Performance analysis of a solar dryer integrated with thermal energy storage using PCM-Al2O3 nanofluids

Babu Sasi Kumar Subramaniam1 · Arun Kumar Sugumaran2 · Muthu Manokar Athikesavan3

Received: 18 May 2021 / Accepted: 7 February 2022 / Published online: 2 March 2022
© The Author(s), under exclusive licence to Springer-Verlag GmbH Germany, part of Springer Nature 2022

Abstract
Solar energy will assist in lowering the price of fossil fuels. The current research is based on a study of a solar dryer with thermal storage that uses water and waste engine oil as the working medium at flow rates of 0.035, 0.045, and 0.065 l/s. A parabolic trough collector was used to collect heat, which was then stored in a thermal energy storage device. The system consisted of rectangular boxes containing stearic acid phase change materials with 0.3 vol % Al2O3 nanofluids, which stored heat for the waste engine oil medium is 0.33 times that of the water medium at a rate of flow of 0.035 l/s which was also higher than the flow rates of 0.045 and 0.065 l/s. The parabolic trough reflected solar radiation to the receiver, and the heat was collected in the storage medium before being forced into circulation and transferred to the solar dryer. At a flow rate of 0.035 l/s, the energy output of the solar dryer’s waste engine oil medium and water was determined to be roughly 12.4, 14, and 15.1, and 9.8, 10.5, and 11.5 times lower than the crops output of groundnut, ginger, and turmeric, respectively. The energy output in the storage tank and the drying of groundnut, ginger, and turmeric crops with water and waste engine oil medium at varied flow rates of 0.035, 0.045, and 0.065 l/s were studied. Finally, depending on the findings of the tests, this research could be useful in agriculture, notably in the drying of vegetables.

Keywords Solar dryer · Thermal energy storage · Nanofluids · Waste engine oil · Drying crops

Introduction
The energy needs of cooking is increasing day by day. LPG, firewood, and other power sources are commonly used as fuel in India. The available fuel is currently expensive and known for low availability in the market. Solar cooking is the best option to cook food as it is free of environmental problems. Noman et al. (2019) developed a polished parabolic trough solar cooker having a concentration ratio of 9.86 which at means absorption of solar radiation in the collector produced a theoretical efficiency range of 50 to 30% under stationary conditions. Asmelash et al. (2014) investigated parabolic trough collector (PTC), installing indoor cooking portions, while outdoor soya bean oil collector parts transferred energy from the absorber through 30-mm copper pipe into the cooking stove. The greatest temperatures were determined to be 191 °C in the mid-absorber loop and 119 °C in the cooker, with a system efficiency of 6%. (Shukla and Khandal 2016) investigated the impact of increased parabolic collector solar intensity on collector exergy output, exergetic, thermal efficiency was increased. The performance of a solar cooker was compared to that of a standard cooker (Chaudhary et al. 2013). In comparison to a standard cooker, a solar cooker with a black painted outer glazing surface stored 32.3% and phase change materials (PCMs) as 28% more heat. Wollele and Hassen (2019) designed a solar cooker that took 45 min to cook 1 kg of rice, with a temperature and power equivalent of 355 K and 421 W absorbed heat from the sun. The same water temperature was reached in 40 min when the solar cooker was put on an insulated tank and filled with water through the
bowl. De et al. (2014) described the approach for reducing “on-stove time” and energy-saving cooking procedures. These trials also revealed the importance of heat sensitivity and the use of only a small quantity of cooking energy. The methods for cooking 1 l of dry rice on the stove, preserving nutrient energy food, and safeguarding the environment by reducing CO₂, as well as hazardous emissions, have all been explained. For a stove without a pressure cooker, the resultant time and energy were 1.5 MJ and 2640 s, respectively. The hazardous emissions linked with all information were addressed using methods for cooking 1 l of dry rice while keeping food nutrient energy and saving the environment by decreasing CO₂. Yahuza et al. (2016) investigated the box-type solar cooker (SC) at 1.5, 1, and 0.5 l of water. With water levels of 1 kg and 0.5 kg, the maximum cooking temperatures were 81.6 °C and 81.7 °C, respectively, with fluctuations dependent on the rise in solar radiation. Ball-akrishnan et al. (2012) tested the arrangement of the parabolic solar oven with emphasis on sunlight in the center of a black-coated metal tray without a glass cover. The greatest temperature reached by this system was 104 °C. Ronge et al. (2016) conducted studies with the cooking system static and tracking systems in a stationary position, achieving a 41.2% output in around 11–12 h and a 27.6% total performance. However, in the tracking position, it performed at 53.1% in 11–12 h and 40.6% overall. This study examines the various methods of solar cooking for reducing CO₂ emissions and increasing the pot’s efficiency. Panwar et al. (2012) investigated the solar cooker’s initial and exit energy at a variety of applications. They discovered that solar energy is the best source of cooking energy. Wang et al. (2014) tested a ten-connected solar collector coupled to a parabolic cooker with a circular concentrator shape. The heat exchanger was a U-shaped evacuated tube attached to the concentrator form. Warm air was injected into the tube, which gradually heated up and flowed into an exchange. The heat exchanger produced an air outlet temperature of over 200 °C, according to the results. AR et al. (2014) designed and built an oven for drying ginger under atmospheric conditions with an evacuated tube solar collector. The temperature ranges for the collector outlet and chamber were 74–130 °C and 50–87 °C, respectively, while the environment temperature range was 29.5–33.2 °C. During the day, the greatest drying efficiency of musket grapes was 29.92%. When compared to natural solar drying, they discovered a collector oven that lowered the drying period from 13 to 6 h. A new solar dryer with an integrated solar collector pipeline was built by Lamnatou et al. (2012). A hot air pipeline passage was incorporated in the solar dryer container without any preheating to dry vegetable products. The collector’s sources of heat for convective, indirect solar drying process are discussed. Kim and Seo (2007) used both practical and numerical methods to investigate solar collector heat output. Four different types of absorbents medium were used in these approaches. These solar collectors demonstrate that absorption medium provides the best heat transfer. Shah and Furbo (2007) developed a computational fluid dynamics model of a solar collector in a glass construction that could be used in a variety of situations. The planned evacuated tube collector was attached to a manifold channel in either horizontal or vertical directions. Under the varied operating conditions, the findings showed just a minor change in energy. Ma et al. (2010) investigated the heat loss coefficient and efficiency factor of individual solar collectors, as well as the copper tube and fin absorption tubes intended for generating energy capacity. The results revealed a nonlinear heat loss coefficient between the absorber surface of the solar collector coating and the ambient air temperature. The overall efficiency of the solar collector heat pipe and the solar collector water-in-glass tube was investigated by Hayek et al. (2011). The heated pipe has a 15–20% better efficiency than the solar water-in-glass collector. Medugu (2010) designed and produced an evacuated solar dryer tube for cardamome drying. The solar dryer produced a temperature of 55.7% higher than the ambient temperature, showing a net saving of 50% in drying compared to the open solar dryer. Gumus and Ketebe (2013) tested drying corn and ogbono at different temperatures of 110 °C, 120 °C, and 130 °C. Drying at 110 °C was shown to be the most effective in generating soft, uniformly dried maize and ogbono under all favorable conditions. To test sliced ginger, Loha et al. (2012) utilized a forced convection type dryer. The experiment was conducted at four different drying air temperatures: 45, 50, 55, and 60 °C, with a pre-defined air velocity of 1.3 m/s. The thermal conductivity of ginger was also investigated under various humidity levels.

**Thermal energy storage system in solar dryer: experimental approach**

Panchal et al. (2019) investigated the utilization of sensitive and latent heat storage materials for daytime and overnight heat storage. Saini et al. (2016) conducted studies employing natural circulation of water and thermal oil medium in a solar cooker with a PTC and thermal storage device. The substance for the storage system was acetanilide. When compared to water, the temperature of the thermal oil was 10 to 24 °C higher, and the heat trapped by PCM was enhanced by 19.45 to 30.38%. Using an oil/pebble-bed (Thermal energy storage) TES simulation model, Mawire et al. (2008) studied indirect solar cooking as an energy source. The variable flow rate was discovered to be useful for cooking since it resulted in less heat loss and the ability to endure a high temperature. Mawire et al. (2010) employed two variable flow approaches to replicate the start and exit capability of a solar cooker.
The variable flow rate was continuously maintained at a greater temperature than the constant flow rate. Very few experimental studies on solar dryer efficiency enhancement with TES are seen in literature, with experimental studies of different flow rates using stored medium of PCM-Al2O3 nanofluids with working medium of water and waste oil. This research examines the solar dryer study, heat output, and productivity of various crops at flow rates of 0.035, 0.045, and 0.065 l/s as a working fluid water and waste oil medium.

**Nanofluids in thermal energy storage: experimental approach**

Despite the existence of many other energy resources, solar energy has been reported as the best alternative to conventional energy by Farhana et al. (2019). Nanofluids could also help solar collectors work more efficiently. This research looks at six different types of solar collector output. The researchers employed nanoparticles such as TiO2, CuO, ZnO, Al2O3, and MWCNTS in base fluids. Saxena and Gaur (2018) investigated the impact of various nanofluids in various solar collectors. The addition of nanofluids resulted in a significant increase in output. Hussein et al. (2008) investigated the ZnO/Ethylene Glycol-Pure Water (ZnO/EG-PW) in a parabolic trough collector with various volume concentrations of 1.0%, 2.0%, 3.0%, and 4.0%. Experimentally, in the 0.3% volume and a mass flow rate of 0.045 kg/s, the maximum collector performance was found to be 62.87%.

Tahmasbi et al. (2020) showed that varied volume fractions of nanoparticles are implemented into multi-block porous media to explore the impact of varying volume fraction values on Nu number. The heat transfer is increased by 20.4 under the optimization condition. The effects of an appropriate working fluid flow rate and absorber tube rotational velocity, according to Amir et al. (2021), increased PTC performance and temperature control of the absorber by about 60% reduction in the fluid-tube temperature difference and 15% reduction in the maximum surface temperature. Furthermore, the PTC’s efficiency has increased by roughly 17%. Teuku Azuar Rizal et al. (2022) demonstrated that cylindrical through collector water heaters could produce 16 l of hot water that could be kept at 40–60 °C for 4 h. The water temperature of the same capacity can be maintained at 40–60 °C for roughly 5 h with the addition of beeswax. This method produced a great outcome, producing up to 60 l of water each day and enhancing the efficiency of solar thermal energy. Milad Tahmasbi et al. (2021) proposed using porous metal foams to cool PV cells and improve thermal and electrical efficiency. The findings showed that using porous media can improve both electrical and thermal efficiencies (between 3 and 4% for electrical and 10 to 40% for thermal efficiency), but at the cost of a pressure loss that damages the system and adds expenditures. To lower the high surface temperature and maximize solar energy absorption, Amir Mohammad et al. (2020) recommended rotating the absorber tube at a specific frequency. In addition, the heat-carrying fluid is a nanofluid (Al2O3-therminol). The effects of several parameters on the collector efficiency were investigated, including rotating speed, absorber tube material, flow rate, and nanoparticle concentration. As a result, the collector’s thermal efficiency can be increased by 15% on average, and the absorber tube temperature can be reduced by 64 K on average. The influence of nanoparticles of copper (Cu) to paraffin wax solid–liquid phase change characteristics of the system performance was explored by Raja Elarem et al. (2021) who combined an evacuated tube solar collector with a nano-PCM with fins. It was discovered that as the fin thickness increases thinner, the PCM melts faster. Halil et al. (2021) deliberated the environmental impact analysis, energy payback time, and CO2 mitigation for the expected lifetime of the system. The performed evaluations indicated that the developed system was a highly efficient technology for the industrial drying process both in terms of energy use performance and environmental sustainability. Mohammad Mahdi et al. (2020) investigated the performance of the lithium-ion batteries storage system using phase transition materials. Nanoparticles, fins, and porous metal foam are utilized alongside PCM to enhance TMS performance, and their effects on system are compared. Sepehr Mousavi et al. (2019) evaluated the presence of a PCM-Al2O3 nanoparticles as well as horizontal radial copper fins in a vertical cylindrical storage unit. The use of nano-PCM (5% Al2O3) and fins (three fins) resulted in a melting time reduction of up to 28.3%. In an active mode experiment, Singh and Gaur (2021) compared the performance of a dryer with and without an ETC. Three high-moisture seasonal crops, tomato, ginger, and bottle gourd, were dried both inside and outside the drier in both cases. For tomato, ginger, and bottle gourd, the average convective heat transfer coefficients for dryers with ETC are 153%, 3.8%, and 305.4% greater than for dryers without ETC, respectively. The overall efficiency of the dryer for the three crops varies between 14.22 and 27.99% for dryers with ETC, and between 9.63 and 24.88% for dryers without ETC. Literature shows the PTC enhanced thermal storage using PCMs – nanofluids attempt as improved the performance.

**Objectives of the work**

By adopting PCMs-Al2O3 nanofluids, this work offers a maximum energy output for drying purposes by increasing the arrangement of the PTC, ST, and SD efficiency. PTC designed an aluminum foil reflecting sheet to gather sun rays...
focused on the receiver coil using a tracking mechanism to improve energy efficiency. To enhance the storage capacity of an energy insulated storage tank that contains a rectangular box enclosed with PCMs-$\text{Al}_2\text{O}_3$ nanofluids—for storing the greatest heat energy, which is then used for the cooking drying process.

**Design of the parabolic reflector**

Figure 1 shows a small-scale model consisting of a metal support frame, a reflecting sheet, and a parabolic trough receiver tube that was designed and fabricated. The reflector’s width and length are 1.5 and 3 m, respectively, and its rim angle is $84^\circ$ in this configuration. This study project seeks to use $4.5\,\text{m}^2$ of thermal energy from the entire space produced collector; the sheet absorbed heat by coating the aluminum foil reflected sheet with any smooth, non-porous surface which can be covered with a rollable reflecting film. This reflector design was concerned with providing a significant cost savings over glass mirrors. The geometrical specifications of the PTC and receiver tube are shown in Table 1.

### Preparation of PCM with nanofluids

The temperatures range from 50 to 90 °C for frying, roasting, and baking foods. Stearic acid has a melting point of 69.3 °C and a boiling temperature of 361 °C as a phase change property. The $\text{Al}_2\text{O}_3$ nanoparticles size distribution revealed a larger concentration of metal and oxides between 10 and 40 nm, indicating that a significant effort was made

| Table 1 | Geometrical parameters of parabolic trough (a) collector, (b) absorber tube, and (c) reflector sheet |
|---------|--------------------------------------------------------------------------------------------------|
| S. No   | Properties                                   | Dimensions   | S. No   | Properties                                   | Dimensions   |
|---------|---------------------------------------------|--------------|---------|---------------------------------------------|--------------|
| Parabolic trough collector | Collector aperture area | 4.5 m² | 1 | Vacuum tube Outer diameter | 0.051 m |
| 1       | Aperture width                              | 1.5 m       | 2       | Receiver tube Outer diameter | 0.047 m |
| 2       | Length-to-Aperture ratio                    | 0.642       | 3       | Vacuum tube inner diameter | 0.043 m |
| 3       | Rim angle                                   | 67.8 °3     | 4       | Thickness of the tube | 0.04 m |
| 4       | Coating absorptance                         | 0.944       | 5       | Length (cover tube) | 3 m |
| 5       | Coating emittance                           | 0.9         | 6       | Materials | AISI type 304 SS |
| 6       | Mirrors reflectivity                        | 0.91        | 7       | Specific heat capacity | 0.5 J/g-°C |
| 7       | Concentration ratio                         | 13.1        | 8       | Thermal conductivity | 16.2 W/m–K |
| 8       | Slope error                                 | rad ± 1 2   | 9       | Melting point | 1400–1455 °C |
| 9       | Specularity                                 | rad ± 13    | 10      | Solidus | 1400 °C |
| 10      |                                             |              | 11      | Liquids | 1450 °C |
| Reflector sheet | Specular reflectance | 94%         | 4       | Water vapor Transmission | Negligible |
| 1       | hemisphereal reflectance                    | 94%         | 5       | Operating temperature | −40 to + 90 °C |
| 2       | Nominal thickness                           | 0.1 mm      | 6       | Temperature difference | 6 to 8 °C |
| 3       |                                             |              |         |                                              |              |

© Springer
to improve heat transmission efficiency. Recent studies have focused on improving the stability of nanofluids in terms of thermal conductivity, viscosity, and heat transfer properties. Nanofluids are more suitable for use in actual heat transfer processes because they have a larger potential for heat transfer improvement. The encapsulated PCM in solid state with a stearic acid seal of 0.3% Al₂O₃ nanofluids is shown in Fig. 2a and b, with Al₂O₃ nanofluids in stearic acid-PCM in 75% of the containers and 25% as a single container free to expand during charging and discharging processes. The storage system was completely isolated using making glass wool insulating materials. A uniform dispersion of Al₂O₃ nanoparticles with SA-PCM was purchased from SWASCO Laboratories, Mumbai. Al₂O₃ nano-powder average particle size was 40 nm. This nano-powder was mixed with a calculated proportion 0.3% in PCM. After coating and sealing, the mixture was melted and poured into rectangle boxes. The digital image of PCM with 0.3 vol% of Al₂O₃ nanofluids is shown in Fig. 2c. In nanoparticles of all concentrations, uniform dispersion and longer dispersion stability were observed. As a result, the prepared nanofluids can help to increase thermal conductivity. Tables 2 and 3 show the thermophysical properties of the PCM, Al₂O₃ nanoparticles as prepared.

### Storage tank

The tank used in the experiment has an 80-l capacity. It was constructed of mild steel with a thickness of 2.5 mm, and its outer surface was entirely insulated with glass wool materials with a thickness of 0.05 m, which was utilized to maintain the stored working fluid temperature and reduce heat loss in the storage tank. A rectangular box encased with PCM-0.3% vol of Al₂O₃ nanofluids (size: 40 cm x 40 cm x 4 mm thickness) was arranged in a parallel manner from the left to the right side of the storage tank in the research work, as shown in Fig. 3a. Using PCM-0.3% vol Al₂O₃ nanofluids throughout the day and in cloudy situations helped to raise the outlet heat transfer fluid temperature. A small PTC-enhanced TES was designed and built at the Chennai, India (latitude 13° 4’ 2.78” North and longitude 80° 14’ 15.42” East). Glass wool materials composed of fiber type insulation as shown in Fig. 3b aid to maintain efficient thermal insulation, shield personnel from hot surfaces, and limit temperature variations, all while enhancing efficiency and providing a safer work environment.

### Table 2 Thermophysical properties of the stearic acid (phase change materials)

| S. No | Properties            | Value/type  |
|-------|-----------------------|-------------|
| 1     | Melting point °C      | 69.6        |
| 2     | Density (g/cm³)       | 0.847       |
| 3     | Boiling point         | 376.1       |
| 4     | Insoluble             | Water       |
| 5     | Insoluble             | Ether       |
| 6     | Freezing points       | 55 to 7 °C  |
| 7     | Chemical name         | n-octadecanoic acid |
| 8     | Chemical structure    | CH₃(CH₂)₁₆ COOH |

### Table 3 Thermophysical properties of the Al₂O₃ nanoparticles

| S. No | Properties                  | 0.3 vol % Al₂O₃ | Uncertainty |
|-------|-----------------------------|-----------------|-------------|
| 1     | Thermal conductivity (W/m/K) | 0.669           | 0.001       |
| 2     | latent heat (kJ/kg)         | 1916            | 0.12        |
| 3     | Specific heat capacity (J/kg K) | 4.026       | 0.01        |
| 4     | Viscosity (mm²/S)           | 4.026           | 0.002       |
| 5     | Density (kg/m³)             | 1.034           | 0.001       |
| 6     | Atomic volume (m³/kmol)     | 0.0055          | 0.001       |
| 7     | Energy content (kJ/kg)      | 0.175           | 0.01        |
| 8     | Bulk modulus (MPa)          | 0.148           | 0.01        |
| 9     | Elastic limit (Kpa)         | 0.350           | 0.015       |
| 10    | Shear modulus (MPa)         | 0.130           | 0.1         |
Crops used in dryer

The solar dried product meets export standards and provides livelihood for farmers. This type of solar dryer plays a significant role in fostering growth in agriculture. This form of the solar dryer can be used for various applications such as dehydration and drying. It not only removes fossil fuels but also helps protection of the atmosphere from toxic emissions and pollution from the green air. Readings were taken from the different agricultural products which included groundnut, ginger, and turmeric. The highest observed radiation intensity was 590 W/m². For prevailing thermal loss, the drying unit consisted of an insulated solar cooker. It allowed the solar cooker’s heated working fluid (water and waste oil) to flow. When the fluid was cooked, it went through the crop, evaporating and drying the moisture. The weight disparity revealed how much liquid had evaporated. Glass wool insulation makes a significant contribution in ensuring efficient thermal insulation, energy consumption, noise pollution, protecting personnel from hot surfaces, and by reducing fluctuations of temperature in buildings, creating a safer work environment, whilst improving personal comfort and efficiency.

Working medium

George et al. (2010) used five samples to examine the lubricating and cooling properties of several multi-grade SAE 20 W-50 engine oil samples. The higher mixing rate of multi-trade oil, as well as the higher specific heat of oil with lower internal energy and less viscous qualities, was shown in the result. The sample with high energy, less viscous lubricates was thought to be better for heat transfer qualities. Table 4 shows the thermodynamic parameters of the working medium of water and waste engine oil.

Mathematical calculations

Temperature distribution between the absorber tube and collector efficiency

The rate of useable heat produced by a solar collector is equal to the rarity of energy collected by the heat transfer fluids minus the direct or indirect heat loss from the surface to the surroundings under steady-state conditions (Kalogirou 1997).

The rate of useful energy collected from the collector of area Ac can be obtained:

\[
Qu = Ac[Gi(\tau_{\alpha}) - UL(T_p - T_a)] = mC_p(T_0 - T_i)
\]  

Table 4  Thermodynamic properties of the waste engine oil and water

| S. No | Properties                        | Waste engine oil | Water          |
|-------|-----------------------------------|------------------|----------------|
| 1     | Boiling temperature               | 400 °C           | 99,974 °C      |
| 2     | Bulk modulus elasticity           | 4.7×10⁹ Pa       | 2.15×10⁹ Pa    |
| 3     | Critical temperature              | 235 °C           | 373.946 °C     |
| 4     | Critical pressure                 | 890 and 960 kg*m⁻³ | 220.6 bar     |
| 5     | Critical density                  | 940 kg/m³        | 0.322 g/cm³    |
| 6     | Latent heat of melting            | 389              | 334 kJ/kg      |
| 7     | Latent heat of evaporation(100 °C)| 145.6 btu/lb     | 40.657 kJ/mol  |
| 8     | Melting temperature (at 101.325 kPa) | 10 to 40 °C | 0 °C = 32 °F |
| 9     | Specific heat                     | 2483 J/kgK       | 4184 J·kg⁻¹·K⁻¹|
| 10    | Kinematic viscosity               | 5×10⁶ kg/ms      | 1×10⁶ kg/ms    |
| 11    | Thermal conductivity              | 0.1314 W/m k     | 0.6            |
| 12    | Prandtl number                    | 84               | 17.8           |
Gi (τα) the solar radiation absorbed by absorber plate (W/m²).

UL(Tp-Ta) The product of the overall heat loss coefficient represents the thermal energy lost from the collector, as well as infrared radiation.

Tp Absorber tube temperature.

Ta ambient temperature.

The thermal efficiency of collector or storage medium is obtained by:

\[ \eta_{th} = \frac{mC_p(T_0 - T_i)}{Ac[Gi(\tau\alpha)]} \]  

(2)

Energy losses for collector

Heat losses to the environment by numerous modes of heat transmission in all thermal systems (Kalogirou 2004):

\[ Q_t = \frac{(T_p - T_a)}{RL} = ULAc(Tp - Ta) \]  

(3)

RL simple resistance = \frac{1}{ULAc}

UL Overall heat coefficient based on collector area (W/m²k).

Energy losses from collector absorber to the glass is the same from the glass cover to ambient

The heat lost from the absorber plate to glass:

\[ Q_{loss} = ACh_p\epsilon_p(Tp - Ta) + \frac{ACr(Tp^4 - Ta^4)}{\left(\frac{1}{\epsilon_p}\right) + \left(\frac{1}{\epsilon_g}\right) - 1} \]  

(4)

h_p_g Correction heat transfer coefficient between the absorber plate and glass cover (W/m² k).

\( \epsilon_p \) infrared emissivity of absorber plate

\( \epsilon_g \) infrared emissivity of glass cover.

Thermal analysis of storage systems

The capability (Qs) of a fluid storage unit at uniform temperature, operating over a finite temperature differential (ΔTs), for fully mixed or deposition energy storage is given by (Kalogirou 1997):

\[ Q_s = (mC_p)\Delta T_s \]  

An energy balance of the storage tank gives

\[ \frac{(mC_p)dT_s}{dt} = Q_s + Q_r + Q_t \]  

(5)

where

Q_s rate of collected solar energy delivered to the storage tank (W).

Q_r rate of energy removed from storage tank to load (W).

Q_t rate of energy loss from storage tank (W).

Utilized energy output for solar dryer

The fluid temperature (Kalogirou 2004):

\[ TF = \frac{(T_p + Ta)}{2} \]  

(6)

\[ Re = \frac{md}{(A\mu)} = \frac{\rhoUD}{\mu m} \]  

(7)

where \( m = \sqrt{UL/k\delta} \)

\[ Nu = 0.0158(Re)^{0.8} \]  

(8)

\[ Nu = \frac{hcD}{k} \]  

(9)

hc = Actual heat transfer coefficient W/m²k

Useful Heat Output (Qu) = \( hcAc(Tp - Ta) \)

(10)

Experimental work

The purpose of the observation was to detect a solar dryer with thermal heat storage and an enhanced PTC, as depicted in Fig. 4 of the rapture and the systematic arrangement of the system as shown in Fig. 5. The system worked by pumping fluid water and waste oil into a parabolic receiver at room temperature via a check valve. Solar energy captured by the parabolic collector was reflected and focused in the receiver, and working fluid flowing via the parabolic receiver was delivered to the thermal storage system via solar energy conversion. Cooking was done with the stored energy.

The entire procedure was continuing from 8.00 am to 8.00 pm. The purpose of the observation was to detect the performance of the PTC-enhanced ST through the use of PCM with 0.3% Al2O3 nanofluids at 0.035, 0.045, and 0.065 l/s flow rate of working medium, as illustrated in Fig. 5. There were two tracks in the system. Initially, the transfer liquid was made in storage system at room temperature. This transfer fluid was pumped into the PTC receiver through a check valve to absorb heat from the receiver and store it in the storage tank. The heat transfer fluid in the ST is pumped into the SD through a check valve in the
other route. The experiment was carried out continuously. The suction inlet of the storage tank was fitted with a 0.5 HP motor-driven pump. It was designed to pump water and engine waste oil at a steady speed. PTC and ST temperatures at the intake and exit were carefully monitored to within ±0.05% utilizing K-type thermocouple sensors at required locations and connected to a data acquisition device (MAX6675) for monitoring.

**Assessment of uncertainty**

An M-parameter quasi-dynamic model can be used to characterize the collector’s performance.

\[
\eta = C_1 P_1 + C_2 P_2 + \ldots + C_m P_m
\]

where \( P_1, P_2, \ldots, P_m \) are quantities, while \( C_1, C_2, \ldots, C_m \) are characteristic constants that derived through testing.

**Dynamic system test method**

The data acquired over a wide range of operating situations is then matched to a transient mathematical model of the collector performance after testing. Given the equation helpful for transient energy equation, the test data are measured every 5–10 min (Morrison et al. 2001).

\[
Q_h = \eta_0 [k_O, B, G_B + k_O, D, G_D] - a_0 (T - T_a) - a_1 (T - T_a)^2 - C (dT/dt)
\]

where \( \eta_0, a_0, a_1, C \) the coefficients are \( k_O, B, k_O, D \) are determined by the test measured data’s correlation.

**Efficiency parameters conversion**

The efficiency is displayed against \( (T_m - T_a)/G_t \) using the average temperature, \( T_m \), which is defined as the arithmetic average of the input and output temperatures.
\[(Ti + To)/2\]. The collector’s instantaneous efficiency is given by in this situation.

\[\eta = Fm(\tau_0) - FmUL(Tm - Ta)/Gt\]

\(Fm\) is the mean temperature collector efficiency factor.

The parameter connected with the result of a measurement that characterises the dispersal of the values that could properly be attributed to the measured is known as measurement uncertainty (Sabatelli et al. 2002).

Uncertainties arise from a combination of uncertainties encompasses the entire measurement, taking into consideration all available data such as sensor uncertainty, data logger uncertainty, and uncertainty arising from any variations between the measured values seen by the measuring instrument (Michaelides et al. 1999). Based on the above relationship, the estimated data’s volatility was found to be 0.12.

**Results and discussion**

The device’s aim was to track the mean heat output value and efficiency of the determined and measured parameters in SD at flow rates of 0.0350, 0.045, and 0.065 kg/s for groundnut, ginger, and turmeric crops under a working medium of water and waste oil. The research was carried out in the fourth week of April 2018, which is noted for its typical Indian summer. The data were performed over a 4-week period, with temperatures ranging from 28 to 40 °C.

**Comparison of heat output of solar dryer**

The aim of this research is to extract heat from a storage tank (ST) that was allowed to pass through a solar dryer for cooking. At flow levels, the SD output in water and waste engine oil was around 4.68 and 5.85 times higher than the PTC receiver and 1.33 times lower than ST. The solar dryer’s charging and discharging procedures recorded energy output values for a water and waste engine oil working medium at flow rates of 0.035, 0.045, and 0.065 l/s, respectively, from 8:00 a.m. to 8:00 p.m. At volume levels of 0.035, 0.045, and 0.065 l/s, solar dryer losses in water and waste engine oil were approximately 0.9 times lower than the ST. At 1.00 pm, the solar dryer output was 8939 W and 11,923 W for water and waste engine oil medium at a flow rate of 0.035 l/s, and 7107 W and 9851 W for waste engine oil medium at a flow rate of 0.045 l/s, respectively. The flow rate of waste engine oil medium was 1.33 times faster than the water output, according to the results. Figure 6 shows energy outputs of 7080, 4808, and 2893 W in the waste engine oil medium in the SD at a flow rate of 0.035 l/s at 6.00, 7.00, and 8.00 p.m., respectively, and outputs of 5686, 3629, and 1777 W at a flow rate of 0.045 l/s.

Due to the lower flow rate, the flow rate for waste oil medium under higher radiation absorption was 0.035 l/s. It also decreased environmental losses and raised the temperature in the storage tank. Because of the difference in temperature between the working fluid and the ambient temperature, there were reduced energy losses to the environment due to radiation, conductivity, and convection losses in the surrounding environment, as well as the occurrence of higher heat flow rates.

The PCM-0.3 Al2O3 vol% nanofluids helped improve heat efficiency by 25 to 35% during charging and discharge, according to the experiment. As a result, the time it took to melt the PCM material was approximately 40 to 50%. When compared to the 0.045 and 0.065 l/s flow rates, the energy storage rate was lower. The higher flow rate was absorbed
when heat was taken out of the flow route, and the increased heat loss was attributable to the surroundings.

**Comparing heat output for crops (0.035 l/s)**

The performance of a solar dryer for drying crops under meteorological conditions was tested. The thermal efficiency of the suggested dryer resulted in a decrease in the moisture content of the crops at different hours. Due to its solar dryer, the recital and quality demonstrated a rapid drying rate that helped to store heat and was more efficient than other drying ways. By measuring crop temperature, researchers were able to assess the heat output and efficiency of a variety of agricultural goods, including groundnut, ginger, and turmeric.

As demonstrated in Fig. 7, the heat output performance of SD crops employing water and waste oil at a flow rate of 0.035 l/s, as well as the heat removal rate and humidity loss, was all higher in the SD system. Groundnut, ginger, and turmeric crops in the SD reached output energy of 738 W, 620 W, and 561 W in the WEO medium, and 701 W, 589 W, and 532 W in the water medium, respectively, at 9.00 a.m. Groundnut, ginger, and turmeric crops in the SD reach output power of 1987 W, 1669 W, and 1510 W in the waste oil medium, respectively, and 1886 W, 1584 W, and 1433 W in the water medium at 1 p.m.

The average discharge of water was 0.94 smaller than the average output of waste engine oil. At 5.00 pm, the SD groundnut, ginger, and turmeric crops had output capacities of 1220 W, 1025 W, and 877 W in the waste oil medium. In the water medium, these were 1158 W, 973 W, and 832 W, respectively. The amount of crop energy absorbed in groundnut was 6 times less than in WEO and 4.6 times less than in SD. This was attributed to heat losses being transferred through several heat transfer processes in the ambient environment. The SD groundnut, ginger, and turmeric crops in the waste oil medium had production capacities of 1220 W, 1025 W, and 877 W at 5.00 pm. These were 1158 W, 973 W, and 832 W in the water medium, respectively. In groundnut, the amount of crop energy absorbed was 6 times lower than in WEO and 4.6 times lower than in SD. This was ascribed to heat losses in the ambient environment, which were transported through several heat transfer processes.

**Comparing heat output for crops (0.045 l/s)**

At a rate of 0.045 l/s, the working media of water and waste oil are compared to the heat output of crops in Fig. 8. Groundnut, ginger, and turmeric crops in the SD obtained output energy of 714 W, 600 W, and 543 W in the waste oil medium at 9.00 a.m.

The water around was 658 W, 553 W, and 500 W, respectively. At 1 p.m., the energy outputs of groundnut, ginger, and turmeric crops in the SD were 1886 W, 1584 W, and 1433 W in the water medium, respectively, and 1921 W, 1614 W, and 1460 W in the waste oil medium, with the water medium output being roughly 1% lower than the WEO medium output. At 1 p.m., the SDs for water and waste oil at a flow rate of 0.045 l/s were 7977 W for water and 11,008 W for waste oil. Due to increased losses of radiation, conductivity, and convection in the surroundings, the absorbed energy by sun dryer was found to be roughly 6, 4.2 times lower than waste oil and water when compared to groundnut, ginger, and turmeric.

**Comparing heat output of crops (0.065 l/s)**

Figure 9 compares the energy output of crops on a water and waste oil medium at a rate of 0.065 l/s. At 9.00 a.m., the

---

**Fig. 7** Heat output of crops with respect to time (0.035 l/s)
groundnut, ginger, and turmeric crops produced 699, 597, and 531 W in the waste oil medium, respectively, and 701, 589, and 532 W in the water medium. At 5 p.m., groundnut, ginger, and turmeric crops produced output energy of 1155, 970, and 831 W in the waste oil medium and 1015, 873, and 730 W in the water medium, respectively. Because of the high volume flow rate, the charge rate for the drying crop was lower than the flow rates of 0.035 and 0.045 l/s, at the same time as the absorbed heat was drawn through the flow path.

At 1 p.m., the outputs of groundnut, ginger, and turmeric were approximately 1882, 1581, and 1430 W in the waste oil medium and 1654, 1389, and 1257 W in the water medium. In the water mean output, it was around 1.14 times lower than in the waste oil medium. When SD absorbed energy output was found to be 5.2, 6.2, and 8.2 times lower than waste oil for groundnut, ginger, and turmeric, and 5.3, 5.9, and 5.6 times lower than waste oil due to radiation, conductivity and convection losses were observed in the surrounding environment, indicating that higher heat flow rates occur at a high heat loss rate.

Comparing the efficiency of crops (0.035 l/s)

Figure 10 illustrates a comparison of crop efficiency in the water medium and waste engine oil at a rate of 0.035 l/s. Groundnut, ginger, and turmeric crops had efficiency of 38, 32, and 29% in the waste oil medium, and 36, 31, and 28% in the water medium, respectively, at 9.00 a.m. The efficiency of groundnut, ginger, and turmeric in the water medium was 73.4, 61.6, and 55.7%, respectively, and in the waste oil medium was 77, 65, and 59%. After 1 p.m., the efficiency values fell due to lower sun radiation
and heat loss in the surrounding area. Crop efficiency for groundnut, ginger, and turmeric crops at a rate of 0.035 l/s at 6.00 pm was 54, 45, and 41% for waste oil, and 51, 43, and 39% for water medium, respectively, and after output at 7.00 and 8.00 p.m., it declined from 4 to 9%. The yield of waste oil was approximately 4% higher than the water medium for all crops.

**Comparing the efficiency of the crops (0.045 l/s)**

Figure 11 demonstrates the efficacy of the crops in the water and waste oil medium at a flow rate of 0.045 l/s. At 9.00 a.m., the groundnut, ginger, and turmeric crops had efficiency of 35, 30, and 27% in the waste oil medium and 34, 29, and 26% in the water medium, respectively. At 1 p.m., the water efficiency was 69, 58, and 52%, respectively, while the waste oil efficiency was 71, 59, and 54%. At 5.00 p.m., the crops on the WEO medium were 56, 47, and 42% efficient, whereas on the water medium, they were 54, 45, and 41% efficient.

After 1 p.m., efficiency values dropped because of a drop in SR and heat loss caused by the environment. The efficiency of groundnut, ginger, and turmeric crops at 0.035 l/s flow rates at 6.00 p.m. was 49, 41, and 37% for waste oil, and 48, 40, and 36% for water medium, respectively, and after its efficiency at 7.00 p.m. and 8 p.m., it declined 8%. The total amount of waste oil produced by all crops was just 3% greater than in the water medium.
Comparing the efficiency of the crops (0.065 l/s)

In the crop efficiency on the water and WEO medium, a flow rate of 0.065 l/s is shown in Fig. 12. At 9.00 a.m., the efficiency of groundnut, ginger, and turmeric crops in the waste oil medium was 35, 30, and 27%, respectively, and 32, 27, and 24% in the water medium. At 1 p.m., the crops were 64, 54, and 49% efficient in terms of water and 71, 59, and 54% efficient in terms of waste oil, respectively. Due to decreasing sun energy and ambient temperature loss, values dropped after 1 p.m. At 5.00 p.m., the crops in the WEO medium were 56, 47, and 42% efficient, while the crops in the water medium were 51, 42, and 38% efficient.

At 6.00 pm, the efficiency of groundnut, ginger, and turmeric crops at 0.065 l/s flow rates was 49, 41, and 37% for waste engine oil and 45, 38, and 33% for water medium, respectively, following their efficiency at 7.00 p.m. and 8.00 p.m. which declined by 4 to 8%. Waste oil output for all crops was 7% higher than in the water medium. Because of the large volume flow rate, the crop flow rate efficiency of 0.065 was lower than 0.035 and 0.045 light/s. At the same time, the radiated heat was drawn out over the flow path, and a greater amount of heat was lost due to the surroundings.

Comparison of results of experiments

According to Tesfay et al. (2014), the stored heat output of 1227.4 kJ per unit is acceptable for drying at a temperature of 180° C. The PCM melted in around 100 min, and the heat stored was 730 kJ, according to the research. The output that was tested was effective in fringing potatoes. The experiment was carried out for 12 h during the

Table 5 Literature survey comparing the efficiency of several nanofluids

| S. No | Authors                        | Nanofluids                                      | Thermal efficiency | Reference No |
|-------|--------------------------------|-------------------------------------------------|--------------------|--------------|
| 1     | Kasaecian et al. (2017)        | 0.2% of carbon dispersed in ethylene glycol    | 75%                | 41           |
| 2     | Mwesigye and Meyer (2017)      | Silver, copper, alumina nanoparticles           | Improved by 13.9%, 12.5%, and 7.2% for silver, copper, and alumina | 42           |
| 3     | Coccia et al. (2016)           | TiO2, SiO2, Fe2O3, ZnO, Al2O3, and Au nanofluid | 63.14, 63.14, 63.12, 63.14, 63.14, and 63.15% | 43           |
| 4     | Mwesigye et al. (2016)         | Copper Nanoparticles                             | Improved by 12.5%  | 44           |
| 5     | Bellos and Tzivanidis (2017)   | Al2O3, CuO, TiO2, Al2O3, and Cu nanoparticles dispersed in base thermal oil Sytherm 800 | Improved 1.75% in nanofluids compare to pure thermal oil | 45           |
| 6     | Bellos et al. (2016)           | Thermal oil, with nanoparticles, and pressurized water | Improved 4.25% by using the nanoparticles | 46           |
| 7     | Potenza et al. (2017)          | Air-disperse Copper dioxide nanopowder          | 65%                | 47           |
| 8     | Present work                   | PCM-0.3 vol % of Al2O3 nanofluids               | Improved by 30% by using 0.3 vol % | 50629        |
PCM-nanofluids storage for charging and discharging process at higher beam radiation time and obtained PTC at higher temperature of 78.7 °C and its corresponding heat output of 2.285 kW and storage temperature of 125 °C and heat output of 13.455 kW, while the crops obtained the highest temperature and heat output of 77.35 °C and 1987 W, respectively. When compared to too much researcher effort, usable heat output and efficiency were higher from the experiment work (Table 5).

**Conclusion**

The performance of solar dryers for drying groundnut, ginger, and turmeric crops for water and waste motor oil medium has been effectively demonstrated at flow rates of 0.035, 0.045, and 0.065 l/sec.

- During the experiment, the waste engine oil medium produced 0.33 times more energy than the water medium at a rate of flow of 0.035 l/sec. The storage medium of PCM-0.3 vol % Al$_2$O$_3$ nanofluids was used in the procedure, which resulted in a 25 to 35% increase in charging and discharging efficiency. Not only that, but it also enhanced the amount of solar radiation needed to melt the PCM-0.3 vol % of Al$_2$O$_3$ nanofluids by about 40 to 50%.
- For both water and waste engine oil medium, the energy output at a flow rate of 0.035 l/sec was higher than the flow rates of 0.045 and 0.065 l/sec.
- At a flow rate of 0.035 l/sec, the energy output of the waste engine oil medium of the solar dryer was found to be approximately 12.4, 14, and 15.1 times lower than the crops output of groundnut, ginger, and turmeric, respectively, and the energy output of the water medium of the solar dryer was found to be approximately 9.8, 10.5, and 11.5 times lower than the crops output due to radiation, conductivity, and convection losses in the surrounding environment, as well as the occurrence of higher heat flow rates.
- At flow rates of 0.035, 0.045, and 0.065 l/sec, the output of groundnut, ginger, and turmeric crops in the waste oil medium was 4, 5.9%, and 5.9% greater than in the water medium, respectively. Due to the high rate of heat extracted out along the flow path and ambient heat losses, the rate of flow output of the crops of 0.035 l/sec was higher than the rates of 0.045 and 0.065 l/sec. At a rate of 0.035 l/sec, it was extremely adaptable for drying food in a variety of conditions.
- Crop efficiency decreased by 11 to 13% when the sunshine at flow rates of water and waste oil medium at 5:00, 6:00, and 7:00 p.m., respectively.

**Nomenclature**

**Abbreviations**

PCM: phase change material; PTC: parabolic trough collector; TES: thermal energy storage

**Symbols**

$I$: solar radiation; $A$: concentrator aperture area; $C_p$: specific heat capacity; $T_i$: collector's inlet temperature; $T_o$: collector's outlet temperature; $T_f$: film temperature; $Q_u$: useful heat gain; $Q_i$: heat in; $Re$: Reynolds Number; $Pr$: Prandtl Number; $L$: length; $d$: diameter; $h$: average heat transfer Coefficient; $N_u$: Nusselt number

**Acknowledgements**

The authors would like to thank the Principal and management of the Kings Engineering College for their assistance in completing this research project, as well as the University Malaysia Pahang for providing financial support through research grant RDU190386.

**Author contribution** Babu Sasi Kumar Subramanian: investigation, project administration, writing original draft.

Arun Kumar Sugumaran: data curation, software, review and editing.

Muthu Manokar Athikesavan: review and editing.

**Funding** There work was funded by the University Malaysia Pahang financial support through research grant RDU190386.

**Data availability** All data are given in the manuscript.

**Declarations**

**Ethics approval and consent to participate** Not applicable.

**Consent for publication** Not applicable.

**Competing interests** The authors declare no competing interests.

**References**

AR, U. S. (2014) Drying kinetics of muscat grapes in a solar drier with evacuated tube collector. Int J Eng 27(5):811–818

Asmelash H, Bayray M, Kimambo CZM, Gebray P, Sebbit AM (2014) Performance test of parabolic trough solar cooker for indoor cooking. Momona Ethiop J Sci 6(2):39–54

Balakrishnan M, Claude A, Arun Kumar DR (2012) Engineering, design and fabrication of a solar cooker with parabolic concentrator for heating, drying and cooking purposes. Arch Appl Sci Res 4(4):1636–1649

Bellos E, Tzivanidis C (2017) Parametric analysis and optimization of an Organic Rankine Cycle with nanofluid based solar parabolic trough collectors. Renew Energy 114:1376–1393

Bellos E, Tzivanidis C, Antonopoulos KA, Gkinis G (2016) Thermal enhancement of solar parabolic trough collectors by using nanofluids and converging-diverging absorber tube. Renew Energy 94:213–222
Chaudhary A, Kumar A, Yadav A (2013) Experimental investigation of a solar cooker based on parabolic dish collector with phase change thermal storage unit in Indian climactic conditions. J Renew Sustain Energy 5(2):023107

Coccia G, Di Nicola G, Colla L, Fedele L, Scattolini M (2016) Adoption of nanofluids in low-enthalpy parabolic trough solar collectors: numerical simulation of the yearly yield. Energy Convers Manage 118:306–319

De DK, Nathaniel M, De Nath N, Ajaero-khekuchukwu M (2014) Cooking rice with minimum energy. J Renew Sustain Energy 6(1):013138

Elarem R et al (2021) Numerical study of an Evacuated Tube Solar Collector incorporating a Nano-PCM as a latent heat storage system. Case Stud Thermal Eng 24:100859

Farhana K, Kadirgama K, Rahman MM, Ramasamy D, Noor MM, Najafi G, …, Mahamude ASF (2019) Improvement in the performance of solar collectors with nanofluids—a state-of-the-art review. Nano-Struct Nano-Objects 18:100276

George NJ, Obianwu VI, Akpan AE, Obot IB (2010) Lubricating and cooling capacities of different SAE 20W–50 engine oil samples using specific heat capacity and cooling rate. Arch Phys Res 1(2):103–111

Gumus RH, Ketebe E (2013) The effect of temperature on drying rate of agro food: Corn (Maize) and Ogbono (Irvingia gabonensis). IOSR J Eng (IOSRJEN) 3(3):36–42

Hayek M, Assaf J, Tleif W (2011) Experimental investigation of the performance of evacuated-tube solar collectors under eastern Mediterranean climatic conditions. Energy Procedia 6:618–626

Hussein EMS, El-Ghetany HH, Nada SA (2008) Experimental investigation of novel indirect solar cooker with indoor PCM thermal storage and cooking unit. Energy Convers Manag 49(8):2237–2246

Kalogirou SA (1997) Design, construction, performance evaluation, and economic analysis of an integrated collector storage system. Renew Energy 12(2):179–192

Kalogirou SA (2004) Solar thermal collectors and applications. Prog Energy Combust Sci 30(3):231–295

Kasaeian A, Daneshzarian R, Pourfayaz F (2017) Comparative study of different nanofluids applied in a trough collector with glass-glass absorber tube. J Mol Liq 234:315–323

Kim Y, Seo T (2007) Thermal performances comparisons of the glass evacuated tube solar collectors with shapes of absorber tube. Renew Energy 32(5):772–795

Lamnatou C, Papanicolaou E, Belessiotis V, Kyriakis N (2012) Experimental investigation and thermodynamic performance analysis of a solar dryer using an evacuated-tube air collector. Appl Energy 94:232–243

Loha C, Das R, Choudhury B, Chatterjee PK (2012) Evaluation of air drying characteristics of sliced ginger (Zingiber officinale) in a forced convective cabinet dryer and thermal conductivity measurement. J Food Process Technol 3(130):2

Ma L, Lu Z, Zhang J, Liang R (2010) Thermal performance analysis of the glass evacuated tube solar collector with U-tube. Build Environ 45(9):1959–1967

Mawire A, McPherson M, Van den Heetkamp RRJ (2008) Simulated energy and exergy analyses of the charging of an oil–pebble bed thermal energy storage system for a solar cooker. Sol Energy Mater Sol Cells 92(12):1668–1676

Mawire A, McPherson M, Van den Heetkamp RRJ (2010) Discharging simulations of a thermal energy storage (TES) system for an indirect solar cooker. Sol Energy Mater Sol Cells 94(6):1100–1106

Medugwu DW (2010) Performance study of two designs of solar dryers. Arch Appl Sci Res 2(2):136–148

Michaelides IM et al (1999) Comparison of the performance and cost effectiveness of solar water heaters at different collector tracking modes, in Cyprus and Greece. Energy Convers Manage 40(12):1287–1303

Mousavi S, Siavashi M, Heyhat MM (2019) Numerical melting performance analysis of a cylindrical thermal energy storage unit using nano-enhanced PCM and multiple horizontal fins. Numer Heat Transfer A Appl 75(8):560–577

Mwesigye A, Meyer JP (2017) Optimal thermal and thermodynamic performance of a solar parabolic trough receiver with different nanofluids and at different concentration ratios. Appl Energy 193:393–413

Mwesigye A, Huan Z, Meyer JP (2016) Thermal performance and entropy generation analysis of a high concentration ratio parabolic trough solar collector with Cu-Thermoln VP-1 nanofluid. Energy Convers Manag 120:449–465

Noman M et al (2019) An investigation of a solar cooker with parabolic trough concentrator. Case Stud Thermal Eng 14:100436

Panchal H, Patel J, Chaudhary S (2019) A comprehensive review of solar cooker with sensible and latent heat storage materials. Int J Ambient Energy 40(3):329–334

Panwar NL, Kaushik SC, Kothari S (2012) State of the art of solar cooking: an overview. Renew Sustain Energy Rev 16(6):3776–3785

Potenza M, Milanesi M, Colangelo G, de Risi A (2017) Experimental investigation of transparent parabolic trough collector based on gas-phase nanofluid. Appl Energy 203:560–570

Rizal TA et al (2022) Integration of phase change material in the design of solar concentrator-based water heating system. Entropy 24(1):57

Ronge H, Niture V, Ghodake MD (2016) A review paper on utilization of solar energy for cooking. Impr Int J Eco- Friend Technol 34

Sabuteli V, Marano D, Braccio G, Sharma VK (2002) Efficiency test of solar collectors: uncertainty in the estimation of regression parameters and sensitivity analysis. Energy Convers Manage 43(17):2287–2295

Saini G, Singh H, Saini K, Yadav A (2016) Experimental investigation of the solar cooker during sunshine and off-sunshine hours using the thermal energy storage unit based on a parabolic trough collector. Int J Ambient Energy 37(6):597–608

Saxena G, Gaur MK (2018) Exergy analysis of evacuated tube solar collectors: a review. Int J Exergy 25(1):54–74

Shah LJ, Furbo S (2007) Theoretical flow investigations of an all glass evacuated tubular collector. Sol Energy 81(6):822–828

Shukla SK, Khandal RK (2016) Design investigations on solar cooking devices for rural India. Distribut Gener Alternat Energy J 31(1):29–65

Singh P, Gaur MK (2021) Heat transfer analysis of hybrid active greenhouse solar dryer attached with evacuated tube solar collector. Solar Energy 224:1178–1192

Tahmasbi M et al (2020) Mixed convection enhancement by using optimized porous media and nanofluid in a cavity with two rotating cylinders. J Therm Anal Calorim 141(5):1829–1846

Tahmasbi M et al (2021) Thermal and electrical efficiencies enhancement of a solar photovoltaic-thermal/air system (PVT/air) using metal foams. J Taiwan Inst Chem Eng

Tesfay AH, Kaysay MB, Nydal OJ (2014) Solar powered heat storage for Injera baking in Ethiopia. Energy Procedia 57:1603–1612

Wang PY, Guan HY, Liu ZH, Wang GS, Zhao F, Xiao HS (2014) High temperature collecting performance of a new all-glass evacuated tubular solar air heater with U-shaped tube heat exchanger. Energy Convers Manag 77:315–323

Woltele MB, Hassen AA (2019) Design and experimental investigation of solar cooker with thermal energy storage. AIMS Energy 7(6):957–970

Yahuza I, Rufai Y, Tanimu L (2016) Design, construction and testing of parabolic solar oven. J Appl Mech Eng

Publisher’s note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.