric and subsurface domains, (b) nodal configuration within the finite element model, and (c) visualization of the generated mesh structure employed for computational analysis.



**Fig. 4.** Model of the parabolic solar collector and 2-inch water pipe for analysing the heat transfer rate from the parabolic solar collector to the flowing water within the pipe.

### 3.4 Procedure for setting initial conditions for analysis

After constructing the analysis model based on the specified conditions, the next step is to establish the project for the analysis. In this study, SOLIDWORKS Flow Simulation software will be employed to simulate the problem. For the purpose of this study, SolidWorks Flow Simulation was utilized to simulate the flow field due to its capability to accurately model the behavior of water flow and heat transfer within piping systems under specified thermal conditions. Moreover, it offers seamless integration with CAD geometries developed in SOLIDWORKS, facilitating a more efficient simulation workflow. Thermal boundary conditions for the analysis were obtained from Autodesk CFD results, focusing on temperature data collected from specified points on the surface of the parabolic solar collector. The extracted values were converted into .TXT files to facilitate subsequent analysis and simulation within SOLIDWORKS Flow Simulation. The initial task in setting up the analysis project was to configure the analysis units to the International System of Units (SI). The analysis encompasses both fluid flow and heat transfer, with Earth's gravitational force set to  $-9.81 \text{ m/s}^2$  (negative to indicate the downward direction along the y-axis). For the time-dependent analysis, the simulation duration was set to 1 hour (3,600 seconds). The material properties used in the analysis are outlined in Table 2. Finally, initial conditions were defined prior to computation, including setting the environmental temperature to  $35^\circ\text{C}$  and the initial temperature of the solid materials to  $30^\circ\text{C}$ .

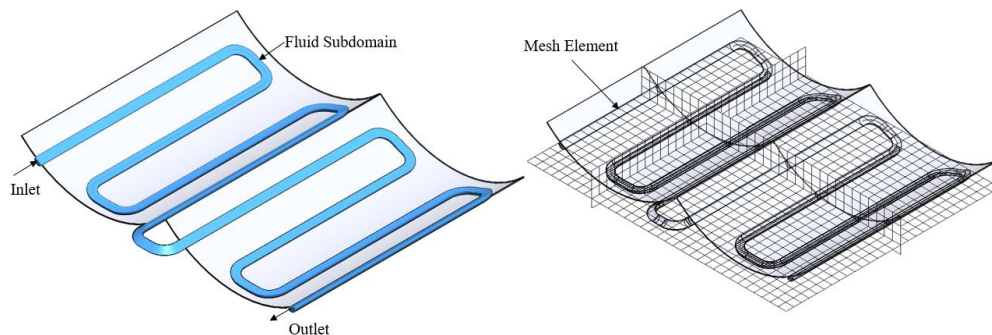
**Table 2:** Material properties for temperature and flow effect analysis modelling [29].

| Materials                   | Properties                              |                                            |                                                                 |                                                        |                                            |                        |
|-----------------------------|-----------------------------------------|--------------------------------------------|-----------------------------------------------------------------|--------------------------------------------------------|--------------------------------------------|------------------------|
|                             | Density<br>( $\text{kg} / \text{m}^3$ ) | Dynamics<br>Viscosity<br>( $\text{Pa.s}$ ) | Thermal<br>Conductivity<br>( $\text{W} / \text{m} - \text{K}$ ) | Specific Heat<br>( $\text{J} / \text{kg} - \text{K}$ ) | Resistivity<br>( $\text{Ohm} * \text{m}$ ) | Emissivity<br>( $NA$ ) |
| Water at $25^\circ\text{C}$ | 997                                     | 0.0008899                                  | 0.60717                                                         | 4,181.6                                                | -                                          | 1                      |
| Zinc at $30^\circ\text{C}$  | 7,140                                   | -                                          | 116                                                             | 389                                                    | 5.961e-08                                  | 0.50                   |

### 3.5 Boundary condition setting procedure

This study begins by defining the conditions and boundaries for the analysis. First, the fluid subdomain is specified to define the properties of water, as shown in Table 2. The water flows through the pipe, as illustrated in Fig. 5(a). Next, the material for the parabolic solar collector and water pipe is set as zinc, with properties listed in Table 2. The boundary conditions are then defined. The flow rate at the pipe inlet is set to 0.25, 0.50, 0.75, and 1 l/min, in the present study, the investigation of flow rate was extended beyond the scope of the prior work conducted by Sutthiphong Kaewpanya and Sulakshana Mongkhon, who examined the thermal performance of a solar heating system under a constant water flow rate of 1.5 liters per minute [1]. The outlet boundary condition is specified at environmental pressure. Numerical simulations with Autodesk CFD showed that solar irradiance on the parabolic

solar collector panels changed over time. To study the effect of different water flow rates, additional simulations were run using SolidWorks Flow Simulation. In these simulations, an average solar irradiance of  $902 \text{ W/m}^2$  was used as the boundary condition. To facilitate the numerical analysis of water flow within the collector, a structured mesh is generated with the following grid parameters:  $N_x = 32$ ,  $N_y = 4$ , and  $N_z = 28$ . The number of computational cells across the channel is characterized as 5, with a refinement level of 2 applied to small solid features. This meshing strategy results in approximately 130,000 elements, as illustrated in Fig. 5(b).



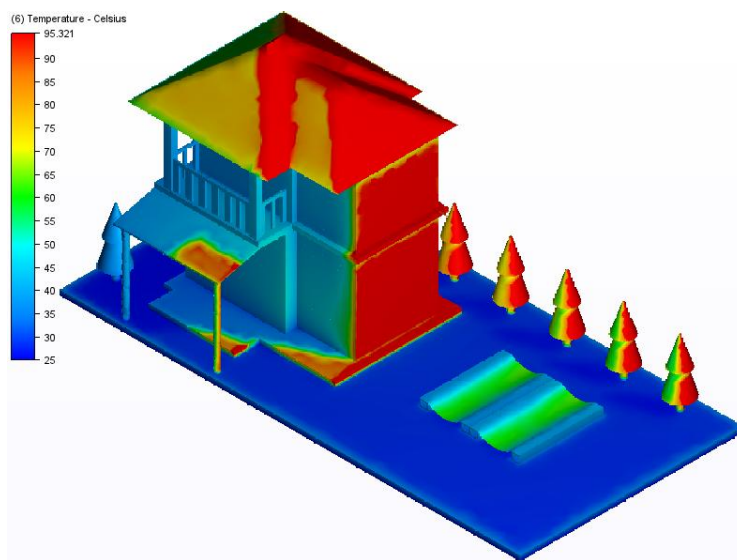
**Fig. 5.** Model of the parabolic solar collector and pipe with defined analysis conditions: (a) Define of the fluid subdomain, and (b) Define of mesh elements for the analysis.

#### 4. Results and discussion

The results obtained from the simulation analyzing the impact of solar heat and heat transfer from the parabolic solar collector to the water in this research are presented in detail as follows:

##### 4.1 Results of the analysis of the impact of solar energy heat

Figure 6 presents the results from the numerical simulation using AUTODESK CFD 2024 software (academic version). The simulation was used to study the effects of the heat source position at the geographic coordinates of  $16^{\circ}31'23'' \text{ N}$  latitude and  $99^{\circ}52'27'' \text{ E}$  longitude, which is in Phitsanulok Province, Thailand. The results show that the temperature from the solar radiation on the parabolic solar collector panel ranges from  $65^{\circ}\text{C}$  to  $70^{\circ}\text{C}$ . This indicates that the parabolic solar collector panel, with a focal point of 250 millimeters (as shown in Figure 1(a)), efficiently absorbs solar radiation.



**Fig. 6.** Computational fluid dynamics simulation results for the solar thermal impact analysis case.

## 4.2 Heat transfer analysis results

Previous studies examined the impact of sunlight on a parabolic solar collector panel. The results showed that the panel's focal point, set at 250 millimeters, can effectively produce heat. In this study, a 2-inch water pipe was cut in half and mounted along the curved shape of the parabolic panel, as shown in Fig. 4, to study the water flow inside. The study tested four different water flow rates: 0.25, 0.5, 0.75, and 1 liter per minute. The goal was to determine the optimal flow rate for the parabolic collector based on the 250-millimeter focal point. Figure 7 illustrates the outcomes of a transient heat transfer analysis performed using the Time-Dependent module in SOLIDWORKS Flow Simulation, demonstrating the influence of different water flow rates on the heat absorption capacity and thermal efficiency of the parabolic solar collector panels.

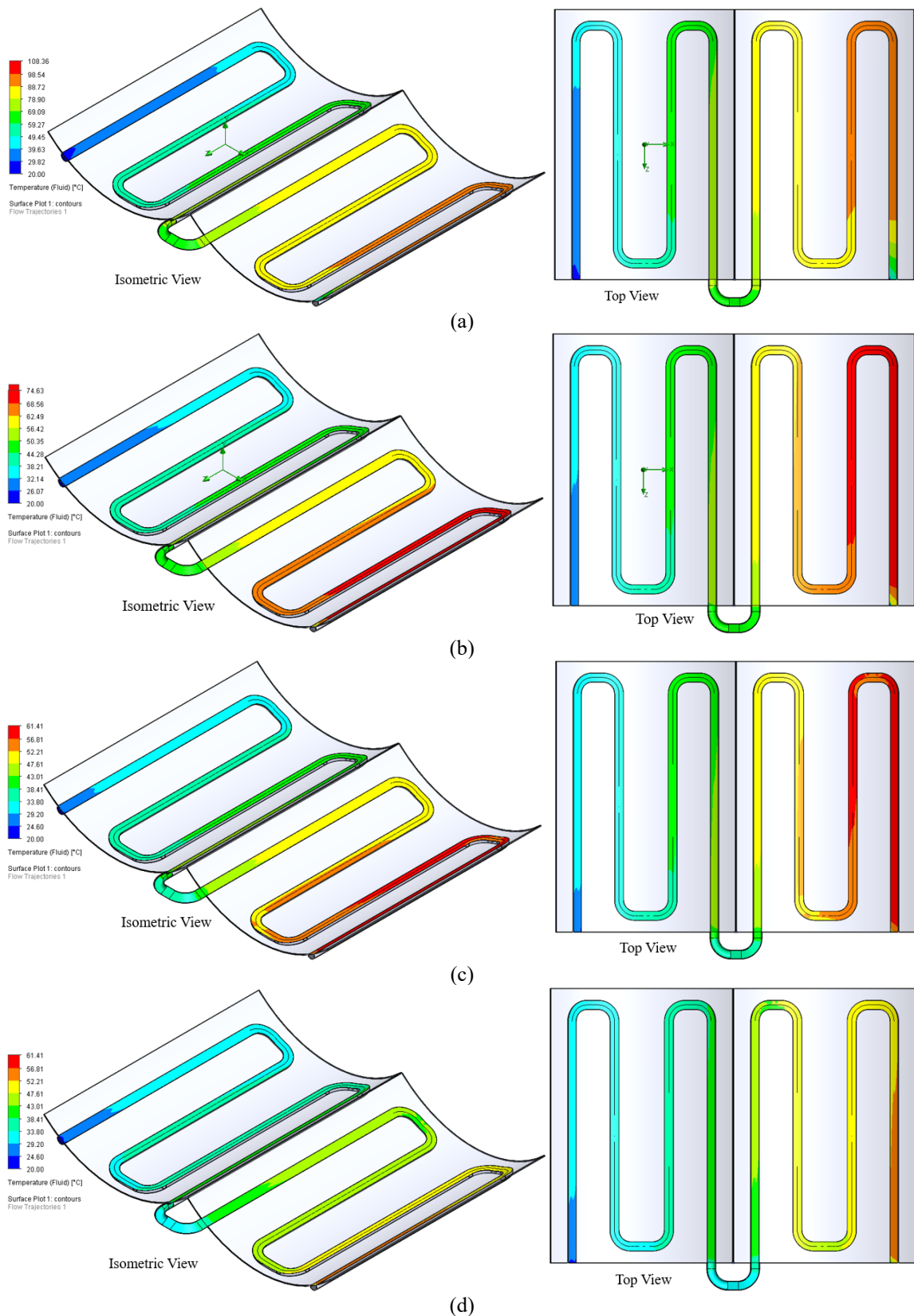
Fig. 7(a), shows the results of the study show that the average temperature at the water inlet is 25.48°C. As the fluid moves through the central region of the parabolic solar collector panel, the average temperature increases to 73.58°C. When the fluid passes through the second solar collector panel, the average temperature rises to 83.24°C, and by the time it reaches the outlet pipe, the maximum temperature reaches 98.64°C. However, the temperature at the outlet end decreases to 63.42°C, which is a result of heat loss to the surroundings through convection and radiation processes.

Fig. 7(b), depicts the results of the study indicate that the water entering the system has an average temperature of 38.12°C. As it flows through the central region of the solar radiation collector panel, the temperature increases to 47.32°C and rises further to 65.47°C when passing through the second solar radiation panel. Subsequently, the maximum temperature at the outlet pipe is 74.63°C, and finally, the average temperature at the system outlet decreases to 62.47°C.

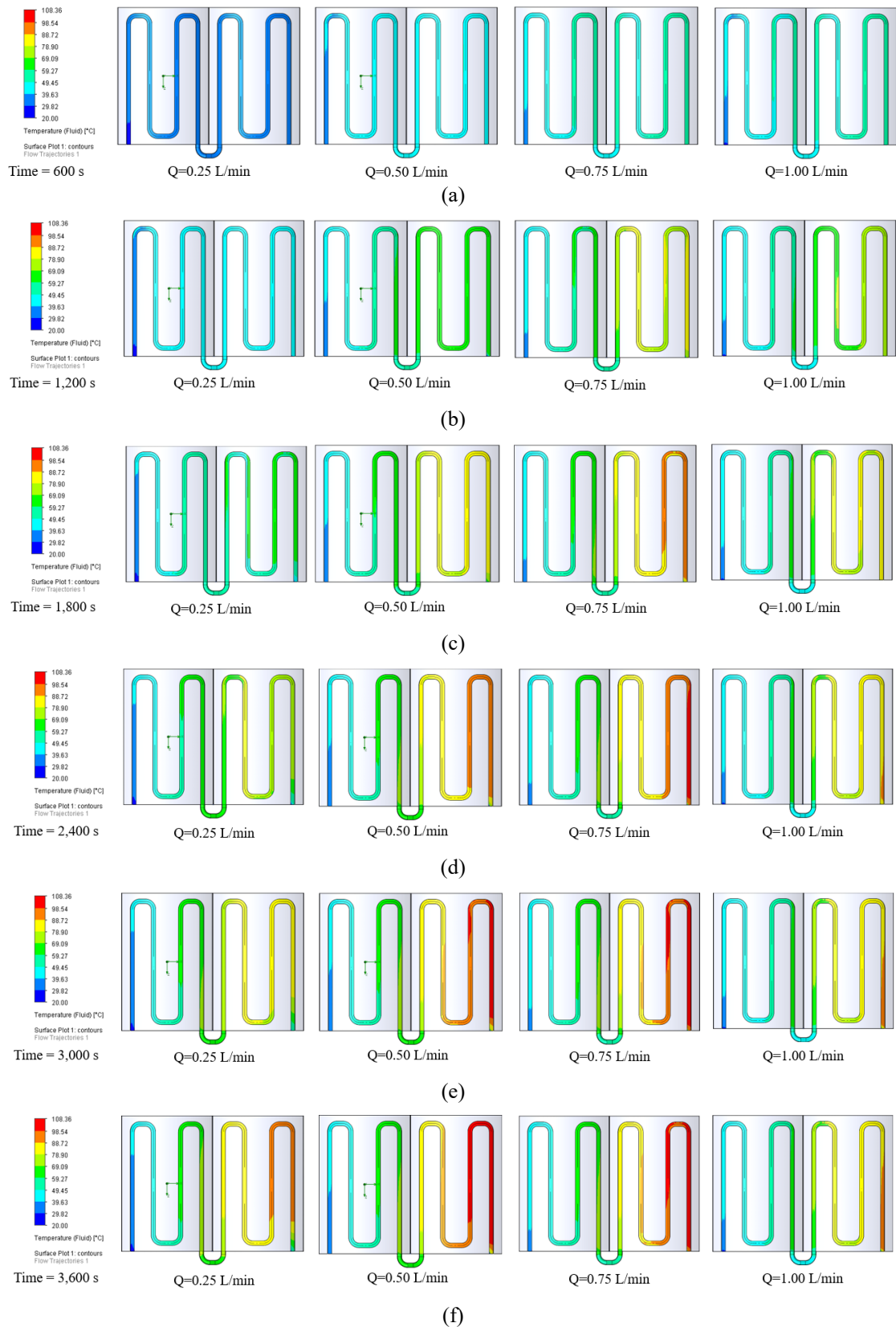
Fig. 7(c) visually shows that the water entering the system has an average temperature of 33.50°C. As the fluid flows through the central region of the parabolic solar collector panel, the temperature increases to 42.53°C and rises further to 52.27°C when passing through the second parabolic solar panel. The maximum temperature at the outlet pipe is 54.63°C, and finally, the average temperature at the outlet decreases to 52.21°C.

Fig. 7(d) illustrates the temperature variation along the flow path. The average temperature at the water inlet is 32.75°C. As the fluid moves through the central region of the solar radiation collector panel, the temperature rises to 40.71°C, further increasing to 47.64°C as it passes through the second solar radiation panel. The maximum temperature at the outlet pipe reaches 54.87°C, and ultimately, the average temperature at the system outlet decreases to 45.87°C.

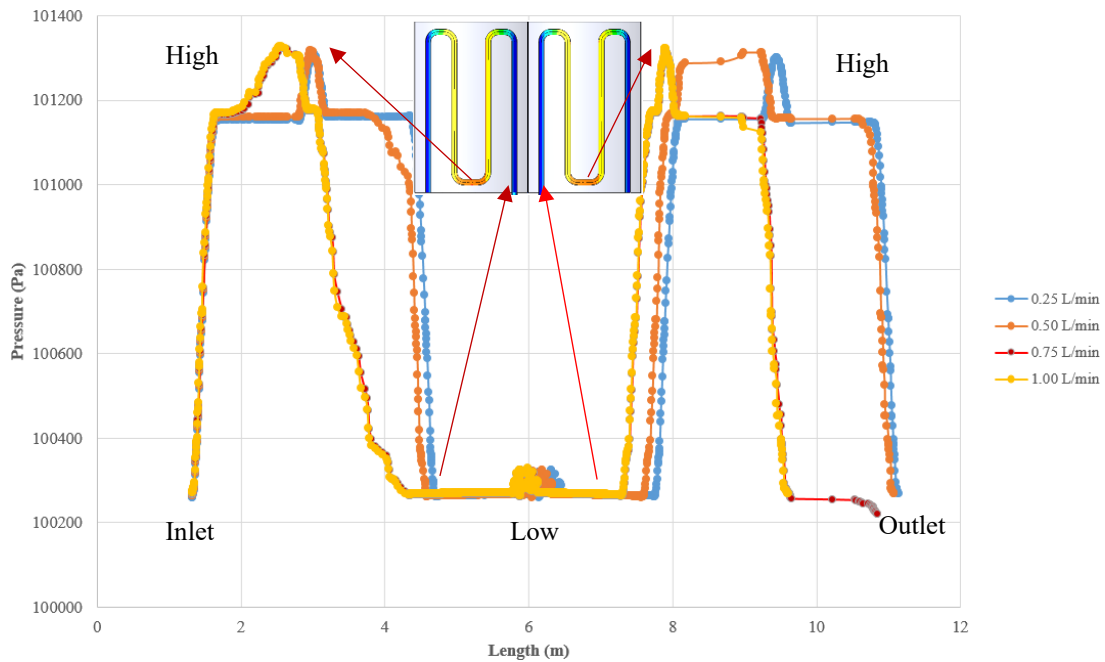
Fig. 8 presents the results of the numerical simulation comparing the temperature distribution of moving water at different flow rates on the parabolic solar radiation collector panel. The relationship between pressure and distance for water flow rates of 0.25, 0.50, 0.75, and 1.00 L/min shows that pressure increases as the flow rate rises. This is due to the higher friction and resistance in the piping system. The highest pressure occurs at the flow rate of 1.00 L/min, while the lowest pressure is at 0.25 L/min. The optimal flow rate for the system is between 0.50 and 0.75 L/min. This range balances heat transfer efficiency and energy consumption, as shown in Fig. 9(a). The pressure distribution for different water flow rates in this research. At the inlet section of the pipe, the pressure gradually increases, reaching its peak at a pipe length of approximately 2.5 m. This peak occurs in the central region of the first parabolic solar collector panel. After this point, the pressure decreases as the water flows toward the lateral sections of the collector panel. A similar pattern occurs in the second parabolic solar collector panel, where the pressure rises again in the central region before gradually decreasing toward the lateral sections. Eventually, the water reaches the system's outlet. These pressure variations highlight the impact of the internal pipe structure on the system's pressure distribution.



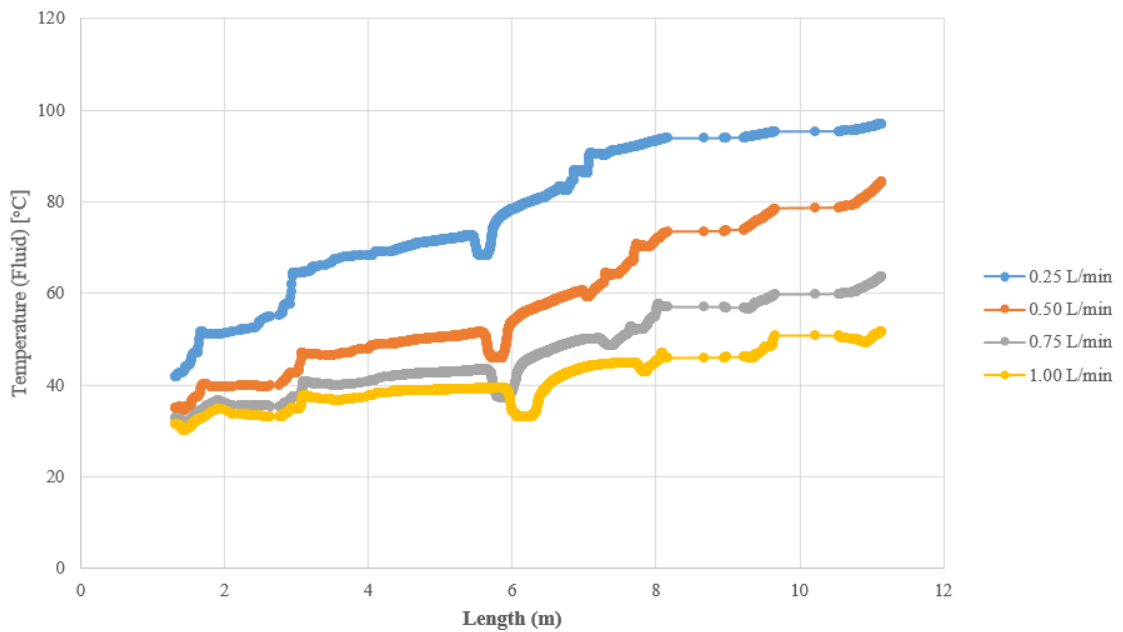
**Fig. 7.** Shows the results of the analysis on the effect of different flow rates on the heat transfer efficiency of a parabolic solar collector panel: (a) 0.25 l/min, (b) 0.50 l/min, (c) 0.75 l/min, and (d) 1.00 l/min.



**Fig. 8.** Results of the comparison of temperature distribution on water at different flow rates at different times.



(a)



(b)

**Fig. 9.** Graphically depicts the numerical results obtained from the analysis at different flow rates: (a) pressure inside the pipe system and (b) heating temperature in the water.

Figs. 7 and 8 illustrate the thermal behavior of the system under conditions in which both parabolic solar collector panels receive an equal amount of incident solar radiation, ensuring a uniform thermal input across the collector surfaces. In the CFD simulation conducted for this study, the inlet water temperature was initialized at 25 °C to represent typical ambient conditions. The two collector panels are connected in series, forming a continuous flow path that enables stepwise thermal energy absorption as the fluid progresses through the system. As the water enters

the first (primary) collector, it absorbs thermal energy from the irradiated surface, resulting in a measurable increase in fluid temperature. This thermally preheated fluid then flows into the second collector, which is designed with a longer flow path to maximize residence time and heat exchange potential. Due to this extended exposure to concentrated solar energy, the fluid continues to absorb heat, leading to a further rise in temperature. The outlet temperature of the fluid exiting the second collector is therefore significantly higher than that exiting the first collector. This staged heating process enhances the overall thermal efficiency of the system by effectively utilizing the available solar energy across both collectors. The flow rate velocity in this study was found to significantly affect the temperature of the water within the pipe. For instance, at the lowest flow rate of 0.25 L/min, the fluid temperature increased the most, as the water had more time in contact with the pipe wall, resulting in greater heat exchange. Conversely, when the flow rate increased to 1.00 L/min, the water temperature increased to a lesser extent due to the faster movement of the water through the pipe, which reduced the time available for heat absorption, as shown in Fig. 9(b).

**Table 3:** Thermal efficiency in this research.

| Q (l/min) | $\dot{m}$ (kg/s) | Absorbed energy (W) | Receiving Energy (W) | Thermal efficiency (%) |
|-----------|------------------|---------------------|----------------------|------------------------|
| 0.25      | 0.00417          | 2,706               | 859.53               | 31.76                  |
| 0.50      | 0.00833          | 2,706               | 975.63               | 36.03                  |
| 0.75      | 0.01250          | 2,706               | 1124.94              | 41.57                  |
| 1.00      | 0.01667          | 2,706               | 914.20               | 33.78                  |

Upon reviewing the results of the study, it was determined that the optimal flow rate falls within the range of 0.50 to 0.75 L/min, with an average value of 0.625 L/min. This flow rate was then applied in the numerical simulation of fluid dynamics for a duration of 3600 seconds (1 hour). The simulation results indicated that the outlet temperature was equal to 67°C. The thermal efficiency of the system was subsequently calculated using the inlet and outlet temperatures, based on Equation (3), and considering volume flow rates of 0.5 and 0.75 L/min. The results indicate that the designed parabolic heat collector can achieve maximum thermal efficiencies of 36.03% and 41.57%, respectively, as presented in Table 3. In this study, the thermal efficiency of the parabolic solar collector panel, determined through computational fluid dynamics (CFD) simulation, was found to be highly consistent with the results reported by Sookramoon et al. [26], who assessed the thermal performance of a prototype parabolic trough solar collector using CFD analysis and reported a maximum efficiency of 68.77%. Similarly, Maurya et al. [30] conducted an analysis of a prototype solar collector and reported that its thermal efficiency in terms of solar radiation absorption ranged between 80% and 90%, further validating the performance of parabolic solar collectors in various configurations. Additionally, Marif et al. [31] investigated the performance of a solar parabolic trough collector, with their findings indicating a thermal efficiency range of 69.73% to 72.24%, reinforcing the potential efficiency of parabolic trough collectors under diverse operational conditions.

## 5. Conclusion

The experimental results on temperature distribution demonstrated that the water temperature increases with the distance traveled through the parabolic solar collector panel. This temperature rise occurs as the water absorbs heat from the solar collector panel and transfers this energy through the pipe. At the lowest flow rate (0.25 L/min), the water has more time in contact with the collector's surface, resulting in greater heat absorption compared to higher flow rates. Conversely, at higher flow rates (1 L/min), the reduced contact time limits heat absorption, leading to a smaller temperature increase. The temperature decrease at the outlet is attributed to heat losses through conduction and radiation to the surrounding environment. Pressure analysis revealed that as the water flow rate increases, the pressure within the system also rises. This increase is due to the heightened frictional forces and resistance within the piping system. At higher flow rates, the increased water velocity generates more resistance, resulting in a rise in internal pressure. The results indicate that the optimal flow rate for this system lies between 0.5 and 0.75 L/min, striking the best balance between heat transfer efficiency and energy consumption. The findings of this study indicate that the system attains optimal thermal efficiencies of 36.03% and 41.57% at flow ratios of 0.50 and 0.75, respectively, under defined operating conditions, facilitating efficient heat transfer while reducing energy consumption. These insights emphasize the critical role of flow rate optimization in the design of solar thermal systems intended for hot water generation, with implications for enhancing both energy efficiency and system feasibility.

## Nomenclature

|                  |                                                                                            |
|------------------|--------------------------------------------------------------------------------------------|
| $x$              | the x-axis of a parabola, mm                                                               |
| $y$              | the y-axis of a parabola, mm                                                               |
| $f$              | the desired design focus point, mm                                                         |
| $w$              | the width of the parabolic solar collector panel support collector, mm                     |
| $Q_u$            | the heat value received from parabolic solar collectors, J                                 |
| $A_c$            | sunlight receiving area of parabolic solar collector, m <sup>2</sup>                       |
| $I$              | solar radiation intensity, W/m <sup>2</sup>                                                |
| $\dot{m}$        | represents the mass flow rate of water passing through the parabolic solar collector, kg/s |
| $C_p$            | specific heat of water, J/kg.°C                                                            |
| $T_{in}$         | temperature of water flowing into the parabolic solar collector, °C                        |
| $T_{Out}$        | temperature of water flowing out of parabolic solar collector, °C                          |
| $n$              | the number of days considered                                                              |
| $\delta$         | the angle of the equatorial plane                                                          |
| $\omega_{Angle}$ | the angle of the Earth's rotation along the meridian of the plane beneath the Sun.         |
| $st$             | the local standard time is considered relative to the noontime in the test area            |
| $Long_{st}$      | the longitude lines used to draw through standard time periods                             |
| $Long_{Loc}$     | the longitude line used to draw through the local time period being tested                 |
| $\rho$           | the fluid density, kg/m <sup>3</sup>                                                       |
| $P$              | the fluid pressure, Pa                                                                     |
| $\mu$            | the viscosity of a fluid                                                                   |
| $c$              | the specific heat capacity of fluid, J/kg.K                                                |
| $T$              | the temperature values at different positions of the fluid under consideration, °C         |
| $Q$              | the water flow rate per unit volume, m <sup>3</sup> /s                                     |

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