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Thermal Performance Analysis of U-pipe Evacuated Tube Solar Heater System with and without PCM

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ABSTRACT

The study presents a comprehensive thermal performance analysis of a U-pipe Evacuated Tube Solar Collector (U-ETSC) system, integrated with Phase Change Material (PCM), for satisfying water demand in domestic applications. The innovative approach of incorporating PCM aims to enhance the system's efficiency during night or off-sunny hours, addressing a common limitation in solar heater systems. The research primarily focuses on the impact of varying mass flow rates of the heat transfer fluid (HTF) on the thermal dynamics of the system. The numerical results reveal that as the mass flow rates of HTF increase from 0.5 to 1 and then to 1.5 liters per minute, there is a notable change in the phase transition times of the PCM. Specifically, the melting time of the PCM is increased by 13% and 16% for the respective flow rates, suggesting a delayed response in energy absorption. In addition, the solidification time of the PCM is recorded by 16% and 18% respectively, indicating a faster release of stored thermal energy. This behavior underscores the PCM's significant role in stabilizing the system's thermal output during varying solar intensities. The findings of this study highlight the potential of integrating PCM in U-ETSC systems to achieve a more consistent and reliable supply of hot water for domestic purposes, especially during periods when solar irradiance is low or absent.

1. Introduction

The exploration and advancement of renewable energy sources have become increasingly imperative in the wake of escalating environmental concerns and the finite nature of fossil fuels. Solar energy, as one of the most abundant and cleanest forms of renewable energy, has attracted significant attention globally. Within this domain, solar water heating systems have emerged as a practical and efficient method for harnessing solar energy for domestic and industrial applications [1]. Among various solar heating technologies, the U-ETSC has gained prominence due to its superior thermal performance and lower heat loss compared to flat plate collectors. The U-ETSC design, featuring a series of evacuated tubes with a U-shaped pipe inside, allows for efficient absorption of solar radiation and minimal thermal loss, making it an attractive option for regions with varying climatic conditions.

Despite their efficiency, U-ETSC systems face challenges in maintaining consistent thermal performance during periods of low solar irradiance, such as during nighttime or overcast days. This inconsistency poses a significant limitation, particularly for domestic applications

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where the demand for hot water is continuous. To address this challenge, the integration of PCM has been proposed as a promising solution. PCMs are substances that absorb or release a significant amount of latent heat during their phase transitions, typically from solid to liquid and vice versa. By incorporating PCM into U-ETSC systems, it is possible to store excess heat during peak sunlight hours and release it during periods of low or no solar irradiance. This approach not only promises to stabilize the solar water heater's output but also enhances the overall efficiency of the system by making solar energy available beyond daylight hours.

O'Neil and Sobhansarbandi [2] conducted an experimental study comparing the thermal performance of a custom-made U- ETSC and a commercially available heat pipe. The research focused on the efficiency of these systems with and without thermal storage media over several days. The results showed that the U-ETSC outperformed in achieving higher peak water temperatures, reaching up to 31 °C more, which resulted in a 13% efficiency enhancement. With thermal storage materials, the U-ETSC showed peak temperatures of 47 °C and 38.7 °C for the fin and water tank, respectively. In contrast, the U-ETSC exhibited maximum temperatures of 60 °C and 36.7 °C. Further enhancement of the U-ETSC system was achieved by PCM with added 1wt% multi-walled carbon nanotubes nanoparticles, leading to peak temperatures of 63.9 °C and 43.3 °C. This incorporation allowed for a slower release of heat, extending the duration of latent heat storage.

Alshukri et al. [3] explored a novel method of integrating PCMs in heat pipe evacuated tube solar water heater collector (HP/ETC). Their experimental approach involved filling one or both the evacuated tube and two separate tanks adjacent to the water tank with PCM, specifically medical paraffin wax for the evacuated tube and grade-A paraffin wax for the tanks. This configuration effectively stored heat for extended periods due to the thermal isolation of the evacuated tube and PCM storage tanks. They conducted comparative studies using four HP-ETC with gravity assist heat pipes, varying the integration of PCM in the evacuated tube and separate tanks. The study revealed that incorporating PCM in both the evacuated tube and the tanks improved efficiency by 55.7%, while adding PCM only in the ET or the separate tanks resulted in efficiency gains of 49.9% and 36.5%, respectively, compared to a PCM-free reference collector. This method notably enhances solar water heater performance by delaying heat release, ensuring prolonged hot water availability during high demand or low solar intensity periods.

Chopra, et al. [4] conducted an experimental assessment of the thermal performance of a heat pipe evacuated tube solar collector system integrated with PCM. The study compared two systems under identical weather conditions: one with evacuated tubes without PCM (collector-A) and the other integrated with SA-67 PCM (collector-B). SA-67 demonstrated remarkable chemical and thermal stability, even after 1500 thermal cycles. The experiment, conducted at five different water flow rates (8, 12, 16, 20, and 24 liters per hour), revealed that the daily thermal efficiency of the system with PCM varied between 42–55%, while that of the system without PCM ranged from 79–87%. Notably, the energy efficiency of the collector integrated with PCM was 37.56% to 35.31% higher than the non-PCM collector across the tested flow rates. The highest thermal efficiency for both systems was observed at the flow rate of 20 liters per hour.

Essa et al. [5] compared two types of collectors: a control system with conventional fins and another with helical fins. Experiments were conducted at various flow rates (0.165, 0.335, 0.5, and 0.665 L/min) using tap water as the HTF. Results indicated that the helical fins provided better temperature uniformity within the paraffin wax along the tube axis compared to conventional fins. For instance, at the same flow rate, the maximum temperature difference was 4 °C for the helical fins system and 12.25°C for the conventional system. Additionally, the daily efficiency of the helical finned system was found to be 15% and 13.6% higher than the conventional system at flow rates of 0.5 and 0.665 L/min, respectively. Furthermore, the phase change from solid to liquid in the helical finned system commenced 30-60 minutes later than in the conventional system, demonstrating its enhanced thermal performance.

Li, et al. [6] focused on the optimization and thermal performance of U-ETSC filled with PCM. They developed a numerical model to evaluate the performance of a U-ETSC with fins and experimentally validated their findings. The study aimed to overcome the intermittent nature of solar radiation in U-ETSC by using PCM to store excess thermal energy during sunny periods and release it when sunlight is unavailable. Their optimization included variables such as the melting point of the PCM, the flow rate, and the diameter of the inner glass tube. The integration of PCM inside the U-ETSC with fins resulted in extended hot water supply duration and reduced peak outlet temperature of hot water flow. Notably, with a PCM melting temperature of 323 K, they achieved a 7.4 K reduction in flow outlet temperature, with thermal efficiency and thermal storage efficiency of 50.72% and 19.20%, respectively.

Algarni et al. [7] conducted an experimental study on enhancing the performance of evacuated U-ETSC using nano-enhanced phase change materials (Ne-PCM). The innovative approach involved integrating the ETSC U-pipe with Ne-PCM into a single unit U-ETSC /Ne-PCM to act as a thermal booster. This integration aimed to extend hot water production and stabilize water temperature by storing heat in the PCM, especially when solar intensity is low or absent. The study found that adding 0.33 wt% of copper/PCM composite to the U-ETSC significantly increased its efficiency by 32%. The U-ETSC /Ne-PCM system was able to provide hot water at up to 50 °C for approximately 2 hours longer than typical ETC systems at a specific mass flow rate of 0.08 L/min. The research also explored how various factors, including weather conditions, HTF flow, the number of U-ETSC tubes, and nanoparticle concentration, affected the performance of the U-ETSC /Ne-PCM system.

Pathak et al. [8] presented a comprehensive review of recent advancements in solar water heating (SWH) systems, focusing on improving thermal performance and energy efficiency. The study highlights the growing importance of solar energy as a cost-effective and environmentally friendly alternative, while addressing challenges associated with its intermittent nature, particularly in water heating applications. The authors classify SWH systems into active and passive types and emphasize that limited solar availability and low heat transfer rates often reduce system efficiency. The review systematically examines various performance enhancement techniques, including modifications to absorber plate geometry, application of selective coatings, optimization of collector tilt angle, adjustment of fluid flow rates, and integration of phase change materials (PCMs) for thermal energy storage. The study concludes that enhancing heat transfer mechanisms and incorporating energy storage solutions are key factors in advancing SWH system performance and supporting sustainable energy development.

Chopra et al. [9] explore the thermal performance of a novel solar collector system integrated with stearic acid as PCM. This system captures solar radiation using evacuated tubes equipped with heat pipes, storing the energy in a manifold integrated with PCM. The stored thermal energy is then transferred to water flowing through a bundle of finned copper pipes inside the manifold. The study includes a detailed examination of the system's design, operating principles, and an experimental evaluation under different mass flow rates. The system's performance was assessed in two charging modes: mid-day and full-day. Results showed that the thermal efficiency varied between approximately 52–62% in full-day mode and 55–72% in mid-day mode, with a maximum efficiency of about 72.52% at a flow rate of 24 LPH in the mid-day charging mode. The efficiency of the PCM remained around 61–64% for both modes.

Olfian, et al. [10] investigated the thermal performance of a U-type evacuated tube solar collector integrated with PCM. The study focused on using PCM to store excess solar energy during the day and release it at night when solar irradiation is absent. Both the charging and discharging processes were modeled, with emphasis on maintaining a stable outlet temperature of around 40°C for domestic use and ensuring complete melting/solidification for maximum energy storage and release. The research particularly examined the impact of the U-type tube diameter on energy absorption and release, testing diameters of 6-, 8-, and 10-mm. Findings showed that the 6 mm diameter tube was the most efficient, yielding a 25% improvement in liquid fraction and a 13.5% increase in fluid outlet temperature at 3:00 PM during charging. Additionally, this diameter delayed the thermal energy release by 20% and increased the fluid outlet temperature by 24% at 9:00 PM during discharging, compared to the other diameters. This study highlights the significance of tube diameter in enhancing the performance of solar collectors with integrated PCM.

Uniyal and Prajapati et al. [11] examined the evolving energy landscape in the context of rapid modernization, increasing population, and rising living standards. The study highlighted that these factors have significantly boosted global energy demands. The paper underscores that energy consumption is a key indicator of a nation's development, yet the predominant reliance on fossil fuels, which account for approximately 80% of total energy needs, poses serious environmental concerns. The extraction and use of fossil fuels contribute to environmental pollution, climate change, global warming, and various other detrimental effects, raising alarms about sustainability. This context sets the stage for their exploration of alternative energy solutions, particularly focusing on the thermal performance of a Copper U-ETSC as a sustainable and environmentally friendly option.

Kumar et al. [12] focused on the advances in ETSC using nanofluids and PCM. Their analysis highlights the widespread application of solar thermal energy in various sectors, including industrial and domestic uses like solar drying, space heating, water heating, and water desalination. The ETSC, known for its minimal convective losses, stands out as a widely used solar thermal collector. The review discusses different types, including heat pipe, thermosiphon, and U-Tube collectors, and various geometrical modifications like reflectors and fins integrated into heat pipes for enhancing thermal performance. However, the most significant improvements were observed when ETSC were combined with nanofluids and PCM. The review also summarizes different numerical models for assessing the energy and exergy performance, along with the economic and environmental impacts of ETSC.

Pawar and Sobhansarbandi [13] investigated the performance optimization of a heat pipe evacuated tube solar collector integrated with phase change materials (PCMs) under both normal and on-demand operating conditions to overcome the limitations caused by fluctuating solar radiation. The study was conducted in two phases. In Phase I, the influence of heat pipe position on the thermal behavior of the system was analyzed. The results showed that the phase change process of the PCM was accelerated by 48 minutes under on-demand operation compared to the conventional configuration, while in normal operation, thermal storage was enhanced with a 24% increase in the PCM melting fraction. In Phase II, the performance of different PCMs, including tritriacontane paraffin, xylitol, and erythritol, was evaluated. Under normal operation, the paraffin-based system achieved a total energy storage of 295.39 kJ/kg, whereas xylitol demonstrated higher fin temperatures by approximately 10 °C. In on-demand mode, erythritol exhibited the highest energy storage of 413.15 kJ/kg, while paraffin showed improved temperature distribution. The study recommends optimized PCM combinations to enhance overall system thermal efficiency.

Weaver et al. [14] studied the enhancement of thermal performance of phase change materials (PCMs) for solar water heating (SWH) applications, addressing limitations related to low thermal conductivity and high melting point. The study focused on paraffin-based PCMs with melting temperatures ranging from 28 to 72 °C, aiming to improve heat transfer and reduce melting onset temperature to accelerate latent heat storage. The research was conducted in two phases. In Phase I, silicone oil was introduced as a heat transfer medium to enhance natural convection within the PCM. This approach resulted in a melting point depression of approximately 3 °C, particularly for PCM72, improving the responsiveness of the material. In Phase II, conductive heat transfer enhancement was achieved by incorporating nanoparticles with different mass concentrations. The addition of 1% multi-walled carbon nanotubes (MWCNT) to PCM72 increased its thermal conductivity by about 3.81%. These findings demonstrate that combining convection enhancement and nanoparticle additives can significantly improve PCM performance.

The main objective of the study is to evaluate and compare the thermal efficiency of a U-ETSC system when it is operated with and without the integration of PCM. The focus is on understanding how the incorporation of PCM can enhance the system's ability to store and release thermal energy, particularly during periods when solar radiation is insufficient, such as at night or during cloudy weather. This study aims to assess whether the inclusion of PCM can lead to a more consistent and reliable hot water supply from solar heaters, thereby overcoming one of the key limitations of solar thermal systems which is their dependency on direct sunlight. The analysis includes examining factors like the impact of different mass flow rates of the HTF on the efficiency of the system, and the melting and solidification dynamics of the PCM, to provide a comprehensive understanding of the performance improvements offered by PCM integration in U-ETSC systems.

2. Methodology

The methodology involves a comparative numerical simulation of two U-ETSC systems, one integrated with PCM and the other without. Both systems are configured with a U-shaped copper tube through which the heat transfer HTF is circulated at a fixed inlet temperature, ensuring uniform conditions for performance assessment. The study focuses on analyzing the thermal behavior and efficiency of these systems under varying operational conditions, particularly examining the heat transfer dynamics and efficiency enhancement due to the PCM. The methodology is underpinned by specific assumptions about the PCM and HTF properties, including the temperature-dependent density of the PCM, constant volume of the PCM before and after melting, and constant thermo-physical properties of the HTF. This approach provides a comprehensive evaluation of the impact of PCM integration on the thermal performance of U-ETSC systems.

2.1 System's configuration

The using ANSYS Modeler, a computational simulation software. In this U-ETSC system is digitally modeled to accurately represent its physical and thermal characteristics. The U-ETSC, typically consisting of a series of evacuated tubes with a U-shaped copper tube inside each for the flow of the HTF, is recreated in the virtual environment of ANSYS. This software allows for detailed simulation and analysis of the heat transfer processes, including the interaction between the HTF, the solar collector tubes, and any integrated PCM. By using ANSYS Modeler, the study can conduct a thorough and precise evaluation of the thermal performance of the U-ETSC, including the effects of various design parameters and operating conditions.

Figure 1 illustrates the geometric configuration of the U-tube ETSC, and the specific region where the PCM is incorporated within the glass tube. This figure presents a detailed cross-sectional view of the ETSC, showing the U-shaped copper tube as the primary conduit for the HTF. The PCM is arranged around the U-tube to enhance thermal energy absorption and storage. These zones are essential for understanding how the PCM interacts with the solar collector system, particularly in terms of heat transfer and thermal storage capabilities. The geometric layout depicted in Figure 1 would be critical for visualizing the physical arrangement of components within the ETSC system, thereby providing a clear understanding of the experimental setup and the expected thermal dynamics in the study.

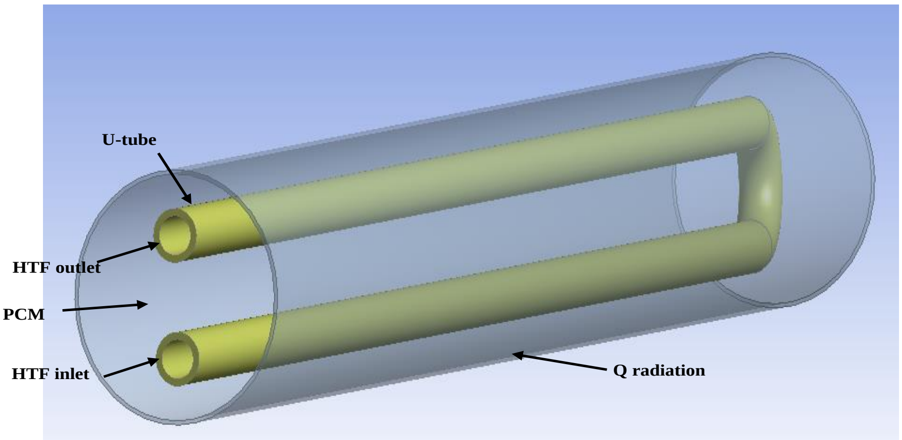

Figure 1. Geometry of U-tube- ETSC and PCMs zones

Table 1: Specification's U-tube- ETSC system

Parameters	Value in (mm)
Outer diameter of glass tube	58
Inner diameter of glass tube	48
U-tube inner diameter	6
Thickness of U-tube	2
Length collector	500
Length of U-tube	500

Table 2: Thermo-physical properties of PCM, HTF and U-tube

Properties	PCM	HTF	U-tube
Type	Paraffin wax (52-62 ^{O}C)	Water	Copper
Thermal conductivity [W/mK]	0.2		398
Dynamic viscosity of liquid paraffin wax [kg/m s]	0.004	0.001	-
Density [kg/m^3]	820	998	873
Specific heat [kJ/kg K]	2000		0.39
Thermal expansion coefficient of paraffin wax [1/K]	0.0006	-	-
Heat of fusion [kJ/kg]	168000	-	-

2.2 Governing equations

The model equations typically encompass the fundamental mathematical and physical principles that dictate the system thermal behaviour. This includes equations that describe heat transfer mechanisms, such as conduction, convection, and radiation, within the U-ETSC and its interaction with PCM, if present. These equations are formulated based on assumptions about the properties of the materials involved, such as the constant thermo-physical properties of the heat transfer fluid and the temperature-dependent density of the PCM. The governing equations also account for the phase transition dynamics of the PCM, ensuring accurate modeling of its melting and solidification processes. : (i) Density of the PCM is the function of temperature while remaining thermo-physical properties are constant (ii) PCM volume remains constant before and after the melting process (iii) Heat transfer fluid holds constant thermo-physical properties.

The governing equations i.e., mass (continuity) and momentum equations for the unsteady melting process of the PCM are written as follows [15]:

Continuity equation:

$$\nabla\vec{V} = 0 \quad (1)$$

where v denotes the velocity vector with components u,v and w in the r, θ and z directions, respectively.

Momentum equation [16]:

$$\frac{\partial\vec{V}}{\partial t} + \vec{V}\cdot\nabla\vec{V} = \frac{1}{\rho}\Big(-\nabla P + \mu\nabla^2\vec{V} + \rho\vec{g}\beta(T - T_{ref})\Big) + S_m \quad (2)$$

Energy equation:

$$\frac{\partial h}{\partial t} + \frac{\partial H}{\partial t} + \nabla\cdot(\vec{V}) = \nabla\cdot\left(\frac{k}{C_p}\nabla h\right) \quad (3)$$

h = sensible enthalpy

H= total enthalpy

where, P, V ρ, and g are represented pressure, velocity and density of fluid flow and gravity acceleration, respectively. The equation for density variation is written as follows Boussinesq assumption [17].

$$\rho = \rho l / (\beta\,(T - Tl) + 1) \quad (4)$$

where ρl represents density of Liquidus.

Also, β, μ and T_{ref} are shown dynamic thermal expansion, viscosity and reference temperature, respectively**.**

In addition, S_m is momentum source that add to momentum equation can be define as 2020:

$$S_m = -A_m \frac{(1-\gamma)^2}{(\gamma^3 + \epsilon)}(v - v_p) \quad (5)$$

Equation (5), depended on enthalpy-porosity methods, estimates the differentiation between solid and liquid phases of PCM. Am is a constant number represent mushy zone coefficient and its amount is usually between 10^4 to 10^7. υ_p is solid velocity because of solids extraction and ϵ is a constant small number of 0.00 1to prevent zero division. Moreover, γ defined as liquid-fraction and present as [15-17]:

$$\gamma = \begin{cases} 0 & T < T_{solidus} \\ \dfrac{T - T_{solidus}}{T_{liquidus} - T_s} & T_{solidus} \le T \le T_{liquidus} \\ 1 & T > T_{liquidus} \end{cases} \quad (6)$$

Further, the Reynolds number calculated from following equation:

$$Re = (\rho u D)/\mu \quad (7)$$

The useful heat transfer rate to HTF presented as:

$$\dot{Q}_{us} = \dot{m}C_p(T_{out} - T_{in}) \quad (8)$$

Total useful heat of all day by collector, by integrating of Equation (8) can be defined as:

$$Q_{us} = \sum_{i=1}^{n} \dot{Q}_{us}\Delta T \quad (9)$$

Total energy absorbed during the collector presented as [10]:

$$Q_{coll} = A\sum_{tsurise}^{tsunset} G(t)\Delta t \quad (10)$$

Where $G(t)$ represents solar radiation intensity

2.3. Mesh and boundary conditions

All the created parts are formed one part and the share topology feature was added to a model which allowing for a continuous mesh across common regions where bodies touch then the problem was meshed and solved by using ANSYS FLUENT. To ensure grid independence solution, three different grid densities were tested for three-dimensional model with a different number of elements for the water and PCM zone 728501, 1083360, 1452180 and 2108840. The compared results show that the total number of elements 1452180 are suitable because it represents the best compromise between the solution accuracy and the consuming time. The cell type was tetrahedral element, and the type is cooper cell for a three-dimensional model as shown in Fig. 2. After reaching a successful mesh, the models were exported to fluent for setup and analysis processes.

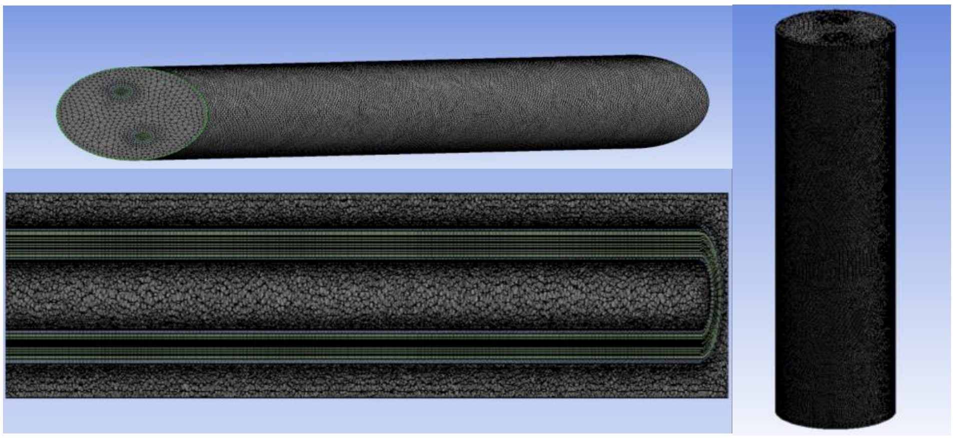

Figure 2. Meshing of three-dimensional geometry for U-ETSC model

The velocity inlet boundary condition type was selected for melting and solidification processes as shown in Table 3. For charging and discharge processes HTF inlet temperature was (300K). Mass flow rate magnitude were taken as 0.5, 1 and 1.5 L/min respectively for with and without PCM. The boundary condition type was set as pressure outlet type for HTF, see Table 3. The outer wall was considered insulated completely, it was in adiabatic thermal condition in the discharge process and exposed to variable heat flux in the charging process. Except walls between PCMs and HTF, it was given coupled thermal condition to allow heat exchange between them.

In order to take into account, the actual amount of solar radiation in each hour and reduce the deviation from reality, solar irradiation is assumed an unsteady heat flux (G (t)). The information on solar radiation was therefore obtained from experimental data. The sun radiation of site Khoshkan village, Choman district, Erbil city (Latitude = 36.5°N, Longitude = 44.99 °E), on 13th January 2021 is shown in Figure 3. The highest solar radiation value (1380w/m^2) took place at 13.00 pm and after that it will decrease at sunset. Equation (11), which is a mathematical formulation, was introduced to the ANSYS FLUENT software by using a UDF and measured data. The terms t and G in the given equation stand for time and solar radiation, respectively. The uniform of G (t) is taken to be the exterior wall under the assumption that the reflector used to apply to the collector.

$$G(t) = -0.6172\,t^2 + 43.04\,t - 691.8 \qquad (11)$$

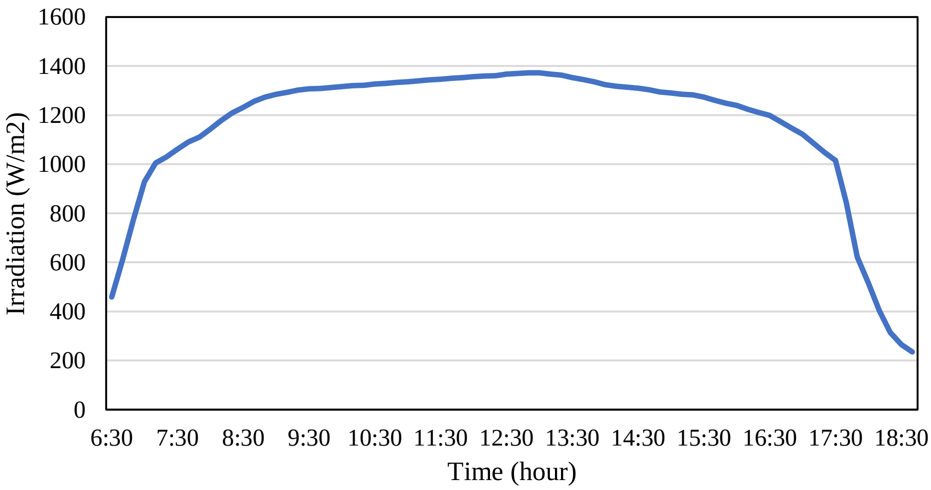

Figure 3. Solar radiation profile utilized in the present work

Table 3: Boundary conditions of all cases for both charging and discharging processes of PCM

Boundary conditions	Melting process	Solidification process
HTF mass flow rate, [L/min]	0.5,1 and 1.5	0.5,1 and 1.5
Inlet temperature of HTF, [^{O}C]	65	30
Intensity of solar radiation, [W/m^2]	G (t) = – 0.6172 t^2 + 43.041 t – 691.81	0
Initialize PCM temperature, [^{O}C]	30	80

3. Results and Discussion

The evaluating U-ETSC with and without PCM, the impact of varying mass flow rates of the HTF - specifically 0.5, 1, and 1.5 liters per minute (l/min) - is a key focus. This section likely presents and analyzes how these different flow rates influence the thermal performance and efficiency of the solar heating system. The results would show the relation between the flow rate and the system's ability to absorb, retain, and transfer heat, both in the presence and absence of PCM. For instance, higher flow rates may lead to more efficient heat transfer but could also affect the thermal storage capacity of the PCM.

Figures 4-6 show the solidification fraction and temperature contours for the solidification process with an initial temperature of 65 °C and HTF flow rate of 0.5, 1 and 1.5 l/min. The contours show the propagation of the solid-liquid interface at different time steps. The complete solidification of PCM inside a U-tube ETSC for mass flow rates 0.5, 1 and 1.5 L/min is achieved at about 112, 142 and162 minutes, respectively. From these figures, we noticed the solidification time increases when the mass flow rate increase. The solidification rate in the upper part is higher than in the lower one. This is mainly because the natural convection forces draw the liquid PCM to the upper section and the solidified PCM sink downward. Moreover, it is noticed that the solid PCM layer around the copper U tube developed as an almost similar circular layer surrounding both sides of the copper U-tube.

This analysis revealed that the developed U-tube inserted with PCM can substantially supply the hot water demand for domestic applications constantly at night/off sunshine hours.

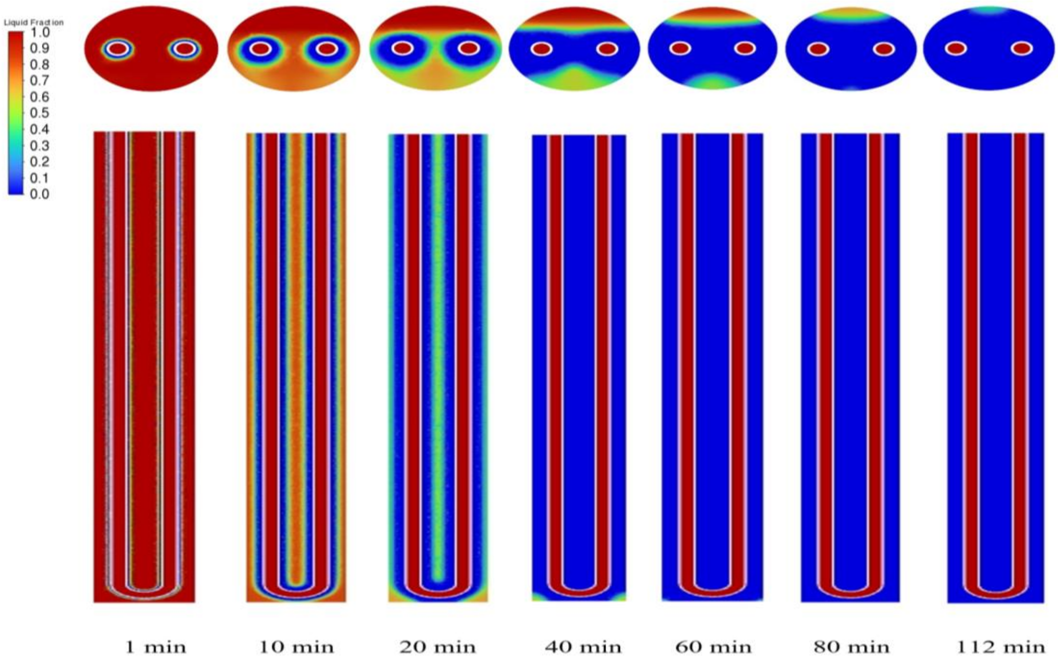

Figure 4. Solidification fraction contours of solidification process in longitudinal and axial directions (U-ETSC) for 0.5 L/min

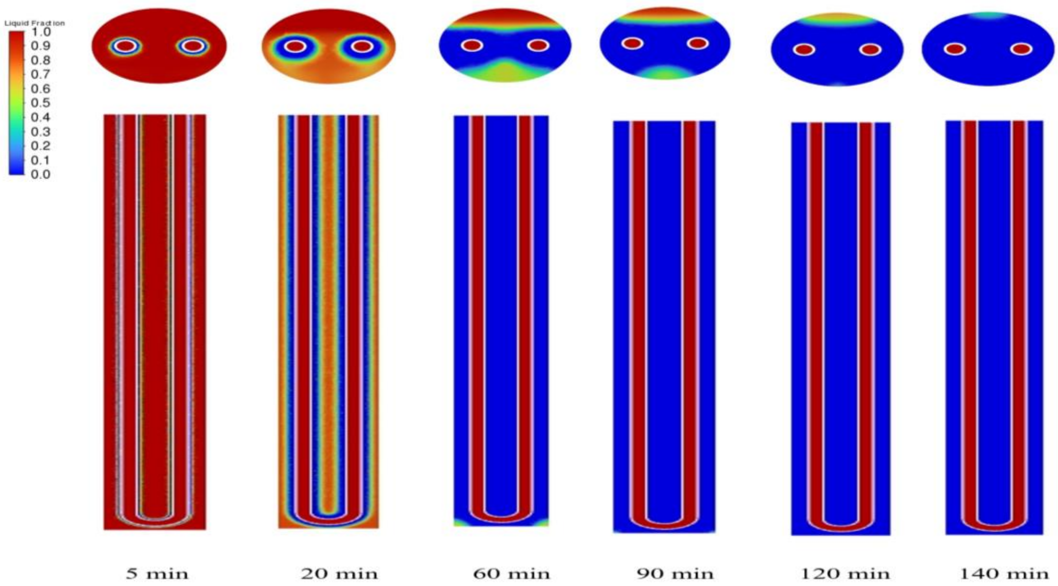

Figure 5. Solidification fraction contours of solidification process in longitudinal and axial directions (U-ETSC) for 1 L/min

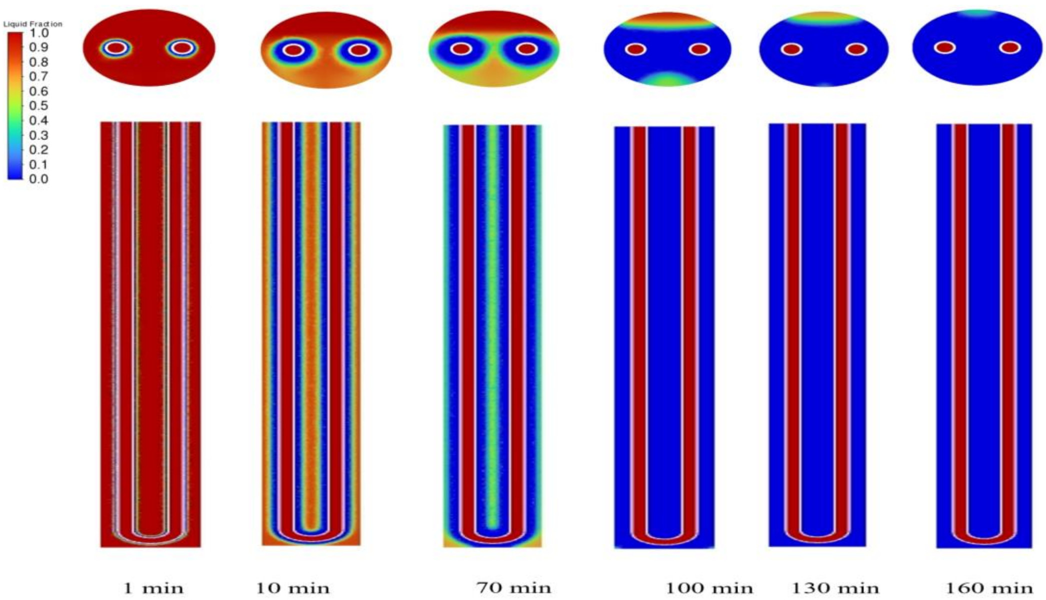

Figure 6. Solidification fraction contours of solidification process in longitudinal and axial directions (U-ETSC) for 1.5 L/min

Figures. 7-9 depict the liquid-fraction contours for the melting processes with an initial temperature of 30 °C and the HTF flow rate of 0.5, 1 and 1.5 l/min, respectively. The contours show the propagation of the solid-liquid interface at different time steps. The complete melting of PCM inside U-ETSC is performed at about 132, 163 and 171 minutes for HTF mass flow rates of 0.5, 1 and 1.5 L/min, respectively. The contours show incomplete PCM melting in the middle reign along the axial direction of the evacuated tube due to the low thermal conductivity of PCM which led to starting melting near the outer pipe when the PCM received solar radiation. In addition, the average temperature of the PCM in the middle and longitudinal sections is strongly influenced by the mass flow rate, indicating that flow conditions play a critical role in heat charging performance and thermal behavior.

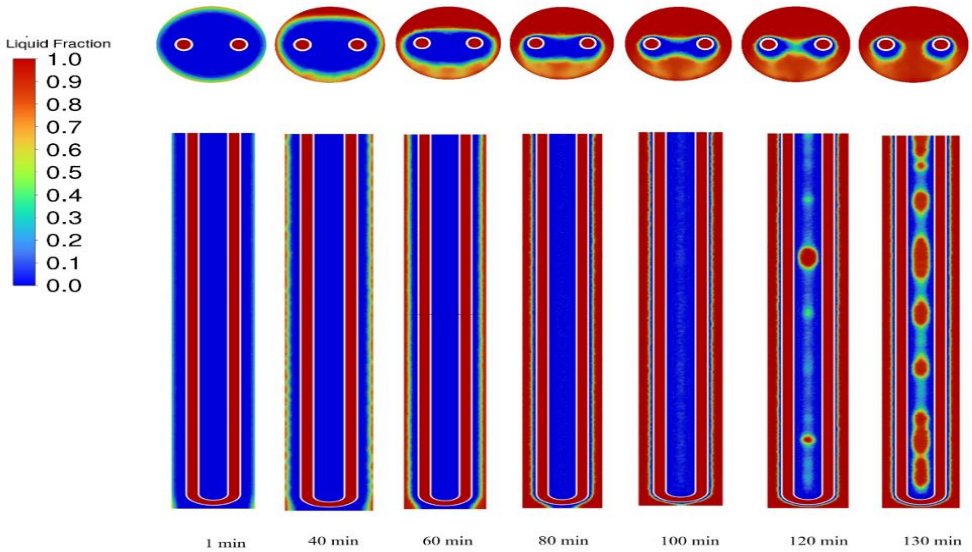

Figure 7. Melting fraction contours in longitudinal and axial directions (U tube-ETSC, 0.5 L/min)

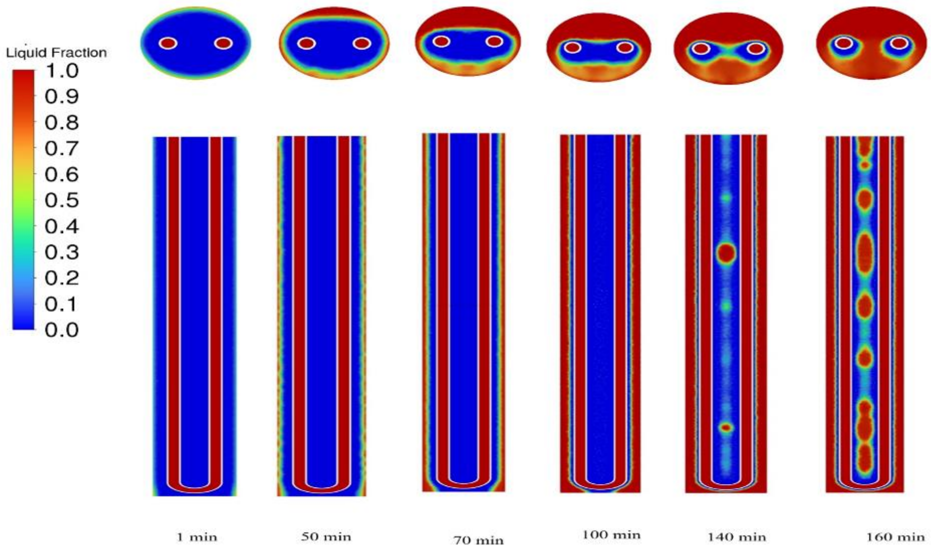

Figure 8. Melting fraction contours in axial and longitudinal directions (U tube-ETSC, 1 L/min)

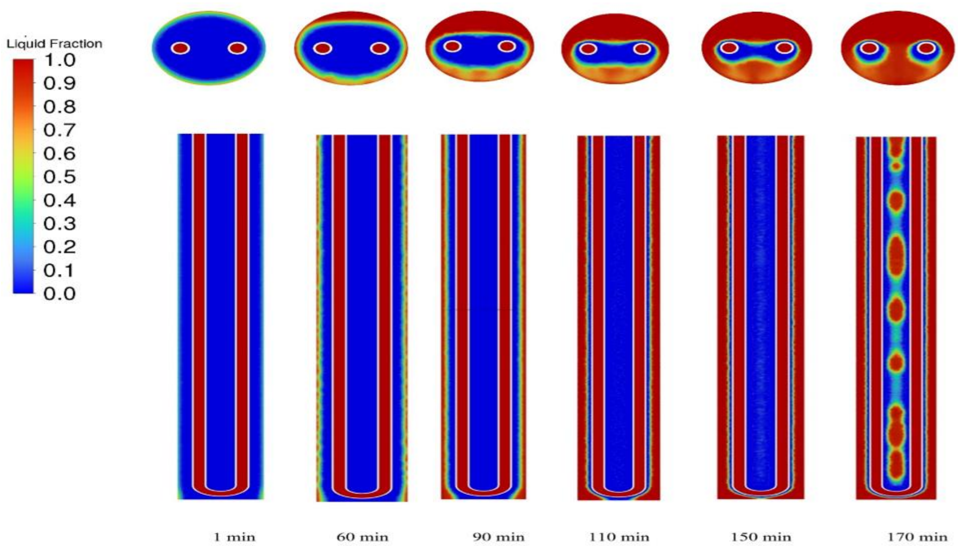

Figure 9. Melting fraction contours in longitudinal and axial directions for (U tube-ETSC, 1.5 L/min)

The effect of HTF mass flow rate on the melting and solidification time is shown in Figures 10 and 11. Figure 10 clarify the variation in the PCM average temperature under different test flow rates (0.5, 1 and 1.5 l/min) of the melting process. As can be seen, the melting time is extended to 13% and 16% when the mass flow rates of HTF increase from 0.5 to 1 and from 1 to 1.5 L/min, respectively. Figure 11 showed the effect of HTF mass flow rates on the average temperature of PCM solidification time. It can be noticed that the solidification time is recorded to 16% and 18% when the mass flow rates of HTF increase from 0.5 to 1 and 1.5 L/min, respectively.

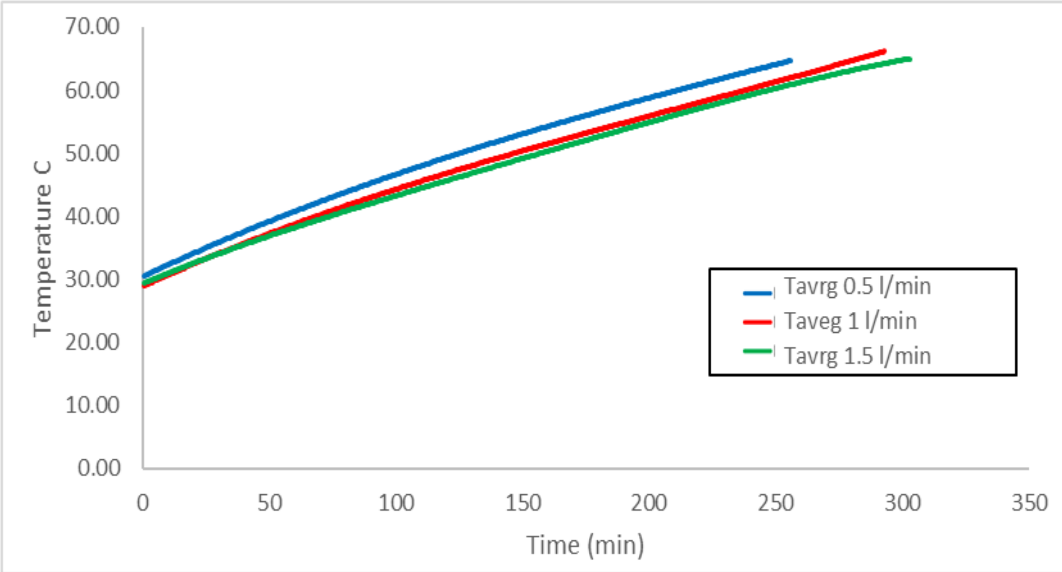

Figure 10. Effect of HTF mass flow rate on the average temperature of PCM during the melting process

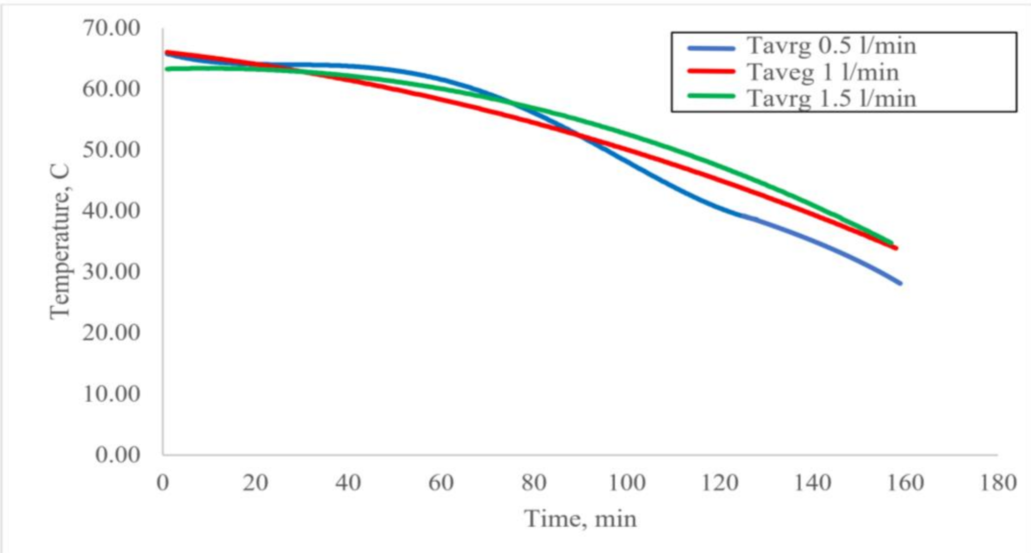

Figure 11. Effect of HTF mass flow rate on the average temperature of PCM during the solidification process

The amounts of useful heat received from the U-tube ETSC system integrated with paraffin for melting and solidification processes, respectively, are shown in figures 12 and 13. When compare U-ETSC solar water heat with and without PCM, it is found that using PCM enhances the useful energy and increases the operating time than conventional system.

The HTF mass flow rate affects the average outlet temperature as well as melting/ solidification process of the PCM. Further, the amount the portion of the thermal energy stored increased with increasing the flow rate from 0. 5 to 1 and 1.5 L/min for both cases compared with the conventional U-ETSC system. The use of paraffin in the U-ETSC system resulted in increases in the amount of useful heat received in the test stand for heating medium flow rates, respectively. It can be conducted that the amount of useful energy received from U-ETSC with and without PCM is directly proportional to the flow rate of HTF.

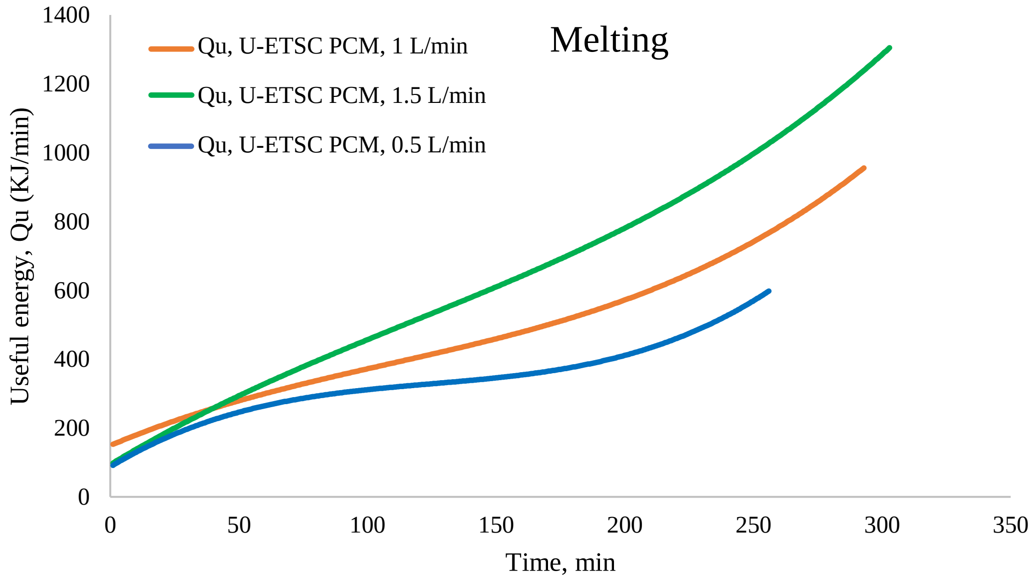

Figure 12. Variation of the useful energy for U-ETSC system integrated with PCM at different flow rates of HTF for melting process

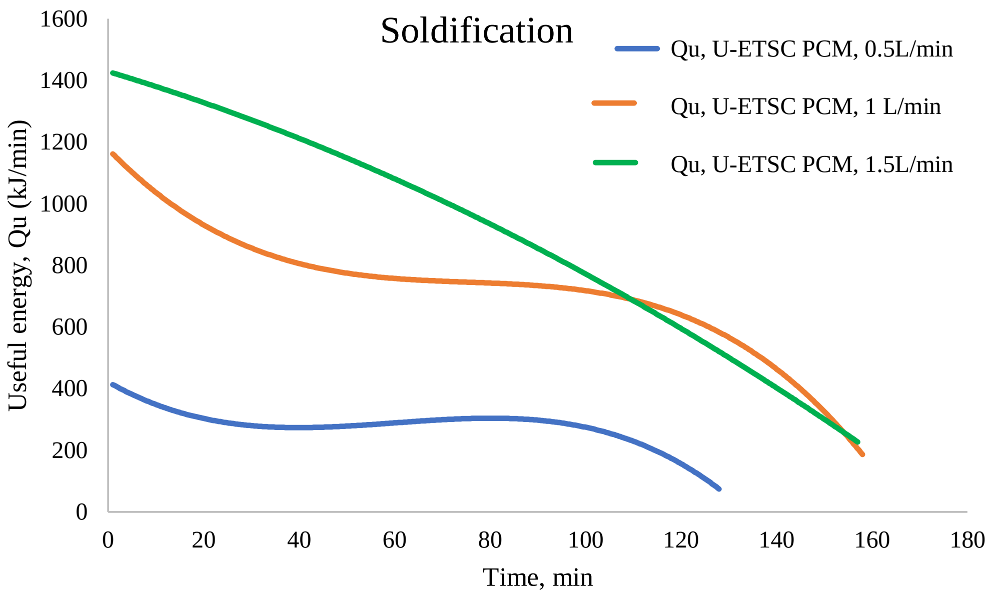

Figure 13. Variation of the useful energy for U-ETSC system integrated with PCM at different flow rates of HTF for solidification process

4. Conclusion

The study successfully developed a U-ETSC integrated with PCM, utilizing paraffin wax as the PCM with a melting point of 62°C and a thermal conductivity of 0.2 W/m°C. The investigation revealed that by increasing the heat charging rate, the temperature in the middle and longitudinal sections of the PCM increased, achieving an average temperature after 132, 163, and 171 minutes for flow rates of 0.5, 1, and 1.5 liters per minute (L/min), respectively. This indicates that the system's efficiency in heat absorption and storage can be significantly influenced by the rate at which heat is transferred to the PCM.

Moreover, simulation results provided key insights into the dynamics of the PCM within the U-ETSC. It was observed that as the mass flow rates of the heat transfer fluid (HTF) were increased from 0.5 to 1 and then to 1.5 L/min, the melting time of the PCM was extended by 13% and 16%, respectively. In addition, the solidification time of the PCM was observed by 16% and 18% for these increasing flow rates. These findings highlight the critical role of HTF flow rates in managing the phase transition times of the PCM, which directly impacts the system’s ability to store and release thermal energy efficiently. This balance between melting and solidification times at different flow rates is essential for optimizing the performance of solar heating systems integrated with PCM.

References

[1] Suman, S., Khan, M. K., & Pathak, M. (2015). Performance enhancement of solar collectors—A review. *Renewable and Sustainable Energy Reviews*, *49*, 192-210.

[2] O’Neil, T. J., & Sobhansarbandi, S. (2022). Thermal performance investigation of energy storage-based U-pipe evacuated tube solar collector: An experimental study. *Sustainable Energy Technologies and Assessments*, 52, 102146.

[3] Alshukri, M. J., Eidan, A. A., & Najim, S. I. (2021). Thermal performance of heat pipe evacuated tube solar collector integrated with different types of phase change materials at various location. *Renewable Energy*, 171, 635-646.

[4] Chopra, K., Pathak, A. K., Tyagi, V. V., Pandey, A. K., Anand, S., & Sari, A. (2020). Thermal performance of phase change material integrated heat pipe evacuated tube solar collector system: An experimental assessment. *Energy Conversion and Management*, 203, 112205.

[5] Essa, M. A., Rofaiel, I. Y., & Ahmed, M. A. (2020). Experimental and theoretical analysis for the performance of evacuated tube collector integrated with helical finned heat pipes using PCM energy storage. *Energy*, 206, 118166.

[6] Li, Y., Liang, X., Song, W., Li, T., Wang, D., & Liu, Y. (2022). Optimization and thermal performance of U-type evacuated tube solar collector filled with phase change material. *Energy Reports*, 8, 6126-6138.

[7] Algarni, S., Mellouli, S., Alqahtani, T., Almutairi, K., & Anqi, A. (2020). Experimental investigation of an evacuated tube solar collector incorporating nano-enhanced PCM as a thermal booster. *Applied Thermal Engineering*, 180, 115831.

[8] Pathak, S. K., Tyagi, V. V., Chopra, K., & Sharma, R. K. (2022). Recent development in thermal performance of solar water heating (SWH) systems. *Materials Today: Proceedings*, 63, 778-785.

[9] Chopra, K., Tyagi, V. V., Pathak, A. K., Pandey, A. K., & Sari, A. (2019). Experimental performance evaluation of a novel designed phase change material integrated manifold heat pipe evacuated tube solar collector system. *Energy Conversion and Management,* 198, 111896.

[10] Olfian, H., Ajarostaghi, S. S. M., Ebrahimnataj, M., Farhadi, M., & Arıcı, M. (2022). On the thermal performance of evacuated tube solar collector integrated with phase change material. *Sustainable Energy Technologies and Assessments*, 53, 102437.

[11] Uniyal, A., & Prajapati, Y. K. (2022). Thermal Performance Study of a Copper U-Tube-based Evacuated Tube Solar Water Heater. *Energy Conversion and Green Energy Storage*, 101-114.

[12] Kumar, A., Tiwari, A. K., & Said, Z. (2021). A comprehensive review analysis on advances of evacuated tube solar collector using nanofluids and PCM. *Sustainable Energy Technologies and Assessments*, 47, 101417.

[13] Pawar, V. R., & Sobhansarbandi, S. (2021). Design optimization and heat transfer enhancement of energy storage based solar thermal collector. *Sustainable Energy Technologies and Assessments*, 46, 101260.

[14] Weaver, R., Lim, C. S., & Sobhansarbandi, S. (2022). Thermal performance improvement of energy storage materials for low operating

temperature solar water heating systems. *Sustainable Energy Technologies and Assessments*, 52, 102298.

[15] Voller, V. R., & Prakash, C. (1987). A fixed grid numerical modelling methodology for convection-diffusion mushy region phase-change problems. *International journal of heat and mass transfer*, *30*(8), 1709-1719.

[16] Shokouhmand, H., & Kamkari, B. (2013). Experimental investigation on melting heat transfer characteristics of lauric acid in a rectangular thermal storage unit. *Experimental Thermal and Fluid Science*, *50*, 201-212.

[17] Nakhchi, M. E., & Esfahani, J. A. (2020). Improving the melting performance of PCM thermal energy storage with novel stepped fins. *Journal of Energy Storage*, *30*, 101424.