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Investigating the Performance of the Flat Plate Collector with Photovoltaic Panel and Phase Change Material

Mohadeseh Ahmadi[1], Akbar Arabhosseini[1], Hadi Samimi-Akhijahani[2]

[1] Department of Agrotechnology, College of Abouraihan, University of Tehran, Tehran, Iran.
[2] Department of Biosystem Engineering, Faculty of Agriculture, University of Kurdistan, Kurdistan, Iran.

Corresponding author: ahosseini@ut.ac.ir

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ABSTRACT

Solar energy is a kind of renewable energy which applicable in many industries, including agriculture. In this research, a new flat plate solar collector including phase change material (PCM) and photovoltaic panel were used to prevent the drying process interruption. In the system, the vertical copper tubes on the collector plate were filled by phase change materials to save extra thermal energy during the charging process. This saved thermal energy was then released in a latent form and helped to accelerate the drying process. Additionally, placing the phase change material beneath the photovoltaic panel effectively cooled the panel and improved its performance. Simulation results showed that paraffin, as the phase change material, effectively maintains thermal stability, increases drying speed, and enhances the system's efficiency. Therefore, this study will explore the potential of combining phase change material and photovoltaic technologies to design an optimized and more sustainable drying system for agricultural applications.

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INTRODUCTION

In recent decades, due to population growth, the use of fossil fuels has increased. Considering the limited natural of non-renewable energy resources, such as fossil fuels, one of the solutions to mitigate the energy crisis is utilizing renewable energy sources. Renewable energy sources are solar energy, wind energy, hydropower, geothermal energy, wave energy, and ocean energy. These kinds of renewable energies do not cause environmental pollution, and its use is essentially unlimited (Panwar et al., 2011).

Among the renewable energy sources, solar energy is the most available one and it's accessible in most regions. Solar energy can be utilized as thermal and electrical energy. It is extensively used in some systems such as solar dryers, solar desalination units, solar water heaters, and others.

Drying is one of the common methods for preserving agricultural products. During the drying process, if the product is not fully dried, it may spoil or deteriorate. Therefore, in solar dryers, thermal efficiency is crucial due to interruptions in the drying process during sunset or unfavorable weather conditions (Sorkhani et al., 2022).

Photovoltaic (PV[1]) panels convert sunlight radiation into electricity using the photovoltaic effect. However, during the energy conversion process, PV panels also generate heat as a byproduct, which is typically released into the environment in conventional photovoltaic systems. In hybrid photovoltaic-thermal (PV/T[2]) systems, this heat is utilized for certain purposes. In these hybrid systems, in addition to electricity generation, the heat produced by the PV panels is collected and used for thermal applications such as heating water or air and also drying agricultural products. Thus, in PV/T systems, the PV panels serve dual purposes: electricity generation and heat production, leading to maximum utilization of solar energy (Siecker et al., 2017).

Photovoltaic systems can convert solar radiation into electricity with an efficiency of 5% to 20%. Consequently, a significant portion of solar radiation is transformed into thermal energy (Aste et al., 2015).

Excessive heat can reduce the thermal and electrical efficiency of PV panels. To address this issue, various cooling methods are employed to enhance the performance of these systems. Cooling techniques for PV panels include using water sprays, nanofluids, and phase change materials (PCM[3]s). Unlike water sprays, PCMs can absorb excess heat and store it through the processes of melting and solidification, without causing evaporation or deposition of materials within the system. Considering these properties, along with their defined melting point, high thermal capacity, and the absence of complex system design requirements, the use of PCMs as coolants is more efficient and cost-effective (Su et al., 2017).

Phase Change Materials (PCMs) absorb heat from the system and undergo a phase change. Therefore, they are used for controlling the temperature of PV cells. This method is considered as one of the passive cooling techniques for PV cells. One of the advantages of this method is the absence of energy consumption during the cooling process (Abdulmunem et al., 2021). Moreover, after sunset or under unfavorable weather conditions, the PCMs transfer back the stored thermal energy to the system, preventing the drying process from halting.

In a laboratory study, several horizontal and parallel aligned rectangular copper pipes were placed beneath a PV panel. The system was examined under two conditions: with and without cooling process. The results showed that the electrical efficiency of the PV panel increased as the panel's temperature decreased. Additionally, the thermal efficiency improved by 15% to 20% with the cooling process (Alzaabi et al., 2014).

[1]- Photovoltaics
[2] - Photovoltaic Thermal System
[3] - Phase Change Material

In another study, 25 copper pipes containing paraffin were arranged in 5 rows with spacing of 5, 10, and 15 cm in a collector. The average thermal efficiencies for these spacings were 53.26%, 54.89%, and 56.29%, respectively (Ahmadi et al., 2023).

In another investigation, the impact of water flow rate variations under constant solar radiation, as well as the effect of solar radiation variations under a constant water flow rate, were studied on the electrical and thermal efficiency of a photovoltaic-thermal (PV/T) system using monocrystalline silicon PV panels. A copper absorber plate and spiral pipes were installed at the back of the PV panel. Cold water flow entered the collector from both the left and right sides through the pipes, cooling the PV cells before exiting from both sides. The results indicated a maximum electrical efficiency of 11.5% and a maximum thermal efficiency of 58.64%. Overall, increasing solar radiation and water flow rate improved the thermal efficiency and overall system efficiency (Abdullah et al., 2020).

In another study, a PV/T system was developed by combining nanofluids and nano-PCM[4] with spiral absorber tubes (PV/T-PCM). Silicon carbide (SiC) nanoparticles were used due to their high thermal conductivity (370–490 W/m.K), low cost, and fluid stability. The highest electrical, thermal, and combined efficiencies of the PV/T system for PV/T-PCM with twisted tubes were 9.57%, 84.74%, and 94.31%, respectively (Al-Aasam et al., 2023).

An experimental study on integrated PV/PVT-PCM system with air ventilation showed that using PCM with a phase change temperature of 52℃ and a thickness of 0.3 mm could maintain the PV panel temperature below 54℃ for 12 minutes under 600 W/m² irradiance, resulting in a 1% increase in system efficiency. Adding an additional of 0.1 mm layer of PCM increased the temperature stabilization time by 60 to 70 minutes. Additionally, the inclusion of metal fins led to a 3% increase in efficiency (Gan & Xiang, 2020).

In a study, a 3D model of a photovoltaic thermal system with phase change material (PVT/PCM) was developed and simulated. The results showed that the PVT/PCM system has lower surface and outlet temperatures than the PV system. Increasing PCM's melting temperature from 40℃ to 65℃ raised the surface temperature and reduced the melted PCM percentage. Improving PCM's thermal conductivity also enhanced the system's electrical and thermal efficiency (Kazemian et al., 2019).

The effect of using pure PCM (white petroleum jelly) and a composite PCM (white petroleum jelly, copper, and graphite) on the thermal behavior and electrical performance of a PV panel was investigated. The results revealed that the electrical efficiency of the PV panels increased by an average of 3% when using pure PCM and by an average of 5.8% when using the composite PCM (Hachem et al., 2017).

In a research, four energy generation systems under PV panels were examined including PV, photovoltaic thermal with water as the fluid, photovoltaic thermal with water and PCM, and photovoltaic thermal with nanofluid and improved PCM, all under identical conditions. The results showed that the efficiency of the fourth system (photovoltaic thermal with nanofluid and improved PCM) was about 21.5% higher than the third system and about 36.6% higher than the second system (Al-Waeli et al., 2017).

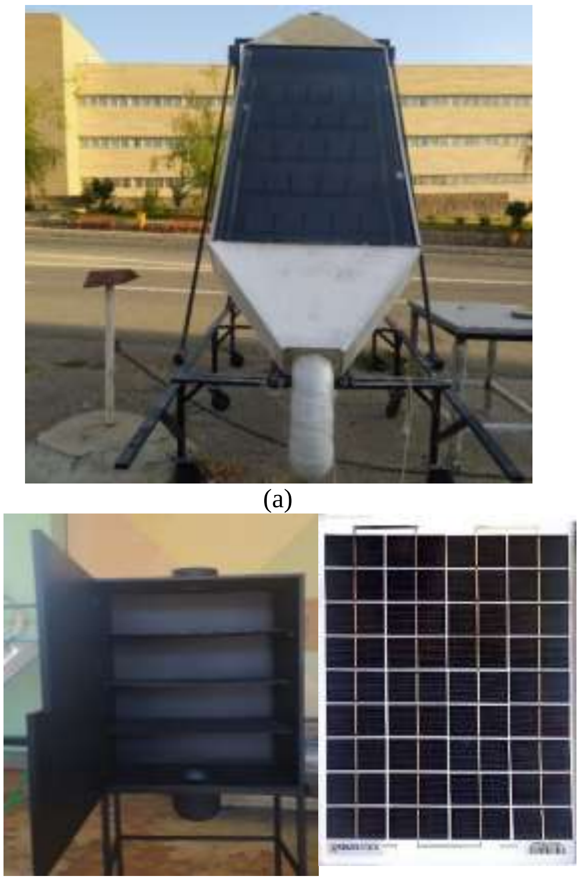
Considering that, review of the previous documents showed lack of a clear basis for selecting the kind of cooling system, pipe material, and pipe arrangement in photovoltaic-thermal (PV/T) collectors. Since no prior research has utilized vertical pipes containing PCM along with PV panels inside the collector, this study proposes a geometric model for the PV/T collector. In this model, the PV panel is positioned above the vertical pipes containing paraffin, located at the top section of the collector. Additionally, heat flow analysis within the collector under the given conditions has been

1- Computational fluid dynamics

simulated using computational fluid dynamics (CFD[1]).

MATERIALS AND METHODS

A laboratory-scale indirect solar drying system with steel trays was used for experiments, which is available at the Renewable Energy Research and Technology Center in Sanandaj, Iran (Figure 1).



(a) (b) (c)

Figure 1 . Solar dryer: a) the whole system, b) solar dryer chamber. c) Polycrystalline PV panel.

The solar drying system consists of a flat-plate solar collector with a heat storage system integrated with a drying cabinet. The main component of the solar dryer system is the collector, which includes a matte black absorber plate to absorb maximum amount of solar energy, 25 copper pipes containing RT50 paraffin, a polycrystalline PV panel, and a single-layer glass cover to allow sunlight pass through. The main part of the solar dryer system is the collector, which includes a DC motor, an electrical circuit, a photosensitive sensor, a galvanized matte black absorber plate to capture the maximum solar radiation, a DC fan at the collector’s entrance to create airflow within the system, copper pipes containing PCM, PV panel, a single-layer glass, and insulated body. The schematic diagram of the system is shown in Figure 2.

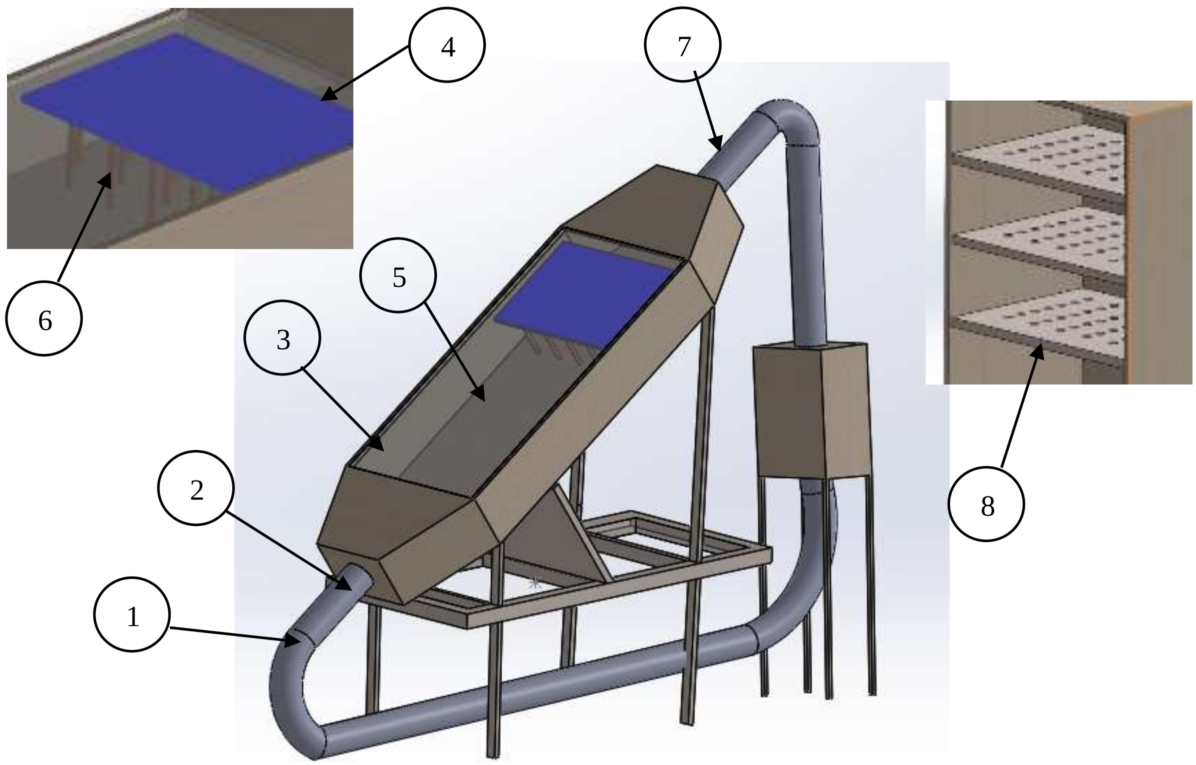


Figure 2. Schematic diagram of solar dryer system: 1) Collector inlet, 2) Fan, 3) Glass cover, 4) PV panel, 5) Absorber plate, 6) Copper pipes containing paraffin, 7) Collector outlet, 8) Sample tray location.

During the sunny days, solar rays strike the collector plate. As sunlight radiates, solar energy is absorbed by the absorber plate, and heat up the air inside the chamber. Additionally, the PV panel captures thermal energy from the sun. The heated air inside the collector is directed into the dryer cabinet through a connecting duct. In this process, the heated air in the collector is transferred to the cabinet via convection and radiation. The warm air flow over the cabinet removes moisture from the samples, influenced by air velocity and heat. When solar radiation is concentrated on the collector plate and reaches its peak intensity (from 12:00 to 15:00), the paraffin inside the pipes undergoes a phase change and melts, storing thermal energy. As the paraffin changes from a solid to a liquid state, the PV panel is also cooled, reducing thermal energy losses in the solar collector. During the periods without sunlight or under adverse weather conditions, the stored energy is released, allowing the system to continue the drying process. In this study, 25 copper pipes containing RT50 paraffin were used. The specifications of the RT50 paraffin is shown in Table 1.

Table 1. Specifications of RT50 Paraffin

Parameter	quantity
Specific heat (kJ/kg K)	0.5
Thermal conductivity (W/m K)	0.2
Density (kg/m^3)	783
Volumetric expansion coefficient (1/ K)	0.000561
Latent heat (kJ/kg)	166
Liquid state temperature (K)	325
Solid state temperature (K)	317.3

Simulation Using CFD

When solar radiation intensity exceeds expectations during the day, the air inside the collector becomes excessively heated, and the temperature of the PV panel increases by increasing radiation intensity. Consequently, the paraffin within the copper pipes changes to liquid state, cooling the PV panel while storing the absorbed heat as thermal energy. As the solar radiation intensity decreases and the ambient air temperature falls below the temperature of the fluid inside the collector, the paraffin's temperature decreases, causing it to undergo a phase change at a specific temperature. During the phase change, the stored latent heat energy is released back into the system, allowing the drying process to continue. For simulation fluid flow and heat transfer, computational fluid dynamics (CFD) was utilized and the block diagram is shown in Figure 3.

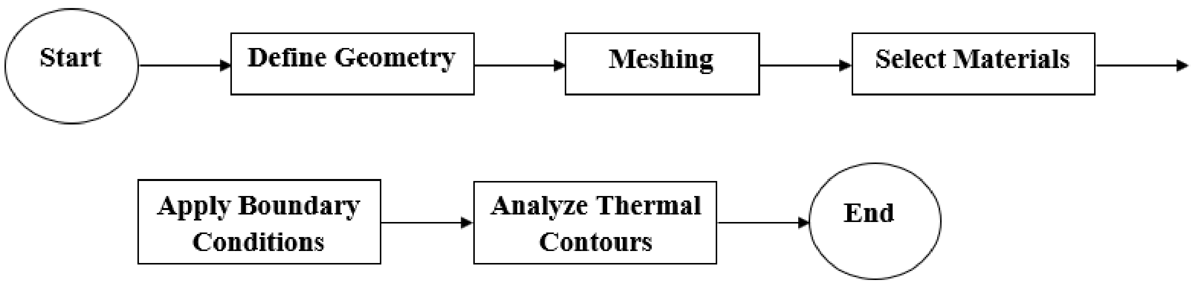


Figure 3. Block diagram of simulation using CFD.

To begin the simulation, the model was initially designed using a CAD software such as Catia, SolidWorks, or Mechanical. After designing the model, it was saved in a compatible format for grid generation. Specifically, the model of the collector was designed in SolidWorks 2020 and then saved in an x-t format, which is compatible with the Ansys Fluent 2019 software for analysis. After importing the model into Ansys Fluent, the components were defined as either solid or liquid, and the meshing process was carried out. Based on the geometry, the software selected the most optimal meshing approach for accurate analysis (Ahmadi et al., 2023). In this study, triangular meshing was used, as shown in Figure 4.

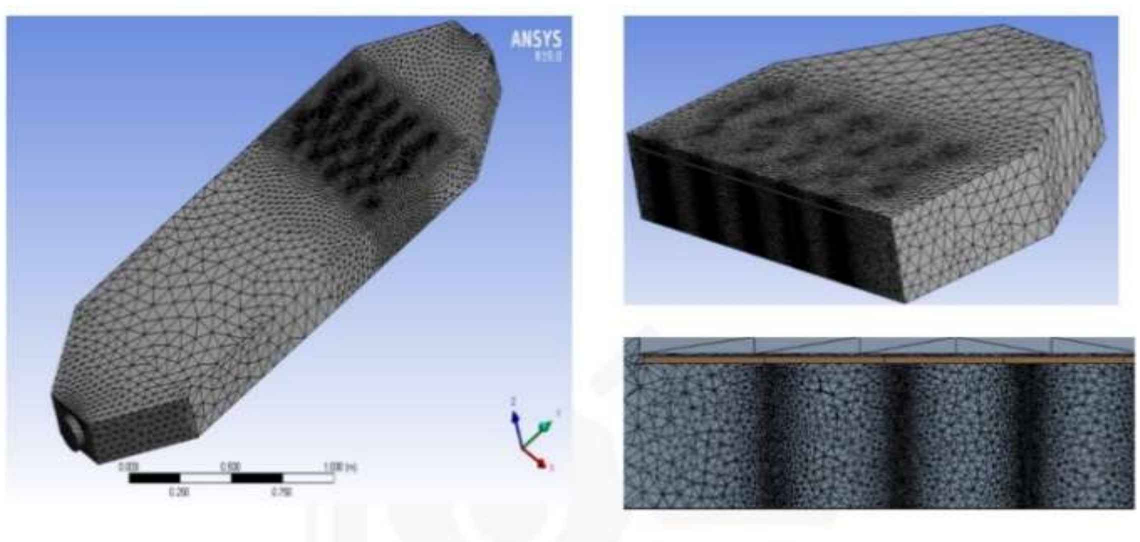


Figure 4. Meshed Model of the Solar Collector.

Considering the Figure 4, finer meshes were applied around the absorber plate, copper pipes, and the PV panel to ensure a more accurate analysis and reliable results. Taking into account the models accuracy, computation time, and process cost, a medium mesh was chosen for the simulation, with the total number of grid cells being approximately 1551924. The skewness criterion was used to assess the mesh quality. For mesh generation of a system, the best and worst meshes correspond to skewness values of 0 and 1, respectively (Vigneshkumar et al., 2021). Therefore, in this study, a medium mesh with a skewness of 0.228 was considered for the collector. The other characteristics of the mesh used are provided in Table 2 for the solar collector model.

Table 2. Mesh Properties Applied for the Solar Collector Model

Parameter	Quality or quantity
Mesh type	Medium
Minimum size	0.0001
Maximum size	0.001
Number of nodes	373862
Number of elements	1551924

After meshing, the type and properties of the materials used in the system were defined, as shown in Table 3.

Table 3. Properties of the Materials Used in the System

Material	Specific Heat (J/kg.K)	Density (kg/m³)	Thermal Conductivity (W/m.K)
Air	1006.4	1.225	0.0242
Glass	840	2579	0.96
PV panel	700	2500	2
Wood	3310	700	0.173
Copper	385	8960	401
Iron sheet	450	7874	80

In the next step, the conditions governing the problem and the boundary conditions, such as the fluid inlet velocity, pressure inlet, and temperature boundary conditions were defined for both charging and discharging states of the PCM. The inlet temperature for the charging state was set at 35℃, while for the discharging state, was set at 30℃. The collector simulation was carried out for the geographic location of Sanandaj (the capital of Kurdistan province), Iran, with latitude of 31.35° and longitude of 45.99°, for August. The standard DO1 model equation in Ansys Fluent was used for solving the radiative transfer equation with homogeneous phase in each cell.

Governing equations

For simulating radiative heat transfer, in addition to the thermal energy equation, the radiation transfer equation must also be used, which is expressed in Equation 1.

$$\nabla(I_\lambda(r,s)s) + (a_\lambda + a_s)\, I_\lambda(r,s) = a_\lambda\, n^2 I_{b\lambda} + \frac{\sigma_s}{4\pi} \quad (1)$$

Where $I_\lambda(r\ ,\ s)$ is the radiation intensity at wavelength λ at position r and direction s (W/m²·sr·nm). a_λ is the absorption coefficient for wavelength λ (1/m). σ_s is the scattering coefficient for direction s(1/m). n is the refractive index of the medium (dimensionless) and $I_{b\lambda}$ is the ideal radiation intensity at wavelength λ (W/m²·sr·nm).

The heat stored in the paraffin during the phase change was calculated using the change in enthalpy, as given by Equation 2.

$$\Delta Q = \Delta H = m.\Delta h \quad (2)$$

Where ΔQ represents the heat change within the paraffin, ΔH denotes the enthalpy change, and m is the mass of the paraffin.

The output thermal power obtained from the PV/T collector was determined based on Equation 3.

$$\dot{Q}_t = C_w \dot{m}(T_w(L) - T_{w,in}) \quad (3)$$

Where $\dot{Q}_t$ is the output heat power (J/s), C_w is the specific heat capacity of water (J/kg·K), ṁ is the mass flow rate of water (kg/s), T_w(L) is the temperature of the water leaving the collector (K), $T_{w,in}$ is the temperature of the water entering the collector (K).

Considering that the flow is steady and there are no significant turbulence fluctuations, the flow is therefore considered laminar. The thermal heat input to the dryer is expressed using Equation 4 (Iranmanesh et al., 2020).

$$Q_{in,dryer} = 10^{-6}[(\int \int_0^t \dot{m}(t).C_p(T_{in,coll} \_T_{out,coll})dt) \_\int_0^t \dot{m}(t).\, C_p(T_{in,s} \_T_{out,s})dt)] \quad (4)$$

Where C_p (J/kg·K) is the specific heat capacity of the fluid, $T_{in,coll}$ and $T_{out,coll}$ (K) are the inlet and outlet temperatures of the collector, respectively, and $T_{in,s}$ and $T_{out,s}$ (K) are the outlet and inlet temperatures of the system.

RESULTS AND DISCUSSION

Figure 5 shows the simulation results for the charging state at 13:00 with a solar radiation intensity of 850 W/m² at the specified geographic location. As shown in the figure, the air has a higher temperature before reaching the pipes, and when it reaches the pipes, the excess heat is absorbed by the PCM. It is clear from Figure 5 that the thermal contours around the pipes are lower compared to other areas. In this condition, a portion of the thermal energy generated by the PCM pipes is stored. When the air passes through the pipes, part of the thermal energy is absorbed by the pipes containing paraffin. This process is known as energy storage or charging .

Similarly, Gan and Xiang demonstrated that PCM can extend the operational time of solar systems by releasing stored energy during periods of low solar radiation (Gan & Xiang, 2020). Additionally, Kazemian et al. highlighted the benefits of PCM in reducing surface temperatures and improving both thermal and electrical efficiencies (Kazemian et al., 2019). Collectively, these studies support the findings of the present research and confirm the vital role of PCM in enhancing system performance (Figure 5).

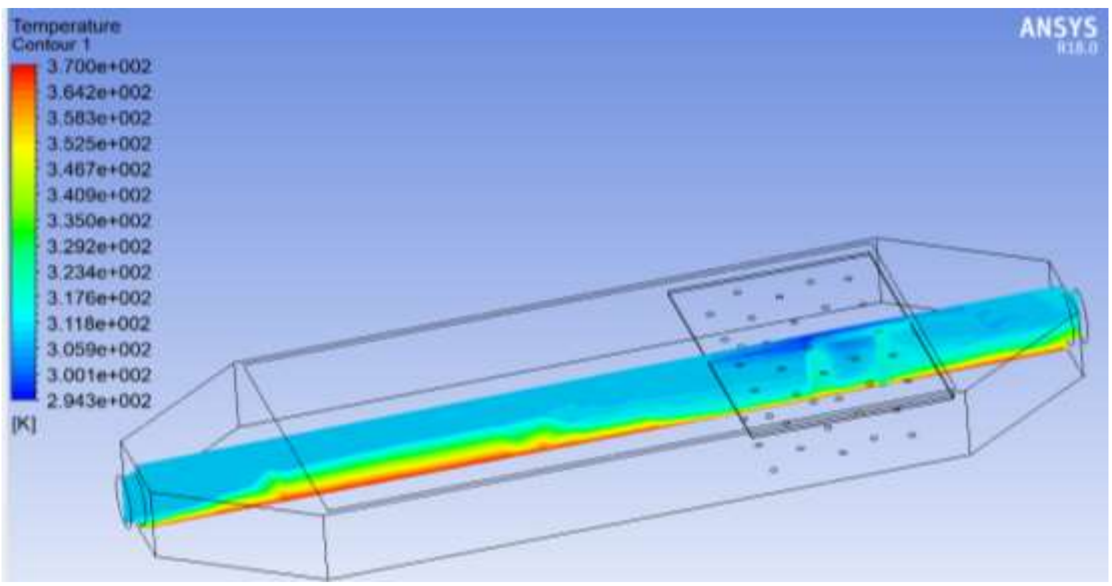


Figure 5. Thermal Contours for the Flat-Plate Solar Collector during the Heat Absorption by the PCM.

As the temperature inside the collector increases, the excess heat in the system is absorbed by pipes containing paraffin. The highest heat transfer occurs from the collector and the PV panel to the pipes. Consequently, as heat is transferred from the top and bottom towards the center of the pipes, the temperature in the middle regions gradually increases. The temperature contours, as shown in Figure 6, illustrate the gradual heat distribution from both ends of the pipes toward the center.

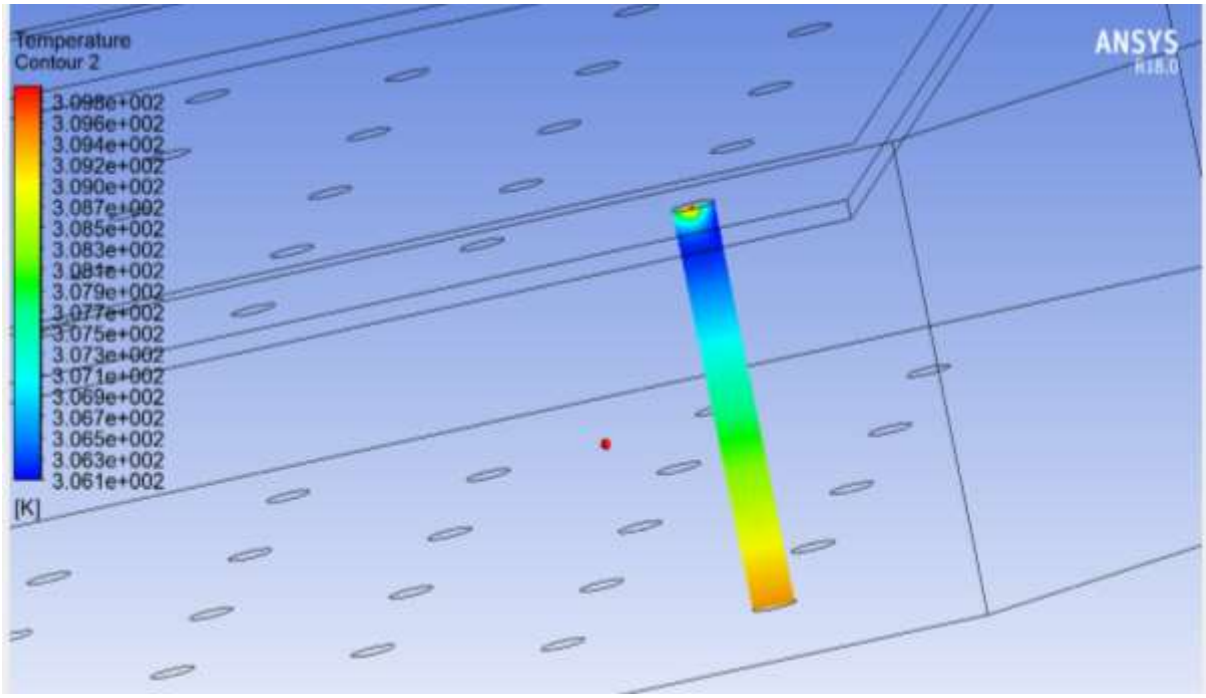


Figure 6 . Thermal contours for the paraffin-containing pipe during heat absorption by the PCM.

The outlet temperature of the collector, for the air velocity of 1 m/s and the pipe spacing of 15 cm, reaches a maximum temperature of 71℃ and a minimum temperature of 36℃ (Figure 7). In similar experimental studies, thermocouples have been used to measure the temperature at the inlet and outlet of collector. According to the simulation results presented in the figure, the thermal contour is highest in the area near the absorber plate.

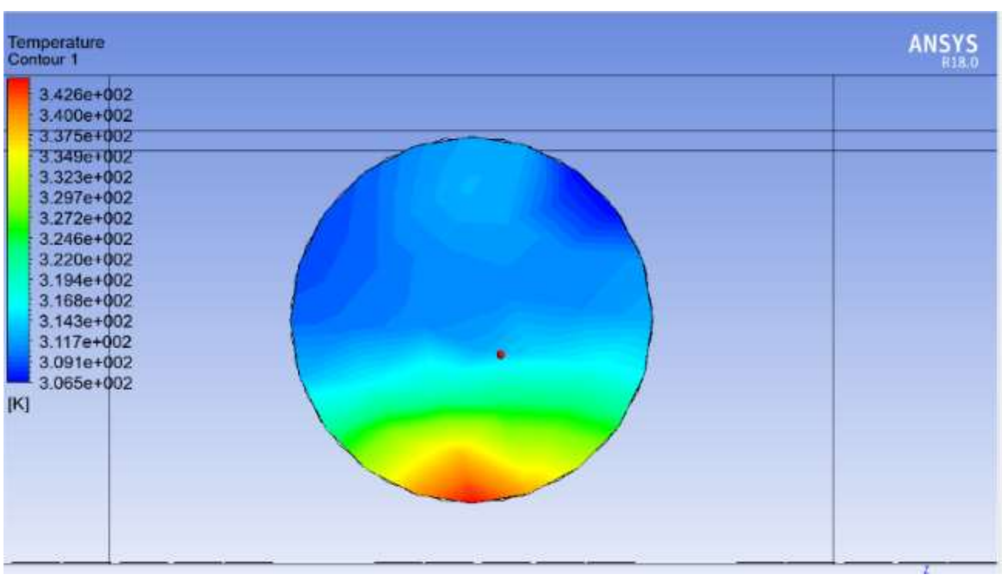


Figure 7. Thermal contours of the collector outlet during heat absorption by the PCM.

The simulation was also conducted for the discharge state at 20:00. During the discharge state, heat is transferred from the PCM to the surroundings. As shown in the figure, the air temperature matches the ambient temperature before reaching the PCM and gradually increases as it passes through the pipes. At this point, the discharge process occurs, and the paraffin transfers its stored latent thermal energy to the system.

This finding aligns with the results of Su et al., who highlighted the role of PCM in reducing interruptions in solar drying processes by providing a stable heat source during periods of insufficient radiation (Su et al., 2017). Additionally, Alzaabi et al. reported similar improvements in thermal efficiency for photovoltaic-thermal systems when cooling mechanisms were implemented, further confirming the effectiveness of PCM integration in the current study (Alzaabi et al., 2014).

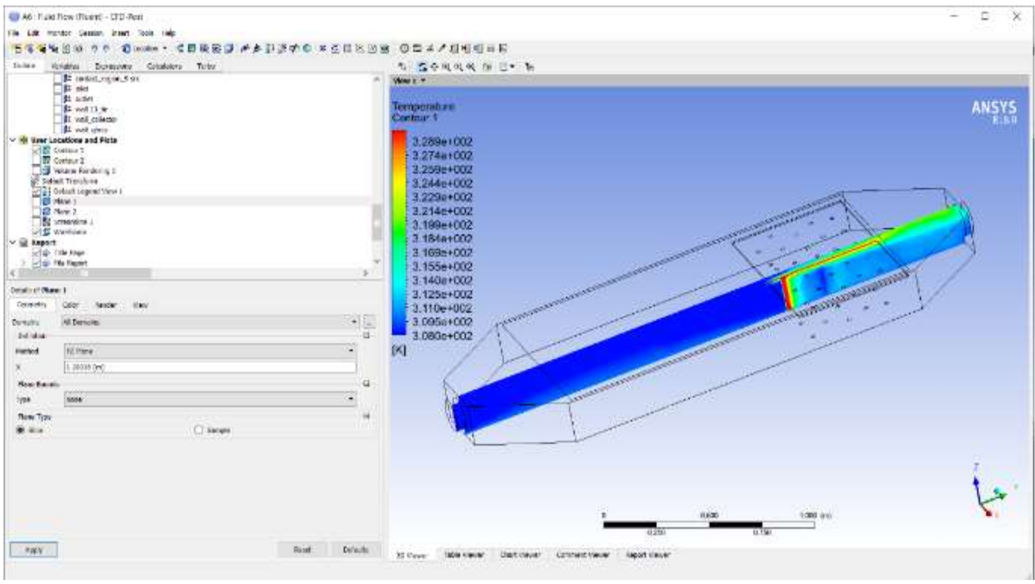


Figure 8. Thermal distribution contours in the collector during the discharge process of the PCM.

According to Figure 9, the outlet temperature of the collector reaches a maximum level of 47 °C and a minimum level of 33°C.

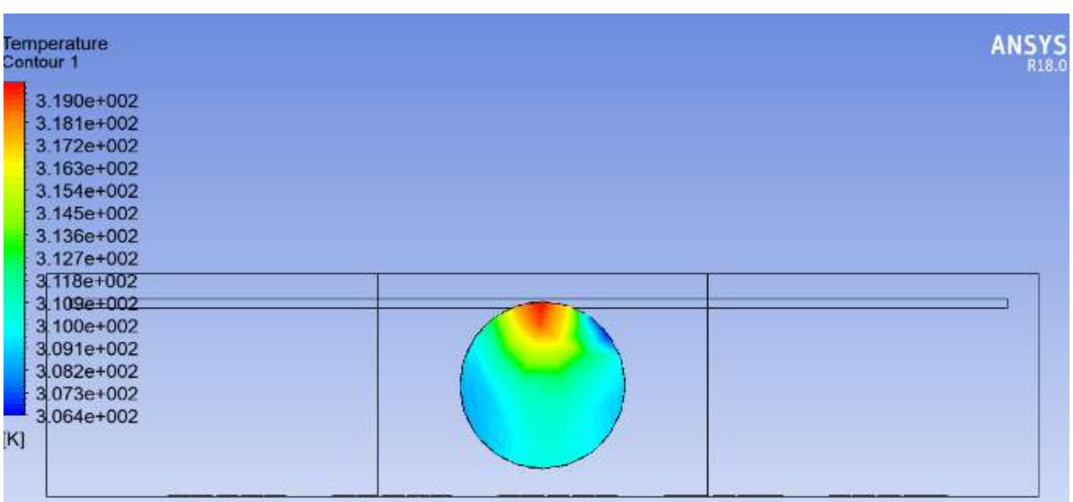


Figure 9. Thermal contours of the collector outlet during the discharge process of the PCM.

CONCLUSIONS

Solar dryers are very suitable and cost-effective for the drying of agricultural products. Given that solar energy is sometimes unavailable during the day. Retaining thermal energy in these systems during the times when solar energy is unavailable is a critical issue. In this study, the temperature distribution was simulated and analyzed using Ansys Fluent 2019 software in a collector with 25 copper pipes arranged in 5 rows, with a 15 cm spacing between pipes in each row, as well as the outlet temperature of the collector for both charging and discharging states, and the temperature distribution in the phase change material (PCM) during charging.

The results showed that paraffin, as the PCM, stores the thermal energy of the system in a latent form during the charging state, where the paraffin is in a liquid form. In the discharging state, paraffin releases its latent thermal energy to the system by losing heat and transitioning into a solid state. Furthermore, to enhance the lifespan and performance of the PV panel, maintaining the temperature in the system is crucial. Therefore, in this study, paraffin was used as a cooling material, and by changing the phase of paraffin during charging, the PV panel is cooled, and the system experiences less energy losses.

As a result, the outlet temperature of the collector was shown to be 69°C during the charging state and 46°C during the discharging state. The simulation results also indicated that the PCM starts melting and storing energy from both the top and bottom of the pipes.

REFERENCES

Abdullah, A. L., Misha, S., Tamaldin, N., Rosli, M., & Sachit, F. (2020). Theoretical study and indoor experimental validation of performance of the new photovoltaic thermal solar collector (PVT) based water system. *Case Studies in Thermal Engineering, 18*, 100595. https://doi.org/10.1016/j.csite.2020.100595

Abdulmunem, A. R., Samin, P. M., Rahman, H. A., Hussien, H. A., Mazali, I. I., & Ghazali, H. (2021). Numerical and experimental analysis of the tilt angle's effects on the characteristics of the melting process of PCM-based as PV cell's backside heat sink. *Renewable Energy, 173*, 520-530. https://doi.org/10.1016/j.renene.2021.04.014

Ahmadi, M., Samimi-Akhijahani, H., & Salami, P. (2023). Thermo-economic and drying kinetic analysis of Oleaster using a solar dryer integrated with phase change materials and recirculation system. *Journal of Energy Storage, 68*, 107351. https://doi.org/10.1016/j.est.2023.107351

Al-Aasam, A. B., Ibrahim, A., Sopian, K., Abdulsahib, B., & Dayer, M. (2023). Nanofluid-based photovoltaic thermal solar collector with nanoparticle-enhanced phase change material (Nano-PCM) and twisted absorber tubes. *Case Studies in Thermal Engineering, 49*, 103299. https://doi.org/10.1016/j.csite.2023.103299

Al-Waeli, A. H., Sopian, K., Chaichan, M. T., Kazem, H. A., Ibrahim, A., Mat, S., & Ruslan, M. H. (2017). Evaluation of the nanofluid and nano-PCM based photovoltaic thermal (PVT) system: An experimental study. *Energy Conversion and Management, 151*, 693-708. https://doi.org/10.1016/j.enconman.2017.09.032

Alzaabi, A. A., Badawiyeh, N. K., Hantoush, H. O., & Hamid, A. (2014). Electrical/thermal performance of hybrid PV/T system in Sharjah, UAE. *International Journal of Smart Grid and Clean Energy, 3*(4), 385-389. https://doi.org/10.12720/sgce.3.4.385-389

Aste, N., Leonforte, F., & Del Pero, C. (2015). Design, modeling and performance monitoring of a photovoltaic–thermal (PVT) water collector. *Solar Energy, 112*, 85-99. https://doi.org/10.1016/j.solener.2014.11.025

Gan, G., & Xiang, Y. (2020). Experimental investigation of a photovoltaic thermal collector with energy storage for power generation, building heating and natural ventilation. *Renewable Energy,* *150*, 12-22. https://doi.org/10.1016/j.renene.2019.12.112

Hachem, F., Abdulhay, B., Ramadan, M., El Hage, H., El Rab, M. G., & Khaled, M. (2017). Improving the performance of photovoltaic cells using pure and combined phase change materials–Experiments and transient energy balance. *Renewable Energy, 107*, 567-575. https://doi.org/10.1016/j.renene.2017.02.032

Iranmanesh, M., Akhijahani, H. S., & Jahromi, M. S. B. (2020). CFD modeling and evaluation the performance of a solar cabinet dryer equipped with evacuated tube solar collector and thermal storage system. *Renewable Energy, 145*, 1192-1213. https://doi.org/10.1016/j.renene.2019.06.038

Kazemian, A., Salari, A., Hakkaki-Fard, A., & Ma, T. (2019). Numerical investigation and parametric analysis of a photovoltaic thermal system integrated with phase change material. *Applied energy, 238*, 734-746. https://doi.org/10.1016/j.apenergy.2019.01.103

Panwar, N. L., Kaushik, S. C., & Kothari, S. (2011). Role of renewable energy sources in environmental protection: A review. *Renewable and Sustainable Energy Reviews, 15*(3), 1513-1524. https://doi.org/10.1016/j.rser.2010.11.037

Siecker, J., Kusakana, K., & Numbi, e. B. (2017). A review of solar photovoltaic systems cooling technologies. *Renewable and Sustainable Energy Reviews, 79*, 192-203. https://doi.org/10.1016/j.rser.2017.05.053

Sorkhani, S., Iranmanesh, M., & Gholamrezaei, N. (2022). Damage Detection and Performance Evaluation of Photovoltaic Panels Used in Rural Area through Thermography Analysis. *Biomechanism and Bioenergy Research, 1*(2), 74-79. https://doi.org/10.22103/bbr.2022.20681.1036

Su, D., Jia, Y., Alva, G., Liu, L., & Fang, G. (2017). Comparative analyses on dynamic performances of photovoltaic–thermal solar collectors integrated with phase change materials. *Energy Conversion and Management, 131*, 79-89. https://doi.org/10.1016/j.enconman.2016.11.002

Vigneshkumar, N., Venkatasudhahar, M., Kumar, P. M., Ramesh, A., Subbiah, R., Stalin, P. M. J., Suresh, V., Kumar, M. N., Monith, S., & Kriuthikeswaran, M. (2021). Investigation on indirect solar dryer for drying sliced potatoes using phase change materials (PCM). *Materials Today: Proceedings, 47*, 5233-5238. https://doi.org/10.1016/j.matpr.2021.05.562