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REVIEW ARTICLE

Review on phase change materials for solar energy storage applications

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Abstract

The energy storage application plays a vital role in the utilization of the solar energy technologies. There are various types of the energy storage applications are available in the todays world. Phase change materials (PCMs) are suitable for various solar energy systems for prolonged heat energy retaining, as solar radiation is sporadic. This literature review presents the application of the PCM in solar thermal power plants, solar desalination, solar cooker, solar air heater, and solar water heater. Even though the availability and cost of PCMs are complex and high, the PCMs are used in most solar energy methods due to their significant technical parameters improvisation. This review's detailed findings paved the way for future recommendations and methods for the investigators to carry work for further system developments.

Keywords Phase change materials · Solar thermal energy storage · Solar energy

Nomenclature

AHP	Analytic Hierarchy Process
ANN	Artificial Neural Network
ASHPWH	Air Source Heat Pump Water Heater
$CaBr_2$	Calcium Bromide
$CaCl_2$	Calcium Chloride
CASHP	Cascade Air Source Heat Pumps
CHPCSP	Combined Heat and Power Concentrated Solar Power Plant
CSP	Concentrated Solar Power Plant
CFD	Computational Fluid Dynamics
DHW	Domestic Hot Water
DPSAHS	Double Pass Solar Air Heater System
DSG	Direct Steam Generation
EGPHE	Expanded Graphite Paraffin Heat Exchanger
FPSAH	Finned Plate Solar Air Heater
GRNN	Generalized Regression Neutral Network
GSHP	Ground Source Heat Pump
HT	High Temperature
HTF	Heat Transfer Fluid
HVAC	Heating Ventilation and Air Conditioning
ICSSWH	Integrated Collector Storage Solar Water Heater
LHSU	Latent Heat Storage Unit
LHTES	Latent Heat Thermal Energy Storage
LHTESS	Latent Heat Thermal Energy Storage Systems
LPG	Liquefied Petroleum Gas
LT	Low Temperature
LPM	Litres per Minute MAT Matrix Laboratory
MCDM	Multi Criteria Decision Making
MLP	Multi Layer Perceptron
MLR	Multiple Linear Regression
OPCM	Organic Phase Change Material
PC	Prefabricated Concrete
PCM	Phase Change Material
PCM-HX	PCM-Heat Exchanger
PCTS	Phase Change Thermal Storage
PCTSU	Phase Change Thermal Storage Unit
PTC	Parabolic Tough Collector
PV	Photovoltaic
PV/T	Photovoltaic Thermal

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RBF	Radial Basis Function
RH	Relative Humidity
SADDL	Stearic Acid (SA)/1, 10 Decanediol
SDPSAH	Spherical Dimple Plate Solar Air Heater
SAH	Solar Air Heater
SEM	Scanning Electron Microscope
SHSU	Sensible Heat Storage Unit
SHTL	Small Heat Transfer Loop
STPP	Solar Thermal Power Plant SWHS Solar Water Heating System
TES	Thermal Energy Storage
TESD	Thermal Energy Storage Device

Introduction

The energy demand around the world is escalating quickly due to enhanced industrialization and population. Conventional fuels and renewable energy resources are the predominant sources existing to meet the energy demand. However, CO_2 emission, availability of conventional fuel, and global temperature rise are the major problems associated with fossil fuel use. Unconventional energy resources like geothermal, wind and solar energy are abundantly available and have no adverse environmental effects. But, unconventional sources of energy have certain limitations, like solar radiation non-existence during nighttime. A suitable technique is necessary for a solar energy system to store the energy during its availability efficiently. So, solar energy system performance is significant in proper usage and energy storage technologies as solar energy is discontinuous. Heat energy retaining is possible through latent heat, sensible heat, and hybrid methods. In which latent heat storage has a predominant role in effectively storing the available energy during phase transformation. Among different latent heat storage methods, PCMs heat storage technique has a significant impact in effectively storing the energy at a specific temperature during phase change. Many research works have been carried in PCMs energy storage methods around the globe to fulfill the requirements, particularly in storing the available solar energy during the daytime. PCMs investigation started in 1940 and gained popularity nowadays, particularly in solar radiation heat storage applications.

Many authors have presented review articles on phase change materialsbased solar energy systems. Liu et al. (2012) conducted the review in PCMs with high melting temperatures and found that such materials can be used as potential energy retaining mediums. Also, reviewed several possibilities to enhance the heat exchange characteristics of PCMs. Salunkhe and Shembekar (2012) carried a review analysis in PCM encapsulation and its significance in enhancing the thermal performance of energy storage medium. Primary encapsulation factors such as shell material and thickness, encapsulation size, and geometry were investigated completely. Xu et al. (2015) focused on phase change materials for different requirements such as phase-change materials-based TES unit into a power production approach, latent heat storage systems in CSP plants, PCM encapsulation technologies, and economic aspects between sensible and latent heat TES systems. Browne et al. (2015) reviewed various techniques used in the thermal management of photovoltaic modules. Specifically, the use of PCM in the thermal management of structures integrated photo-voltaic systems, photovoltaic, and concentrating photovoltaic were reviewed in detail. Sharma et al. (2015) conducted the review in the encapsulation, materials, and use of organic PCMs and imparted detailed information about modern expansion in the utilization of these materials. Wang et al. (2015) analyzed the research methods and structural characterization involved in solar water heating methods with phase change material. Gracia and Cabeza (2016) provide a detailed study of different numerical models used in a PCM-backed bed system. Alehosseini and Jafari (2020) focused on phase change materials, phase change fibers, and encapsulation techniques in energy retaining solar energy systems. Javadi et al. (2020) conducted a review of the current PCM articles combined with solar thermal utilization. B et al. (2020) reviewed PCM utilization for high, medium and low temperature solar oriented thermal methods and the associated environmental and economic aspects. Yang et al. (2020) mainly focused on the effect of adding nanoparticles in phase change materials. This article provides adequate information about the effect on thermophysical properties of PCM due to the addition of nanoparticles. Also, it elucidates the various applications of nanofluid enriched PCMs in solar still, thermal control units, and thermal energy storage. Yang et al. (2021) discussed heat transfer modeling in PCM, application of PCMs in heat energy management techniques, pharmaceuticals, textile, food, solar, construction, and electrical system. Klimeš et al. (2020) A summary and significant investigation of newly published experimental and simulation methods focused on the supercooling PCMs and phase change hysteresis. Aramesh and Shabani (2020) conducted a review on performance, design parameters, and combined types in PCM-assisted evacuated tube solar collectors systems. Also, summarized the merits and demerits of PCM enriched evacuated solar tube collectors. Liu et al. (2020) conducted review in mathematical models used to elaborate the temperature exchange methods in high-temperature PCM composites and simulate the performance of the retaining heat system. Zayed et al. (2020) focused on design parameters and geometrical arrangement of PCM containers, aiming to increase temperature retaining systems' efficiency. Also, it illustrated the different heat transfer enhancement methods such as the addition of nanoparticles, insertion of fins, doping of high photo thermal materials, use of metal foams and graphite, microencapsulated PCMs. Kumar et al. (2020) illustrated different characteristics of Nano-Enhanced and conventional PCMs combined with the photovoltaic thermal system. Latest innovations with the addition of Nano-Enhanced PCMs in the photovoltaic thermal system and its application in ventilation systems were summarised. Christopher et al. (2021) carried review work in multiple PCMs to suffice a primary perceptive of their efficiency corresponding to heat exchange properties, various geometrical parameters, and the impact of input factors on the efficiency of LHTESS. Wu et al. (2020a, b) analyzed heat energy transmission techniques of phonons in PCM and morphology, preparation methods, and thermal conductivity of synthesized PCMs. Tariq et al. (2020) conducted a detailed analysis on the fabrication techniques and applications of Nano-Enhanced PCMs in thermal energy storage systems, solar Collectors, as a coolant in electronic devices, batteries, and textile engineering. Katekar and Deshmukh (2020) conducted a detailed analysis to investigate the best PCM, which can be used in solar still to attain performance and productivity enhancement. The author states that the paraffin wax amongst beeswax, myristic acid, capric acid, lauric acid, bitumen, stearic acid, and palmitic acid is the significant PCM for both active and passive solar still. Zhang et al. (2021) carried review on latent heat dissipation in porous shape PCMs. Palacios et al. (2019) conducted review in various thermal energy storage technologies employed over past two decades. The review also signifies the thermal energy storage techniques experimentally investigated, demonstrated and utilized in concentrated solar power sector with a specific PCM. Gautam and Saini (2020) reviewed the sensible heat packed bed solar TES for low temperature applications. This review focusses on discussion about packed bed, its thermal analysis techniques, heat transfer distribution within packed bed, different design factors influencing its thermal performance and its analysis based on the exergy and energy efficiency. Koçak et al. (2020) attempts to conduct review in recent innovations carried in sensible TES systems that are used in solar energy applications with a significant focus on sustainability. Researcher also indent to provide sufficient details for further research and development that will make solar energy cost-effective method to meet the developing energy demand of the industrial sector. Asghariana and Baniasadia (2019) focused on modelling and simulation of PCM based systems that are used in various TES applications. A detailed investigation is performed to compare the outputs and suitability of various mathematical models, numerical methods and thermodynamic analysis of using various PCMs in different solar systems. Syeda Laraib Tariq et al. (2020) conducts comprehensive review on the preparation methods and applications of nanoparticle enhanced PCMs (NePCMs) in different domains. This review article intends to provide sufficient details to explore the further applications and essential properties of NePCMs. Saxena et al. (2015) focused on the improvisation carried in different parameters of SAH around the world from the 19^{th} century. Also, it discusses several techniques carried to enhance the efficiency of SAH, such as inserting fins, latent or sensible heat storage medium, concentrators to improve the incident solar rays, combining the PV elements with heaters, and varying the dimensions of solar air heater construction equipment. Muthusivagami et al. (2010) presented the significant work in storage type solar cooker and PCM based solar cooker. Cuce (2013) presented the overview of solar cooking technology, the comprehensive narration of different types of solar cookers, and geometry factors influencing the efficiency of solar cookers. Intense designs of solar cookers by considering and without considering PCMs are described, and additionally, the effective techniques available to improve the output of solar cooking are presented. Omara et al. (2020) presented the impact of using PCMs in solar cooker towards its thermal performance and various parameters which influences lower cooking time. Additionally, the author describes the significance of various heat transfer and geometric parameters of PCM on cooking performance.

Based on the outcome from the literature review, none of the review articles presents an overall idea on the application of PCMs in various emerging topics of solar energy systems. Hence an effort is made in this review article to examine the emerging trends in the application of PCMs in solar energy systems. This review article has been segregated into four chapters to discuss an outline and recent developments on PCMs utilization in solar heat energy. The introductory chapter discusses the introduction of the PCMs, the application of PCM in solar energy systems, and reviews work conducted by several investigators. The second chapter discusses the overview and categorization of PCMs to describe the property of different types of PCMs. The third chapter discusses the application of PCMs in solar thermal power plants, solar desalination, solar cooker, solar air heater, and solar water heater. According to the outcome in the above chapters, the conclusion of PCMs in solar energy systems was revealed in the fourth chapter. The years and number of journals are distributed in Fig. 1. The percentage distribution of the number of journals corresponding to different PCM and their applications are shown in Fig. 2. The overall flow chart of this review article is shown in Fig. 3.

Overview of phase change material

Nowadays, in particular, PCMs are extensively used as heat energy retaining mediums. The novelty of this review article states that the major applications of solar thermal energy storage with the utilization of various PCM has

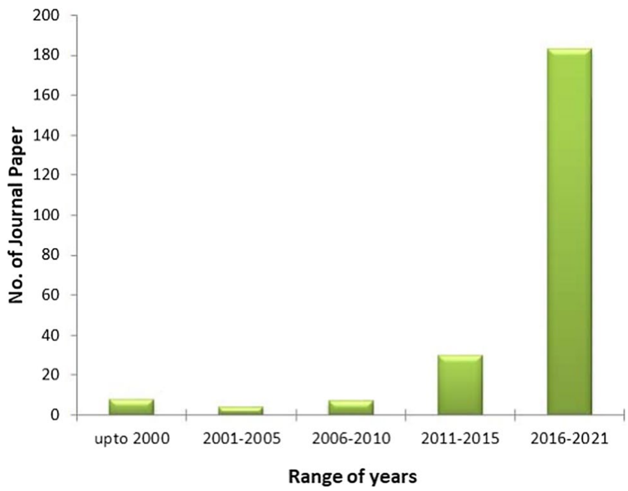


Fig. 1 Distribution of years and number of journal papers

been discussed elaborately. The continuous expanding of thermal properties of various PCM paves the way to utilize different phase change materials in many solar enrgy storage applications. Several researchers conducted numerical and experimental analysis in solar thermal energy storage systems using different PCMs were illustrated in this review article with suitable subheadings and the findings are summarized for immediate understanding and further innovation in this field. The remarkable properties of the PCM makes the application wider when compared to other inventions associated with thermal performance enhancement of solar energy systems. Phase change materials are particularly used as s thermal energy storage medium and it has been widely used in several application in the recent 20 years, yet at the same time the data is quantitatively massive and tough to disclose. Phase change materials have three unique states, namely, solidifying, melting and gasses states where melting and solidifying are the fundamental characteristics. During these states, the PCM have the capacity to retain and dissipate considerable amount of energy. Considering these characteristics, PCMs are applied for retaining thermal energy in many real life applications. However, after reviewing the recent methods and application of PCMs in the solar energy, it is observed that the current methods needs some modifications for improving its features. The main recommendations are improving the thermal conductivity of the PCM using aluminium froth, since the PCMs have low thermal conductivity. Also the thermal energy storage is disposed to adopt a focal part in connecting power to temperature increase and decrease, consequently, the enhancement of proficient modification techniques is intensely vital. Developments of using energy as substance mixes, carbon or non-carbon comprising compound energizes, may probably convene various troubles associated with the energy storage later on energy system. Collectively improving the overall current method by using superior techniques can surely disclose the emerge for a improved energy storage technique in the energy system.

Nowadays, in particular, PCMs are extensively used as heat energy retaining mediums. The utilization of phase change material towards various applications increases continuously due to many recent PCM properties. PCMs have three attractive states: melting, solidifying, and gaseous states, in which solidifying and melting are the primary features. Among these forms, the materials enable to retain and liberate a considerable amount of energy. Owing to these characteristics, PCMs are utilized for absorbing, retaining, and liberate heat in various genuine life applications. Various researchers illustrate the use of PCMs and the parameters involved in developing phase-change materials' performance. Castell (2015) illustrates that, from the primary

Fig. 2 Percentage distribution of the number of journal papers corresponding to different PCM andtheir applications

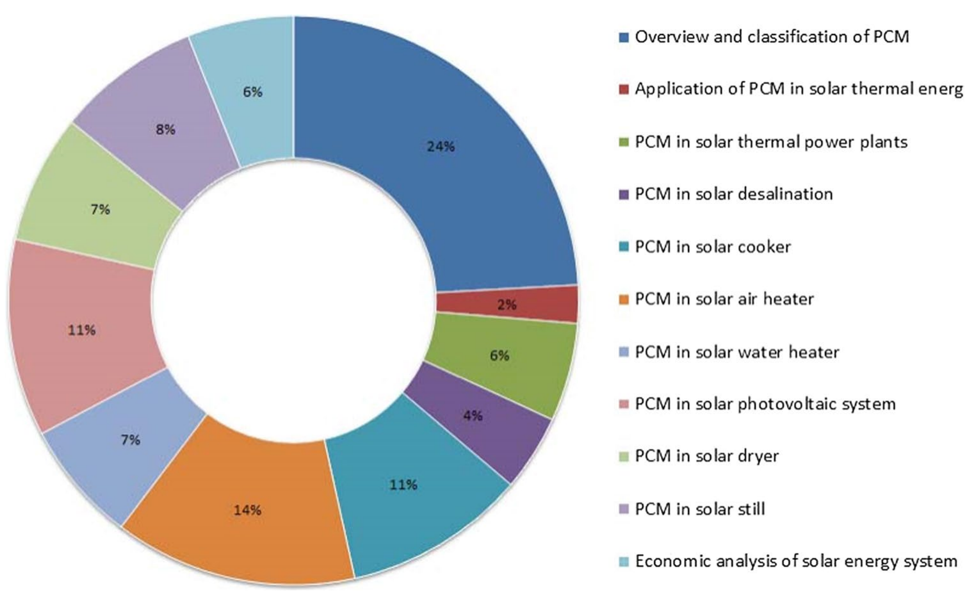
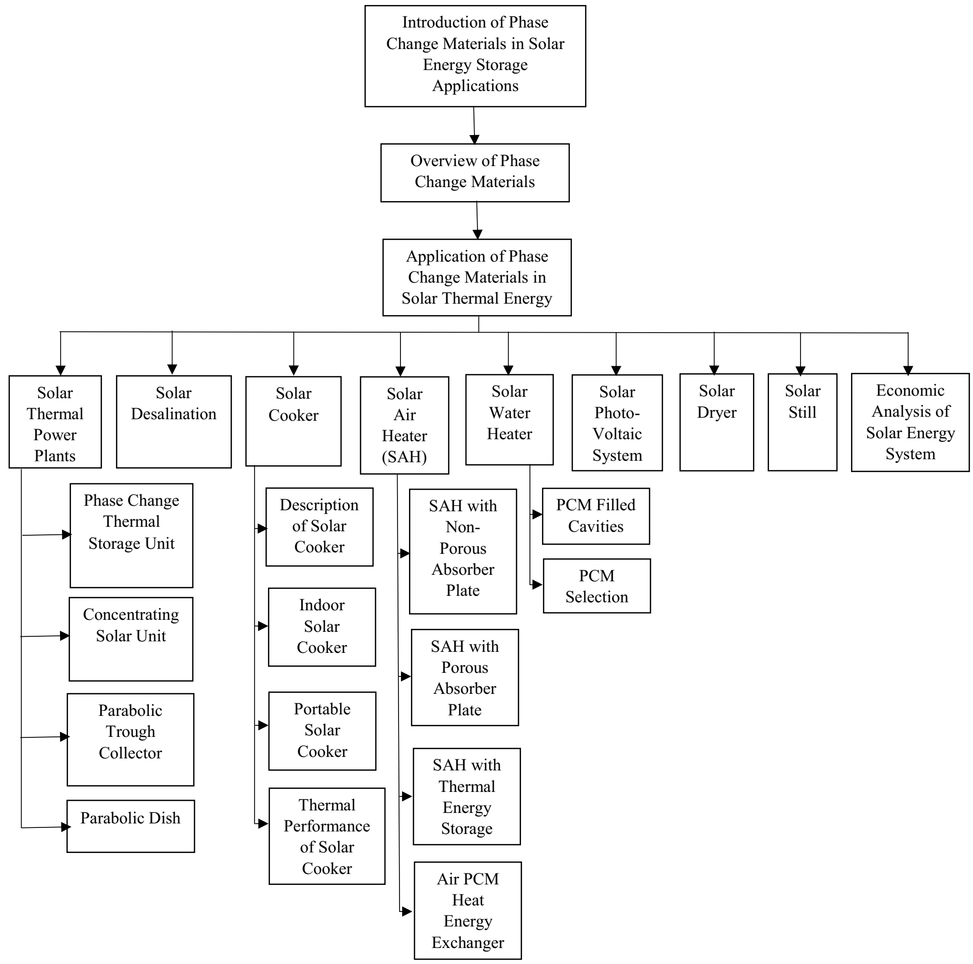


Fig. 3 Overall flow chart of this review article



model to a model developed on the renewable energy transition process, storage of energy can be easily possible. This storage of energy can be easily achieved at a higher rate by PCMs. Subsequently, the developmental processes of phase change material storage systems are still a preventive feature for its operation. Ma et al. (2019) application of phase change material in PV module for thermal directive has fascinated extensive concentration in this region. Maximum photoelectric alteration performance cannot be attained by the fusion of PV-PCM module but by digging out heat energy retaining in PCMs for flow operation.

Classification of phase change material

PCMs are broadly classified into organic, inorganic, and eutectic, which are suitable to retain and dissipate significant energy in a specified range of temperatures. Several organic and inorganic materials in PCM are distinguished based on their melting temperature and latent heat of fusion. PCM is divided into organic, inorganic, and eutectic, which can be accommodated in a minimum space, provide capacity, and dissipate sufficient energy within a specific temperature range. The organic, inorganic, and eutectic PCMs are further classified into several types based on the physical existence, melting point, latent heat, and classification shown in Fig. 4. Castell (2015). No, a unit material possesses many essential properties for a standard heat retaining medium.

Ali and Deshmukh (2020) elucidated the categorization of different salt hydrates and paraffin. According to the disintegrating factors and latent heat fusion, enormous chemically inorganic and organic PCMs were recognized. Farid et al. (2004) illustrate that the inorganic and organic compounds are the two most general groups of PCM. Paraffin waxes, eutectics of inorganic and organic compounds, hydrated salts, fatty acids are the materials that have been significantly considered during the last four decades. The results show that inorganic PCM properties have high thermal conductivity, latent heat per unit volume, the in-flammable and minimum cost in assessing organic compounds. And the properties of organic PCM are non-corrosive, exhibit minimum or zero sub cooling. Sharma et al. (2009) focused and elucidate the classification of inorganic and organic PCM based on the chemical behaviour, thermal behaviour, latent heat fusion and liquefy temperature. And the discussion is

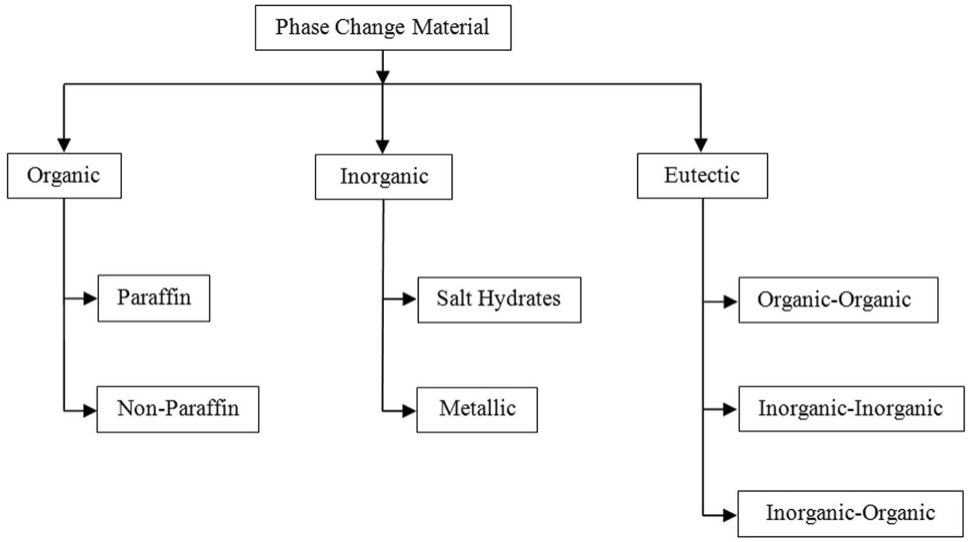


Fig. 4 Classification of phase change material

made on the properties of every sub group creates an impact on the design of LHTESS integrated with PCM.

Organic phase change material

Organic phase change materials are the least cost-effective than inorganic phase change materials. It has a higher fusion collection, minimal latent heat, chemically stable, corrosion-resistant, simple, highly recyclable, and free from under cooling. The stability of the PCM is essential to choose it for a particular application, and it can be done by impregnation of PCM into porous material. Singh et al. (2020) analyzed the heat transfer properties of eutectic organic phase change materials. The microencapsulation method is used to prevent the organic eutectic PCMs from leakage with stable composites. By impregnating phase change materials into supporting/porous material, a different form of stable PCMs have been prepared. The organic PCMs can be used as adequate heat energy retaining and liberating material in a particular temperature range. Sarier and Onder (2012) reviewed the comprehensive development and research studies on the characteristic of organic PCMs, and the result shows that the vast quantity of latent heat is absorbed and dissipated throughout the phase change process when an organic PCM is used, in a definite heat transfer range. Also, the thermal conductivity (K) of phase change material and surface area requirement directly correlates with energy conversion efficiency. Sharma et al. (2015) analyzed the features of the organic phase change materials, and the results show that it requires a large surface area to improve the rate of heat transfer due to its minimum K value (0.15–0.35 W/m K). To keep the exposed region of the system a little bit small, various modifications are considered to improvise the thermal conductivity of the materials. In solar thermal storage media, organic PCMs are highly suitable for food drying due to the lower temperature range of 45 °C –70° C.

Paraffin Paraffin is the essential type of organic phase change material and named paraffin wax. Thermal properties of paraffin waxes is illustrated in Table 1. It has the maximum amount of latent heat capacity, and based on the enhancement in the bonding chain, the melting range of wax gets increased. Paraffin is relatively more nominal cost, reliable, safe and harmless. He and Setterwall (2002) indicated that the paraffin wax consists of straight-chain n-alkanes,

Table 1 Thermal properties of paraffin waxes. Ahmet Sarı et al. (2010)

Paraffin wax	Melting temperature (°C)	Latent heat (kJ/kg)
n-Dodecane	−10	216
n-Tridecane	−5	160
n-Tetradecane	5–6	227
n-Pentadecane	10	205
n-Hexadecane	18–19	237
n-Heptadecane	22	171
n-Octadecane	28	242
n-Nonadecane	32–33	222
n-Eicosane	36–37	247
n-Heneicosane	39–41	201
n-Docosane	42–45	157
n-Tricosane	48.9	142
n-Tetracosane	50–51	160
n-Pentacosane	54	164
n-Hexacosane	56	255
n-Heptacosane	59	159
n-Octacosane	61	202

CH3–(CH2)$_n$–CH3, and they are saturated hydrocarbon mixtures. Both the heat fusion and the melting point increases with an increase in the chain length. There is a tremendous amount of release in the latent heat due to the crystallization of the (CH2)$_n$ chain. Excellent storage systems capital cost investment of enriched paraffin waxes of phase change materials were discussed. Kousksou et al. (2010) elucidated that the paraffin wax has good heat transfer properties such as minimum or zero supercooling, so it acts as the most capable phase change material, and the study is made on the variant concentrations of hexadecane-tetradecane paraffin mixture. The result shows that the temperature range depends on both the maximum composition and heating rate and found that the phase change process takes place in a definite temperature range for the binary mixture. The preparation of paraffin/expanded graphite composite PCM by captivating liquid paraffin into the pores of expanded graphite, posses good thermal conductivity and a significant amount of absorbability by Zhang and Fang (2006). Integration of expanded graphite possesses a significant increase in thermal conductivity and enhances the heat transfer rate of PCM.

Non-paraffin Non-paraffins are abundantly available types of PCMs in nature with a variation in their properties. Thermal properties of non-paraffin waxes is illustrated in Table 2. Each of the non-paraffin materials has variant properties than the paraffin types, but the vital properties were the same. Non-paraffin PCMs are highly combustible, low flash points and unsafe under maximum temperatures. Abhat et al. (1981) investigated the heat exchangers and the suitable latent heat storage for solar heating applications, for instance, hot water production. Impacts of thermal cycling, melting, freezing characteristics and corrosive interaction of 12 substances together with the salt hydrates, fatty acids and kinds of paraffin were studied.

Table 2 Thermal properties of non-paraffin wax PCM. Sharma et al. (2009)

Material	Melting point (°C)	Latent heat (kJ/kg)
Formic acid	7.8	247
Caprilic acid	16.3	149
Glycerin	17.9	198.7
D-Lactic acid	26	184
Methyl palmitate	29	205
Camphenilone	39	205
Docasyl bromide	40	201
Caprylone	40	259
Phenol	41	120
Heptadecanone	41	201
1-Cyclohexylooctadecane	41	218
4-Heptadacanone	41	197
p-Joluidine	43.3	167
Cyanamide	44	209
Methyl eicosanate	45	230
3-Heptadecanone	48	218
2-Heptadecanone	48	218
Hydrocinnamic acid	48.0	118
Cetyl alcohol	49.3	141
α-Nepthylamine	50.0	93
Camphene	50	238
O-Nitroaniline	50.0	93
9-Heptadecanone	51	213
Thymol	51.5	115
Methyl behenate	52	234
Diphenyl amine	52.9	107
p-Dichlorobenzene	53.1	121
Oxolate	54.3	178
Hypophosphoric acid	55	213
O-Xylene dichloride	55.0	121
b-Chloroacetic acid	56.0	147
Chloroacetic acid	56	130
Nitro naphthalene	56.7	103
Trimyristin	33–57	213
Heptaudecanoic acid	60.6	189
a-Chloroacetic acid	61.2	130

Inorganic phase change material

Inorganic PCMs have a maximum heat of fusion, and they are primarily nitrates, salt hydrates and metallics. Inorganic PCMs are readily available and economically feasible. Bao et al. (2020) discussed the features of inorganic PCMs, and the results show that the inorganic PCM has huge melting enthalpy, high thermal energy storage capacity, and inflammability. Due to significant thermal reliability $CaCl_2.6H_2O$ has been considered as an efficient inorganic PCM. The most effective super cooling degree (<1 °C) is obtained by adding a 0.5 wt% flake graphite in CaCl2 6H2O. Li et al. (2013) calculated the enthalpy difference and the melting point of LiCl/ NaCl inorganic salts by an analytical temperature model. This method will provide sufficient information in choosing PCM for solar energy and waste heat recovery. In the succeeding design of a TES system, Schmit et al. (2015) investigated the impact on the maximum storage capacity of $CaCl_2$ $6H_2O$ and $CaBr_2$ $6H_2O$ using different scanning calorimetry. Due to the low cost and high melting enthalpy (190.8 J g-1), $CaCl_2$ $6H_2O$ is the most preferred inorganic PCM in earlier days. The result shows that at a temperature of 15 K, the maximum storage capacity is determined, and the temperature range of calcium bromide + water and calcium chloride + water is 30–45 °C and 25–40 °C, respectively. Thermal properties of fatty acids is illustrated in Table 3.

Table 3 Thermal properties of fatty acids. Sharma et al. (2009)

Material	Melting Point (°C)	Latent heat (kJ/kg)
Acetic acid	16.7	184
Polyethylene glycol 600	20-25	146
Capric acid	36	152
Eladic acid	47	218
Lauric acid	49	178
Pentadecanoic acid	52.5	178
Tristearin	56	191
Myristic acid	58	199
Palmitic acid	55	163
Stearic acid	69.4	199
Acetamide	81	241
Methyl fumarate	102	242

Salt hydrates Salt hydrate is a mixture of inorganic salt and water. After the melting process, it forms either salt hydrates or water particles, and it is a low-temperature phase change material. Wu et al. (2020a, b) analyzed the properties and application of hydrated and crystal hydrated salt PCM. The result shows that the hydrated salt PCM has an appropriate phase change temperature, broadly concerned in the solar energy utilization field, and comparatively possesses a higher latent heat of phase change. A kind of crystal salt carrying crystal water spread loosely and freely around metal ions is known as the crystal hydrated salt PCM. Crystal hydrated salt PCM is used to apply heat energy storage due to its relatively steady thermal properties and high latent heat of phase change and the characteristics elaborated by Erlbeck et al. (2018). Salt hydrates are hygroscopic, corrosive, abundantly available and cheaper (450 €/t, technical grade). Due to its low cycle stability, hygroscopicity and corrosiveness, it is not preferable to PCM, but it can be rectified easily by using appropriate encapsulation. Wang et al. (2017) focused and determined the phase change latent heat of salt hydrate ($Na_2HPO_4.12H_2O$) as a PCM for TES. Sodium carboxyl methylcellulose and alumina powder are selected as a thickening agent and nucleating agent. The results show that the subcooling, phase change latent heat and the phase change temperatures are 4.6 °C, 182.4kJ/kg and 36.0 °C, respectively. Rabin et al. (1995) discussed the application of salt-hydrate phase change material in solar energy retaining. Salt hydrate PCM is used for the solar radiation energy retaining in the ICS system, where it is placed in the collector. Over the immiscible layer of PCM, SHTL floats, and the heat exchanger held over the layer of SHTL have a flow of cold water along its surface.

Metallics It is one type of phase change material with a higher thermal conductivity range, low range of latent heat than the paraffin and high melting temperature. Nguyen and Shabani (2020) analyzed the model of standalone solar hydrogen system along with metal hydride thermal management using PCM. To study the performance of the hydrogen storage system, MATLAB is used to build the dynamic model of the metal hydride hydrogen storage unit. The metal hydride fully absorbs the hydrogen at the proportion generated by electrolyser and by the demand of fuel cell, the absorbed hydrogen gets desorbed.

Eutectic phase change material

A eutectic is the fusion of two or more wedges, each of which melts and stop the blend of part congenially during crystallization. Shen et al. (2020) showed the preparation and the thermal characteristics of the SA-DDL eutectic phase change material. The blending melt technique is used for the preparation of binary eutectic SA-DDL. The results show that the SA-DDL eutectic PCM was best suited for the LHTE storage, and the phase diagram shows the fusion enthalpy and melting point is 247.6 J/g and 56.5 °C at a eutectic point of 86wt% SA. Dong et al. (2018) found out the chances of $CaCl_2$ $6H_2O + NH_4Cl + KCl$ as a PCM by conducting an experiment combined with the computer simulation and determined the quaternary isotherm solubility of $CaCl_2 + NH_4Cl + KCl + H_2O$ at T = 293.15 K by the isothermal method. The result shows that the $CaCl_2 + NH_4Cl + KCl + H_2O$ is an efficient phase change material with the latent heat of 149.6 J/g. Ling et al. (2017) determined the temperature and the effective composition of PCM based on the properties of phase change fusion of $MgCl_2$ $6H_2O$ and $Mg(NO_3)_2$ $6H_2O$ in several ratios. The results show that the eutectic/SiO_2 composite posses enhanced cycle and thermal stability. There is an increase in thermal conductivity about 5% than pure eutectics and by using the fumed silica with $MgCl_2$ $6H_2O$-$Mg(NO_3)_2$ $6H_2O$ stability and thermo-physical properties can be enhanced. Roget et al. (2013) investigated the solid-liquid phase changes in thermal applications of eutectic composition mixtures (LiNO3–KNO3–NaNO3 and LiNO3–KNO3) calorimeter working on huge samples – typically 500 g and with DSC. A narrow revolution of temperature range without hysteresis and probably superior volume enthalpy are the two significant features of eutectic phase change materials. Thermal properties of organic and inorganic eutectics is illustrated in Table 4.

Application of phase change material in solar thermal energy

PCMs are extensively used in heat storage, specifically in the latent heat storage, and it has many new applications in thermal energy storage. Gao et al. (2020) analyzed several properties of rGO modified magnetic phase change

Table 4 Thermal properties of organic and inorganic eutectics. Sharma et al. (2009)

Material	Melting point (°C)	Latent heat (kJ/kg)
CaCl2.6H2O + CaBr2.6H2O	14.7	14.7
Triethylolethane + water + urea	13.4	160
C14H28O2 + C10H20O2	24	147.7
CaCl2 + MgCl2.6H2O	25	95
CH3CONH2 + NH2CONH2	27	163
Triethylolethane + urea	29.8	218
Ca(NO3).4H2O + Mg(NO3)3.6H2O	30	136
CH3COONa.3H2O + NH2CONH2	30	200.5
NH2CONH2 + NH4NO3	46	95
Mg(NO3)3.6H2O + NH4NO3	52	125.5
Mg(NO3)3.6H2O + MgCl2.6H2O	59	132.2
Mg(NO3)3.6H2O + MgCl2.6H2O	59.1	144
Mg(NO3)3.6H2O + Al(NO3)29H2O	61	148
CH3CONH2 + C17H35COOH	65	218
Mg(NO3)2.6H2O + MgBr2.6H2O	66	168
Naphthalene + benzoic acid	67	123.4
NH2CONH2 + NH4Br	76	151
LiNO3 + NH4NO3 + NaNO3	80.5	113
LiNO3 + NH4NO3 + KNO3	81.5	116
LiNO3 + NH4NO3 + NH4Cl	81.6	108

microcapsules (microstructure, optical, thermal and magnetic properties) by different characteristics. The output indicates that the thermal conductivity of magnetic phase change microcapsules is improved by the accumulation of rGO and has minimal effect on phase-change performance in magnetic phase change microcapsules. Abdelsalam et al. (2020) studied the performance of the hybrid and sensible energy storage incorporated PCM with solar domestic hot water integration by conducting the numerical model. The results show that the direct heat exchange method plays a significant role in the thermal storage system incorporated with PCM. Agrawal et al. (2020) found that the heat transfer properties of different PCMs based on variant types of nanoparticles with different mass fractions were used to improve the thermal storage. This paper discussed solar energy storage using variant types of PCMs in thermal energy reservoirs. Fadaei et al. (2018) experimentally studied the impact of PCM on the solar chimney. The experiment was conducted at the University of Tehran. The setup has the chimney whose height and diameter has 3m and 2m, respectively, the radius of the collector is 1.5m and paraffin wax is used as the PCM. Al-Harahsheh et al. (2018) indicates that recently several modifications have been done in solar desalination, such as using different PCMs, phase change materials in conventional solar still integrated with parabolic solar concentrator, phase change materials in flat plate solar field coupled with multi-stage distillation method. The inclusion of PCM in solar desalination improves the period of availability of thermal energy and it subsequently enhances the production rate of any type of solar desalination. Rufuss et al. (2017) found that the NPCM has several enhancements than the phase change materials. The experimental results show that nearly 35% enhancements in productivity when the solar still has a combination of CuO nanoparticles and PCMs. Coccia et al. (2020) attained the ouputs of thermal parameters, which is used to analyze a solar box cooker. When solar cookers are integrated with PCM portable the efficiency of the solar cooker is increased significanlty. John et al. (2015) determined the effects of topping cycle temperature on heat transfer characteristics of galactitol in bulk thermal cycling. At the same time, galactitol is a medium temperature latent heat storage PCM of a solar cooker which provides considerable increase in the thermal performance of the solar cooker.

Solar thermal power plants

Solar thermal plants use solar energy as the primary source of input and produce heat from the sun. The heat absorbed has to be stored in an effective way to regain during necessity. For such reason, the PCMs were used to retain the heat in thermal power plants effectively. Jiang et al. (2018) found that, due to low cost and 626 °C of melting point, the eutectic Na_2SO_4-NaCl salt is used for the solar TES. The SEM analysis of Na_2SO_4-NaCl/α alumina after sintering and 20 thermal cycles is shown in Fig. 5. Specific development is made on the eutectic Na_2SO_4-NaCl salt/ceramic composites to resist corrosion due to the high range of heat in thermal energy storage for STPP. Mao et al. (2018) postulate the better suggestion to consume solar energy utilizing the new heat transfer model extensively. Molten salt used as a working fluid in this method has a considerable negative effect on real-time application. The results show that the overall time for the phase change is about 420 mins, and the melting point of the PCM was found to be 494 Prieto and Cabeza (2019) analyzed the characteristics of the solar thermal electricity plants combined utilizing the phase change energy storage with methodological consideration. Based on the latent energy and the melting temperature of materials, the PCM was organized using four buckets evaluation in PCM energy storage systems. The plant's performance was checked periodically, and the output signifies that the higher performance value of the phase change material system is discarded in trouble and low parasitic losses of the PCM system.

Parabolic concentrated thermal storage unit

A parabolic concentrated thermal energy storage unit contains PCM as a storage medium to store the heat effectively.

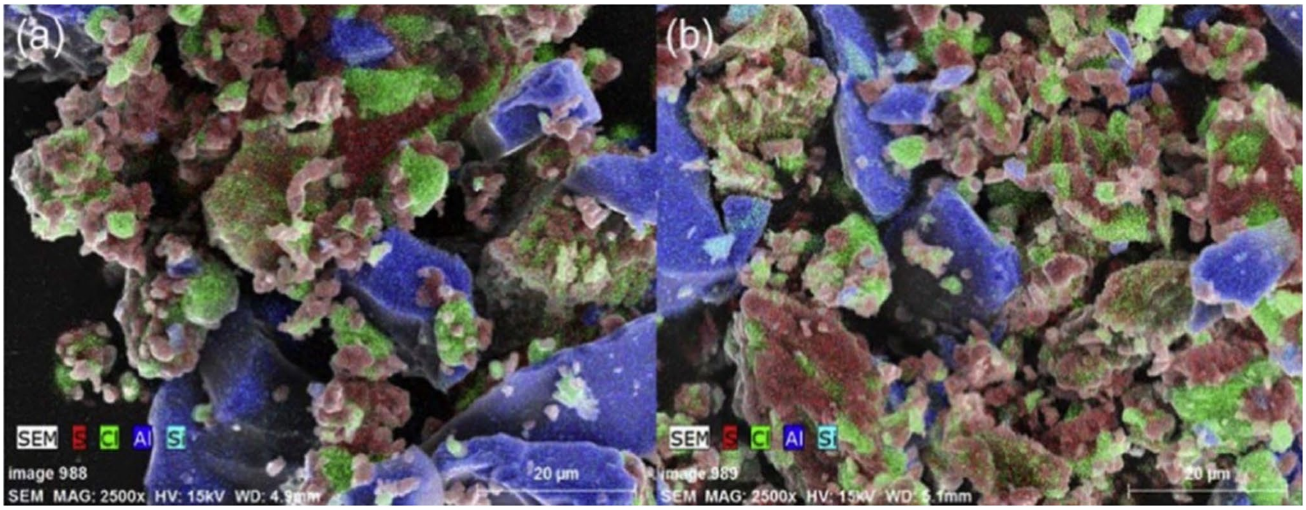


Fig. 5 SEM analysis of Na_2SO_4-NaCl/α alumina after sintering (a); after 20 thermal cycles (b) Jiang et al. (2018)

Senthil and Cheralathan (2019) investigated the development of the heat-retaining ability of a solar receiver using sugar alcohol PCMs in a parabolic dish concentrated solar receiver. The results indicate that the receiver's average energy and exergy efficiencies with PCMs are 14% and 67%. Işık and Yıldız (2020) compared the standard insulated tank and PCM loaded non-finned tank with the newly designed PCM-loaded finned cell-based tank. The inner view of the improved tank with PCM is shown in Fig. 6. The results show that it is more advantageous in-tank efficiency and tank water temperature when the tank is enhanced with phase change material, and the efficiency is increased by 2% in November at 4:00 than the efficiency at 17:00. Liu et al. (2014) studied the performance of the flat plate PCTSU, which is promptly used nowadays. The schematic diagram of the PCTSU showing the PCM containers and circulating fluid channels is shown in Fig. 7. In comparison with ideal sensible heat storage, the liquid sodium can gain 99.4% of electricity to the lattice and the result shows that the liquid fluids are less effective in producing electricity compared with gaseous fluids in phase change material systems.

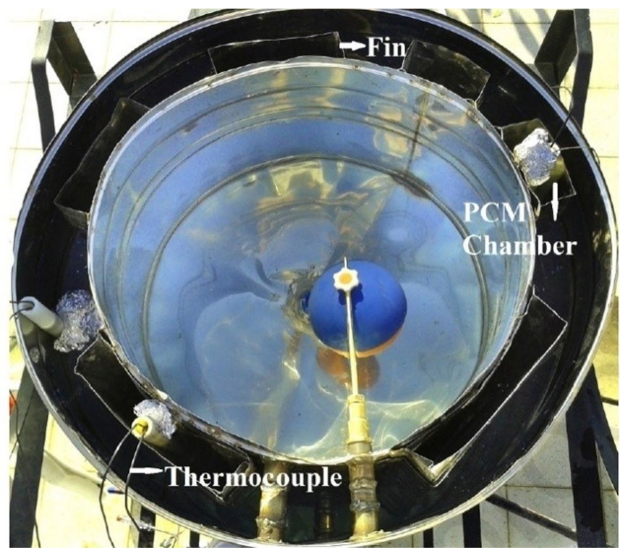


Fig. 6 Inside the improved tank Işık and Yıldız (2020)

Concentrating solar unit

The concentrated solar power system generates electric power at high rates by storing the heat energy and converting it as electric power. The PCMs were used to retain the heat in the storage medium. The properties and the enhancement of the solar unit along with PCM as the storage unit were discussed. Elfeky et al. (2020a, b) focused on the economic and thermal properties in a three-layer thermocline TES tank worn in a CSP plant, based on the impact on PCM volume fraction effect. The result shows that the maximum volume fraction at the bottom part is used to select a concentrating power plant effectively when the three layers thermocline tank is used. Wang et al. (2019) enhanced thermal energy consumption by assembling the concentrating solar power plant and the combined power and heat unit. For designing cooling and heating storage, buildings were incorporated with PCM to produce power saving of interior loads and help achieve the efficient operation of predictable units. The CHP-CSP plant has a reduction in the heat supply cost of incorporated energy and an increase in the output energy compared to the conventional CSP plant.

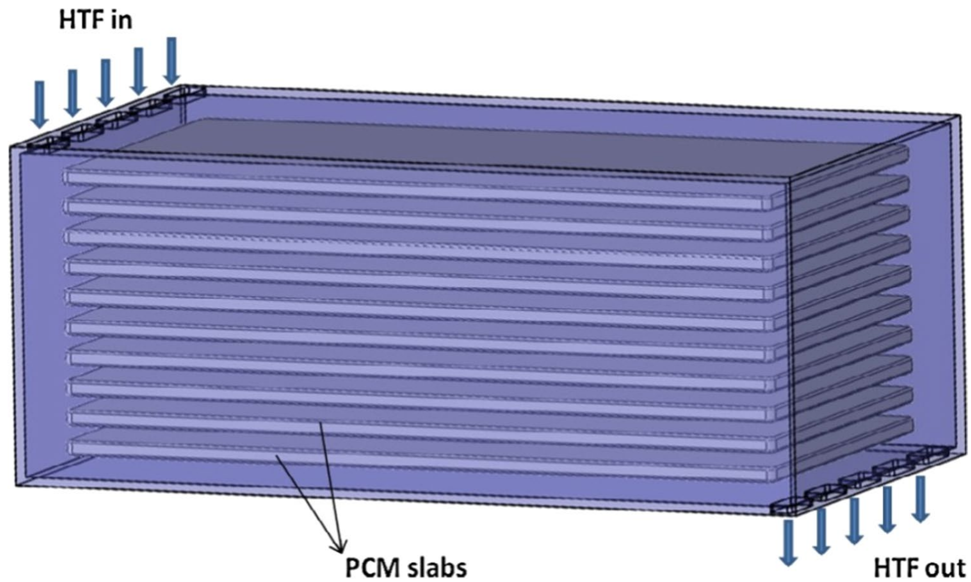


Fig. 7 Schematic diagram of the PCTSU showing the PCM containers and circulating fluid channels Liu et al. (2014)

Parabolic trough collector

The parabolic trough concentrator has a parabolic reflector to reflect the solar thermal radiation to its focal line, which has the working fluid inside the absorber tube situated at the focal point. The heat from the radiation is used to convert the fluid to steam and is used to produce electricity and heat. The heat is stored using phase change materials for future usage. Imam et al. (2016) focused on renovating energy storage into PCM and the solar radiation into thermal energy in the PVT collector arrangement. The results show that the overall efficiency for semi cloudy and clear days is 46%-55% and 55–63%, respectively, and the thermal efficiency for the semi-cloudy and clear days is found to be 40% and 40%-50%, respectively. Kargar et al. (2018) focused the direct steam parabolic trough solar power plant incorporated with TES, which is made of PCM. The results show an increase in output stream quality from 0.2 to 0.5 and a decrease in charging time from 25 to 4.5 h due to the enhancement in the K value of PCM from 0.5 to 5 W/mk.

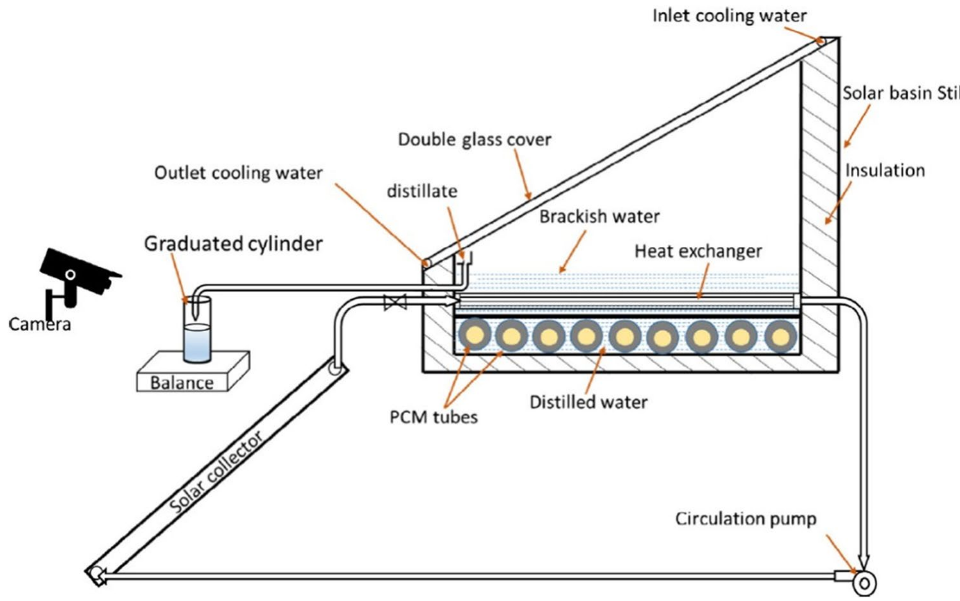
Parabolic dish

The parabolic dish uses solar radiation to generate heat, which can be used for several applications. The parabolic dish focused the radiations in one direction for adequate heating, and the PCM is incorporated to store that heat. A significant quantity of solar power was liberated during the daytime, and some energy was retained for later usage. Senthil (2021) investigated the efficiency of the solar cooker with PCM utilizing a parabolic dish collector whose diameter is 0.9m. Paraffin wax and the internal fins are the two concentric cylinders that are fabricated with a cooker. The investigation results indicate that the mean exergy and energy efficiencies were 2.6% & 22%, respectively, and the time taken of H_2O to attain 90°C with and without phase change material is 2hrs and 1hr 30mins. Lopez et al. (2019) The parabolic dish collector whose working temperature is in the range of low or medium is most preferable for industries. The results show that the cavity-covered receiver's performance is increased by 20% compared to the flat plate receiver with minimal working temperature, and the reduction of temperature is higher than 450 °C at the receiver. Bianchini et al. (2018) monitored the solar thermal parabolic dish system at the exterior enhancement centre of HERA S.p.A. in Forli (Italy) in broad ranges. 11.5 kW thermal values are achieved from the Henergia and a viable concentrating unit, the miniature scale parabolic dish.

Solar desalination

Solar desalination is a process of removal of salt present in the given water sample using solar energy. Recently several modifications have been done in solar desalination, such as using different PCMs, phase change materials in conventional solar still integrated with parabolic solar concentrator, phase change materials in flat plate solar field coupled with multi-stage distillation method. Al-Harahsheh et al. (2018) analyzed solar still coupled with solar collector using PCM. The schematic representation of the modified experimental setup is shown in Fig. 8. The results indicate that the maximum daily productivity was 4300 ml/ day m^2. Kabeel and Elkelawy (2017) evaluated the production rate of solar still enriched with paraffin wax PCM. To enhance the amount of solar irradiance, a parabolic solar concentrator was added, which is absorbed by the still. No other external work is added or removed from the system in a solar desalination system, whereas it is presented from

Fig. 8 Schematic diagram of the modified experimental setup Al-Harahsheh et al. (2018)



the passive type solar desalination system. The experiment reduced salinity from 3000 to 500 ppm and proven that during peak day's energetic efficiency is maximum the expected value. Mousa and Gujarathi (2016) deliberated that the solar stills are used for experiencing a high amount of freshwater during day times. The distillate yield of potable water increases by increasing solar irradiation intensity and using PCM with a higher melting point. Productivity is affected negatively by the presence of PCM with a 40°C melting point. Productivity of 49%could is achieved by decreasing the flow rate from 10 to 1 l/h. Abu-Arabi et al. (2018) considered the excellent arrangement obtained for the unit productivity and temperature profile of basin water. A model is developed to analyze a solar still collected to an exterior-mounted solar receiver using Sodium Thiosulfate Pentahydrate as a PCM. Decreasing the heat transfer coefficient from 10.4 to 2.6 W/m^2K can increase productivity by 100%. Hybrid methods such as flat plate solar field with multi-stage desalination, air conditioning system with humidification-dehumidification desalination unit, solar still integrated with heat storage also provides significant efficiency enhancement. Ghorbani et al. (2020) determined the energy needed for water desalination by coupling a flat plate solar field to a multi-stage desalination system. A TES system is provided to ensure stable working conditions throughout the day. 4500 kg/h hot water and 379.6 kg/h potable water are produced at 65 °C. The cycle's overall exergy efficiency and exergy destruction rate were determined as 63 % and 147 kW and respectively. Wang et al. (2020) confessed the new configuration performance regarding the solar-based desiccant air conditioning system assessed with a humidification-dehumidification distillation unit. An investigation was done under the behaviour of the rotary desiccant wheel. The necessity reveals that regeneration air was preheated before the entry to the desiccant wheel. The best value of distillate water for an air mass flow rate of 0.78 kg/s was about 0.411 and 4.9 l/h, respectively. Asbik et al. (2016) determined the exergy losses during the thermal energy retaining period in solar desalination. Changing the state solid to liquid is done by the phase change material called paraffin wax. Solar still coupled with a latent heat storage system is shown in Fig. 9. The improvement of passive solar still is performed for the minimization of exergy destruction. Abbasi et al. (2019) suggested a solar system for power, potable water and cooling. Based on a novel thermal storage system, the energy required is stored for the night demand as solar energy is not available at that time. Exergoeconomic analysis is performed with dynamic modelling of PCM. It is considered a promising approach. The outcome signifies that the cooling load of the suggested system is 0.71 MW, exergy efficiency is 21 %, while generated distillate and power is 7906 m^3 /day and 5.7 MW PCM to water with various concentrations, preheating with porous material will also have a considerable effect on the productivity of potable water. Mousa et al. (2019) determined the impact of the candle wax as a PCM on the amount of fresh water by using a solar unit. The line schematic of the solar still integrated with PCM tubes is shown in Fig. 10. The varied ratios of mass of PCM to the mass of water are 0, 0.17, 0.35 and 0.51. The appearance of two zones caused by PCM placed in a copper tube immersed in water. Melting of PCM reveals the first zone appearance, and the solidification of PCM reveals the second zone appearance. Elbar and Hassan (2020) studied the optimum preheating flow of salty water. The utilization of porous material and

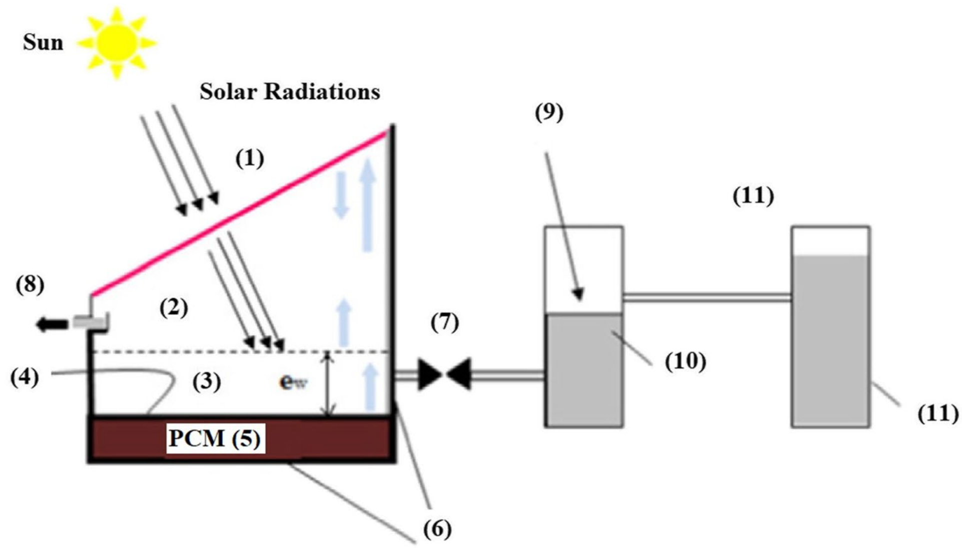


Fig. 9 Schematic diagram: (1) Transparent glass cover; (2) Heated air and steam; (3) Saline water; (4) Basin liner; (5) PCM; (6) Insulator; (7) Non-return valve; (8) Outlet of potable water; (9) Floating water level switch; (10) Input tank; (11) Saline water reservoir Asbiket al. (2016)

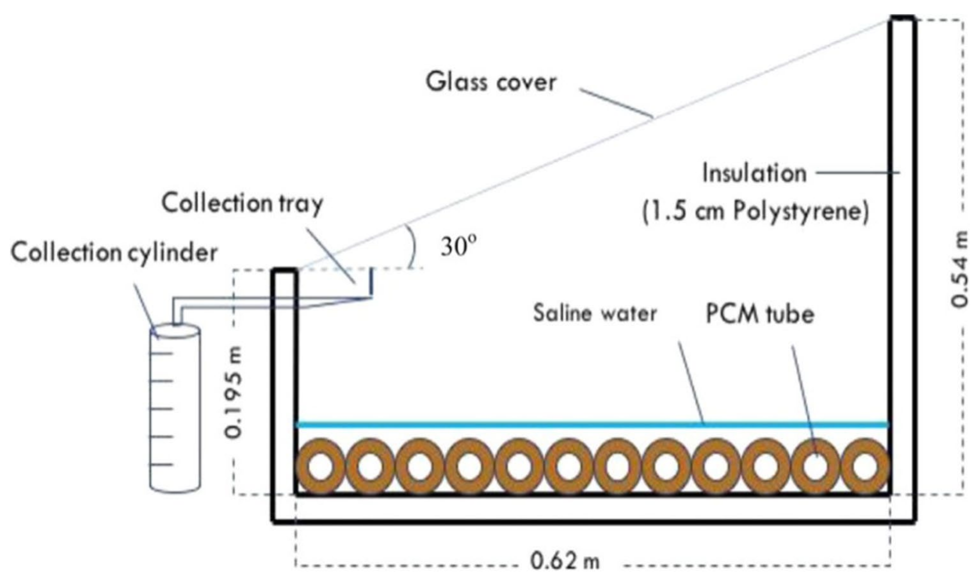


Fig. 10 Schematic diagram of the solar still integrated with PCM tubes Mousa et al. (2019)

saline water preheating is done by the integrated composed solar panel system and solar still. The energy efficiencies of the solar desalination system are 8.2%, 13% and 20%, respectively.

Solar cooker

The need for energy in domestic usage is satisfied by the invention of the solar cooker, which tracks the radiation from the sun and converts it into the form of heat required. There are two types of solar cookers introduced for better performance: indirect solar cooker and hybrid solar cooking system. Coccia et al. (2020) determined the results of main thermodynamic parameters, which is used to analyze a solar box cooker. When combined with TES portable solar box cooker was designed, manufactured and characterized through outdoor tests based on PCM. The PCM utilized is erythritol which is thermal energy storage that contains sugar polyalcohol. John et al. (2015) determined the effects of topping cycle temperature on heat transfer characteristics of galactitol in bulk thermal cycling. At the same time, galactitol is a medium temperature latent heat storage PCM of a solar cooker. The experimental setup for bulk cycling is shown in Fig. 11. Bulk samples have the most significant influence on the degree of subcooling. The amount of latent heat discharge is reduced substantially by the bulk galactitol, which has the degree of subcooling that ranges within 25–40 °C.

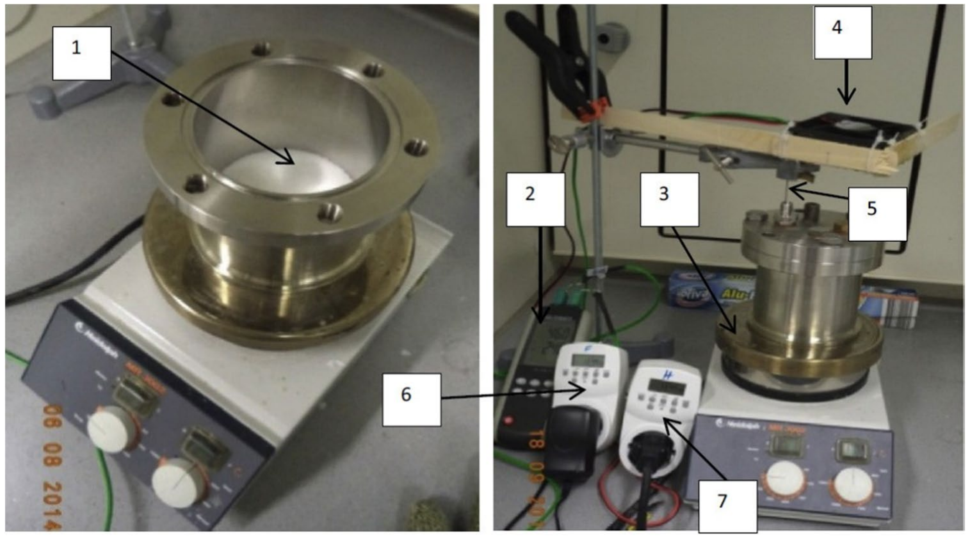


Fig. 11 Experimental setup for the bulk cycling (1) Galactitol sample, (2) temperature data logger, (3) hotplate, (4) electric fan, (5) thermocouple, (6) timer switch (fan), and (7) timer switch (heater) John et al. (2015)

Solar cookers are provided with heat storage systems, and they also have environmental concerns such as reduction in emission of greenhouse gases and eradicate global warming. It has also drawn away to utilize renewable energy sources. HMS. Hussein et al. (2008) under actual meteorological conditions, the construction and testing were done on the indirect SC with integrated indoor PCM thermal storage, flat-plate solar collector, outdoor elliptical cross-section, wickless heat pipes and cooking unit. The cross-sectional side view of the modified solar cooker is shown in Fig. 12. The PCM used is Magnesium nitrate hexahydrate. The merits of the cooker are to heat the meals at night and early morning. Prasanna and Umanand (2011) showed that a hybrid solar oriented cooking system achieves the transportation of solar energy to the kitchen. A thermal energy source does the supplementation of LPG. Dynamic changing of flow rate by using higher power point measuring technique indicates the maximization of energy collected from the sun. The diameter of the pipe improves overall energy transfer. Palanikumar et al. (2019) reviewed to increase the concentration of solar radiation on the cooker. Installations of reflectors were delivered to increase the output of the box-type solar cooker. Experimental verification of temperature change inside the box cavity is evaluated under different periods. Accuracy and the overall efficiency of the solar cooker are 10% and 6.9%, respectively. Mussard and

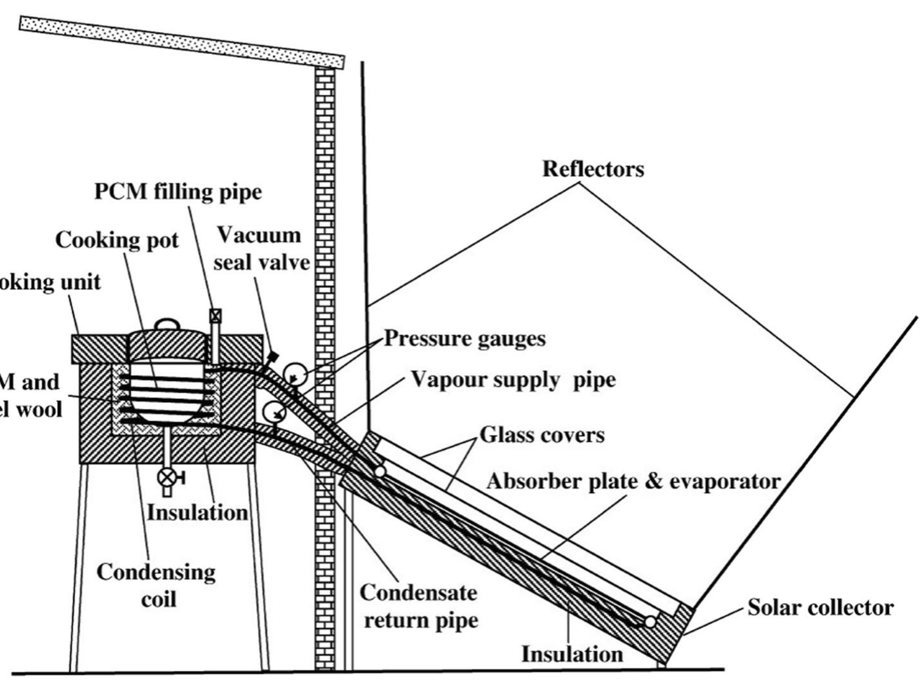


Fig. 12 Cross-sectional side view of the modified solar cooker Hussein et al. (2008)

Nydal (2013) conducted the two charging experiments of solar heat storage. Thermal oil is filled with the coupling of self-circulating solar parabolic trough and heat storage. The main objective of this process is to store heat at a high temperature for cooking. Insulation of absorber tube is done indirectly at first tube and directly at second tube. To store energy with latent heat, nitrate salt is required under the electronic system of the sun. Cuce (2013) focused the geometric parameters affecting the performance characteristics of solar cookers such as heat storage materials, glazing, mirrors, absorber plate and insulation. Analyzation of qualitative evaluation of thermal output afforded by solar cookers and assessment of solar cooking systems in thermodynamics are done. Henceforth, solar cooking technology is considered as a key to deforestation and environmental pollution. Herez et al. (2018) under the implementation of environmental analysis, the main goal is to diminish greenhouse gas emissions. However, solar cookers are served in the reduction of carbon dioxide emissions. Moreover, the solar cooker has a significant effect on cost and ecological aspects. The indirect solar cooker with PCM is shown in Fig. 13. Magendran et al. (2019) showed the excellent properties of organic PCMs. For the preserving process of renewable energy, OPCM combines with the TES system. OPCM is best suited for high thermal energy conductivity applications.

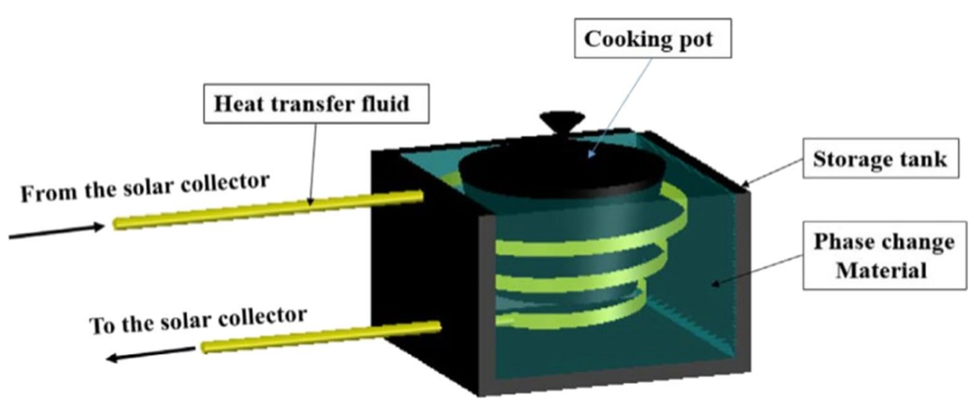
Indoor solar cooker

Indoor solar cookers are used extensively in large households as it is an advanced method in the solar cooker inventions. Solar cookers are provided with a heat storage medium to use under sunshades; as a result, they are incorporated with an evacuated type solar collector and flat-plate solar cooker with concentrating planes along with PCM. Sharma et al. (2005) investigated the evacuated type solar collector. The schematic of the prototype solar cooker and evacuated tube solar collector with PCM storage unit is shown in Fig. 14. The storage of solar energy in heat retaining material during daytime and solar energy utilisation during non-availability of solar radiation is envisaged. Erythritol was used as a PCM, and it was observed that evening cooking was quicker than noon cooking. MRI. Ramadan et al. (1988) analyzed the construction and designation of a simple flat-plate solar cooker with focusing planes and energy storage capabilities. The jacket sand around the cooking pot improves the cooking performance. The heat transfer rate between the source and sink during the investigation period were determined, and 3 hours per day of indoor cooking has been achieved with an efficiency of 28 %. El-Sebaii et al. (2011) investigated the fast thermal cycling of Magnesium chloride hexahydrate on its thermophysical factors such as latent heat of fusion and melting point. It is cycled under the extra water principle in a sealed container to avoid the phase segregation problem. Domanski (1995) determined experimentally that phase change material acted as a storage media for cooking during the daytime. Moreover, two concentric cylindrical vessels were fabricated with 2-cm gaps and the gap was filled by stearic acid PCM. The overall efficiency obtained is 82%. The properties of PCM significantly increased the performance of the cooker in direct correlation with solar intensity.

Portable solar cooker

Portable solar cookers are used as a concentrator which absorbs a considerable amount of radiation and help in converting the justified amount of radiation into heat using reflective materials. The recent works are carried out using a parabolic type concentrator. Lecuona et al. (2013) employed the portable solar cooker with an innovative layout of standard concentrating parabolic type with thermal storage utensil. However, this utensil is made by two typical coaxial cylindrical cooking pots. Conventional heat transfer correlation and a lumped element model are used to evaluate utensil behaviour when subjected to radiation. 115 (2020) is to concentrate the solar radiation and convert heat using different reflective materials. From this experiment, three

Fig. 13 Indirect solar cooker with PCM Herez et al. (2018)



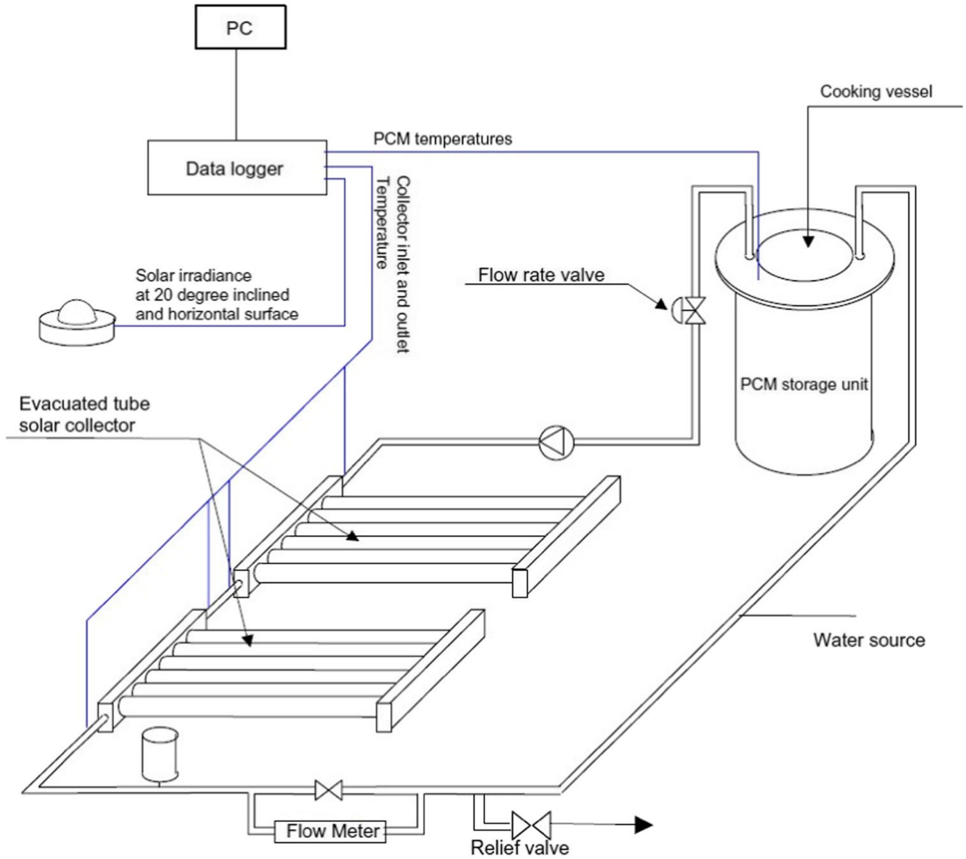


Fig. 14 Outline of the prototype solar cooker andevacuated tube solar collector with PCM Sharma et al. (2005)

various forms of temperature were measured. Initially, the formation of the prototype at 58 °C maximum water temperature was achieved by stainless steel as a reflective material. Then the formation of the second prototype with 74 °C maximum water temperature by an aluminium foil as reflective material. Finally, the third prototype is formed at 74.5 $^{\circ}$ C by Mylar tape as a reflective material.

Thermal performance of a solar cooker

Solar cookers are widely used as a form of renewable energy resource, even though they have some limitations encountered when there is a lack of sunlight produced or received. An alternative method of introducing the TES system is introduced to overcome all such issues, and there could be a high efficiency spotted. To enhance the performance of solar cookers, recent developments were done such as solar box cooker, Quonset solar cooker and single booster mirror. Omara et al. (2020) analyzed the solar cookers using heat storage materials. The main limitation of it is that it can't be consumed during a shortage of sunlight. Henceforth, to overcome this, TES is used. The applications of PCMs improve the performance as a TES medium. The influence of thermal and geometric behaviour is discussed. The overall efficiency obtained is 85%. Solar cooker with PCM storage and equipped with PTC is shown in Fig. 15. Saxena et al. (2020b) proclaimed the solar cookers as a sustainable and renewable cooking system. Fast response and uninterrupted cooking systems are presented by a solar box cooker (SBC). The heat exchange process within the modified solar box cooker is shown in Fig. 15. Under the testing modification of SBC, a cylindrical copper tube is infused with TES. Twelve TES-filled tubes have been brought at the three different levels of configuration and obtained an efficiency of 54 %. Geddam (2015) reviewed the design and development of different soar cookers like oven type, concentrator type and box type. Among these, the box type solar cooker possesses maximum efficiency and thermal performance at a temperature of 100 °C. Sethi et al. (2014) focused on enhancing the performance of the solar cooker by using the parallel shape pipe and a single booster mirror, along with the inclination of an optimally inclined box type solar cooker, especially in winter. The computation is made on the selected latitudes used in the solar radiation capture model and optimal inclination angles to increase the reflected substance of the solar radiation flux that falls on the absorber plate at regular intervals. Khallaf et al. (2020) suggested the solar cooker with minimum and medium temperature cooking activity. The performance factors such as cooking power, cooker efficiency and cooker opt-thermal efficiency are evaluated

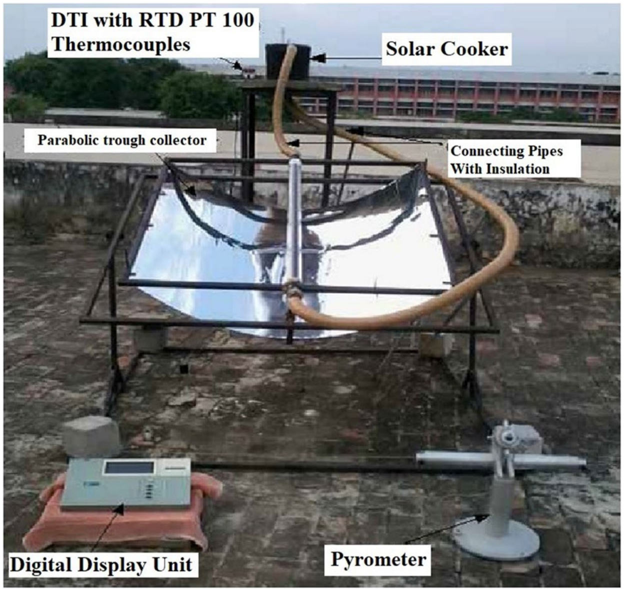


Fig. 15 Solar cooker with PCM storage and equipped with parabolic trough collec- tor Omara et al. (2020)

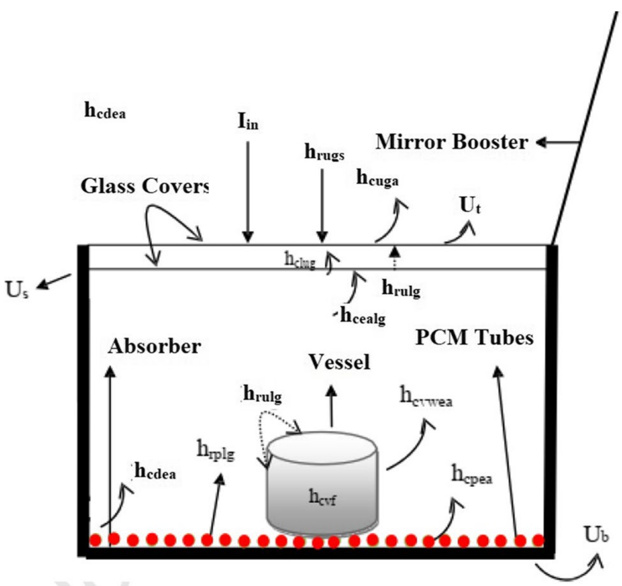


Fig. 16 Heat transfer mechanism within the modified solar box cooker Saxena et al. (2020b)

(Fig. 16). Calculated and measured temperatures have a better arrangement of the cooker elements and other performance parameters. The efficiencies of water and glycerin vary from 6 to 35% and from 9 to 92%, respectively. Sharma et al. (2000) analyzed the designation and development of a solar cooker with a PCM storage unit to store solar power during the daytime. Then the absorbed and retained power was utilized for cooking food in the evening. Whereas, the latent heat storage material used here is acetamide. The comparison of a PCM storage unit with a standard solar cooker reveals the thermal performance. Hence, the conclusion reveals that the solar cooker having a PCM storage unit has better thermal performance characteristics. Kumaresan et al. (2016) focused on the efficiency of a double-walled cooking unit appropriate for an indirect type solar cooking application incorporated with TES. The setup consists of the storage tank, positive displacement pump, cooking unit and the heat transfer fluid as D-Mannitol and the Therminol 55. The result shows that the temperature of the olive oil in the baking setup was 152 °C, and it has very little time consuming, i.e. 15 minutes relatively less than conformist liquefied petroleum gas stove. Sagade et al. (2018) Found that the cooking rate is more effective in the solar cooker having the intermediate temperature (120–240°C), and it has the variant range of cooking option, which minimizes the time of cooking with the higher range of thermal losses. Testing is made on the two variant solar thermal cookers to serve the function with Cooker Opto-Thermal Ratio (COR) as a thermal performance parameter (TPP). MAWIRE et al. (2008) conducted the performance prediction of the TES system in two different ways, namely energy and exergy analysis. Here the TES material is an oil pebble. Energy efficiencies using both methods are differentiable. At a higher level of solar radiation, fixed temperature techniques possess maximum exergy efficiency.

Solar air heater

Solar power is the most effective non-conventional source, and it can be effectively used in solar thermal applications. A solar air heater is used to improve air temperature using available solar energy from the sun. The primary applications of solar air heaters are heating of buildings and drying of agricultural products. To enhance the efficiency of SAH, many modifications have been done along with paraffin wax as a PCM, such as pinned blade, incorporation of DPSAHS. Saxena et al. (2020a) attempted to increase the output of SAH. To enhance the performance of SAH, two models have been created; and the first one is the reference model SAH-A and the second is adjusted model SAH-B which is incorporated with paraffin wax as a PCM for energy storing purposes. Then the SAH-B is further revised into SAH- C by adding some granular carbon powder with paraffin wax. The result shows that the SAH-C is the most economical and optimum model for several heating applications. Figure 17 shows the different elements of the modified SAH. Salih et al. (2019) analyzed the impact of solar irradiance force and air mass stream rate on the thermal performance of the double pass solar air heater contained with paraffin wax-PCM. The outcome of this research work indicates that the enhancement inflow rate of air results in lagging of melting time and reduces melting temperature of the paraffin.

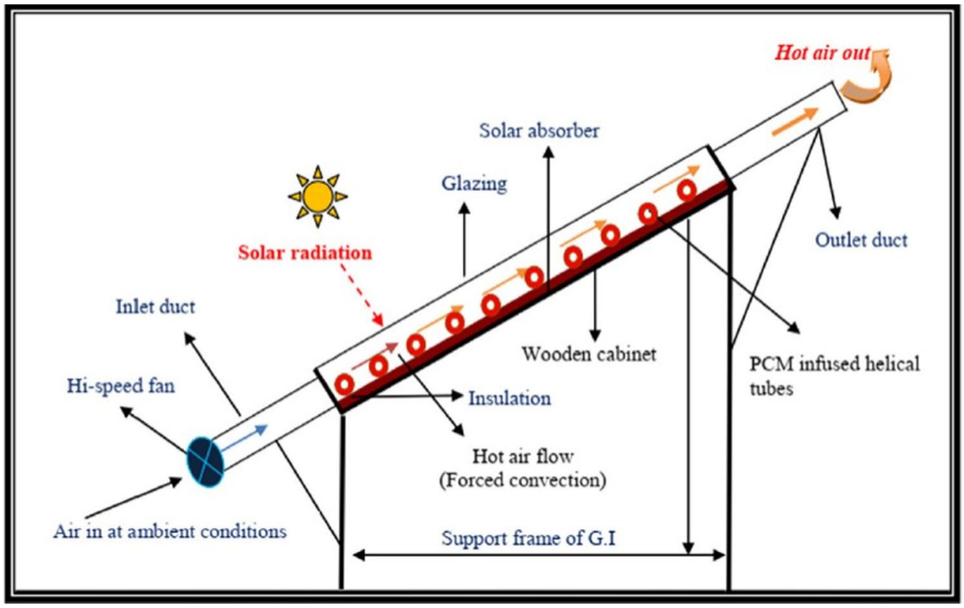


Fig. 17 Schematic view of modified solar air heater Saxena et al. (2020a)

Karthikeyan et al. (2021) focussed the efficiency improvement of SAH by utilizing paraffin wax PCM stuffed in a pinned blade on the absorber surface. The result shows that the exergy efficiency increases from 1.3 to 1.8 % to increase the mass flow rate from 0.037 to 0.043 kg/s. El Khadraoui et al. (2016) the conducted study to enhance the efficiency of a SAH by using paraffin wax phase change material. The schematic section and dimensions of modified SAH with PCM is shown in Fig. 18. Utilizing PCM in the SAH significantly enhances the daily energy efficiency. Results indicate that the daily energy efficiency of the SAH without and with PCM is 17 % and 33 %, respectively. Moradi et al. (2017) experimentally investigated the efficiency of SAH with paraffin wax PCM based energy storage. The result shows that increasing the thermal conductivity of the paraffin wax PCM results in more significant nocturnal temperature differences between the inlet and the outlet of the solar air heater. Raj et al. (2019) focussed on supporting the thermal reaction of the double-pass solar air heater system by the thermal slack of paraffin wax PCM. An average encapsulate efficiency of 67% and 47% were obtained for cylindrical and rectangular macro-encapsulates equipped DPSAHS with PCM.

Solar air heater with the non-porous absorber plate

The incorporation of a non-porous absorber plate in SAH enhances the thermal performance of a solar air heater. So the enhancement in the efficiency of the non-porous absorber plate creates a significant impact on the SAH performance. Improvement in SAH efficiency due to the inclusion of non-porous absorber plate is achieved by performing various modifications such as composite absorber, eliminating airflow above the absorber. Dissa et al. (2016) analyzed solar air collector with composite absorber and explored in

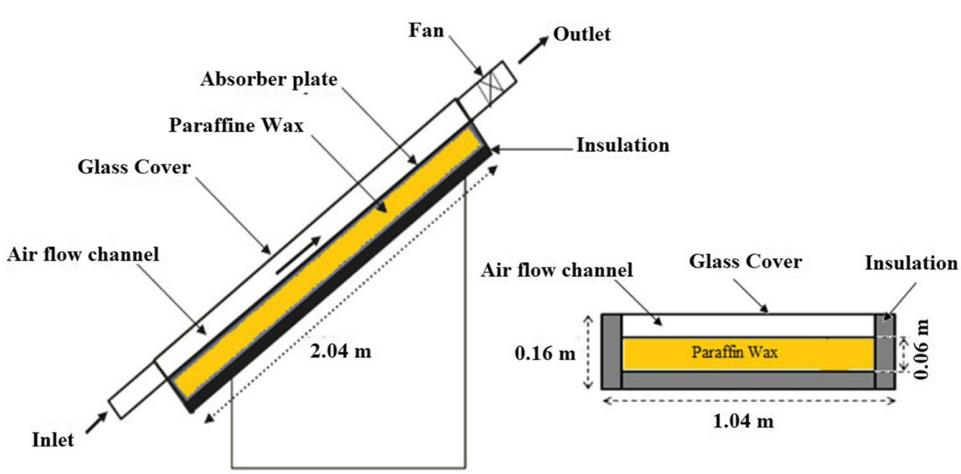


Fig. 18 Schematic section and dimensions of modifiedSAH with PCM El Khadraoui et al. (2016)

different possibilities and the result shows that the mean thermal efficiency reaches up to 61% at sunlight based late morning with the maximum temperatures of 142, 107, 77, and 73 °C separately for non-porous, porous absorber, glass cover and air stream. The result shows that both the unsteady state and the experimental temperatures were very close, and unsteady state techniques were used to predict collector performances. Saxena et al. (2015) analyzed SAHs since 1877 up to now, with a brief look at some novel licenses. The present investigation reports that solar air heaters' efficiency can be increased by adopting the fins with various geometrical shapes, integrating photovoltaic elements with the heaters, using concentrators to receive the available solar radiation, and using sensible or latent heaters energy retaining medium.

Solar air heater with the porous absorber plate

To improve the efficiency of solar air heaters with porous absorber plate, various modifications were carried out, such as a new solar collector with the cone-shaped surface, SAH with thin porous plate, different types of composite wall, finned plate, spherical dimple plate and porous wire screen. Zhang et al. (2021) summaries the utilization of PCMs to retain and expels heat and can significantly meet the energy demand. However, it affects leakage problems and minimum thermal conductivity. The author addressed that the practical solution combines porous supports and PCMs to fabricate shape-stabilized phase change materials. Rajarajeswari et al. (2018) suggested and conducted the experimental analysis on porous and non-porous SAH for the heat transfer and frictional factor characteristics. The result reveals that better performance is achieved at a mass flow rate range of 0.02–0.055 kg/s. Abuska (2017) studied a new solar collector experimentally with the cone-shaped surface with a flat absorber plate, and the result shows that the new design has a significant enhancement of performance that the flat plate absorber. The modified absorber plate with the conical surface can be used as an energy-efficient enhancement option for solar air heaters. Results indicate that the efficiency of SAH primarily depends on solar radiation, surface structure of absorber plate and mass flow rate. Jouybari et al. (2019) analyzed the impact of covering the absorber plate of a solar air heater with a thin porous media. The most significant expansion in the thermal and thermo-pressure driven exhibitions is more than multiple times those got in a solar air heater without a porous medium. The outcome reveals that the heat exchange by conduction in the porous medium highly affects the thermo-hydraulic performances of the solar heater. Ghritlahre and Prasad (2017) utilized Artificial Neural Network to analyze the thermal performance of unidirectional porous bed solar air heater. Levenberg-Marquardt training function is the optimal function for predicting the best performance of porous bed solar air heater for selected MLP ANN model. Ghritlahre and Prasad (2018) four distinct sorts of neural models (MLP, GRNN, MLR, and RBF) have been utilized to analyze unidirectional flow porous bed solar air heater performance. The results obtained by utilizing ANN models are superior to the measurable MLR model. Li and Chen (2019) conducted analysis between the porous layer without and with PCM encapsulated granular capsules in the composite wall for heating. And in comparison with the granular capsules-consisted porous layer without PCM, 20 % enhancement of mean temperature at night time can be achieved in the heating room using a solar air heater when the PCM is packaged in the porous layer. Perwez and Kumar (2019) analyzed the thermal performance of an FPSAH and SDPSAH at different mass flow rate conditions. The output signifies that the maximum efficiency of the SDPSAH is about 35 % greater than the corresponding FPSAH. The experimental setup of modified SDPSAH and FPSAH is shown in Fig. 19.

Solar air heater with thermal energy storage

Thermal energy storage is a device used to absorb and retain energy in the form of sensible heat and latent heat. TES system increases SAH efficiency using paraffin wax PCM, packed bed LHTES filled with encapsulated PCMs, hybrid natural circulation type SAH with TES. Abuşka et al. (2019) analyzed the efficiency and the impact of using honeycomb as an interior fin structure in PCM panel. The heat storage has been tested in two forms, the first heater is only with a PCM, and the second heater is incorporated with honeycomb and PCM. Comparison is made by the third heater, which has a flat absorber plate without PCM. The comparison reveals that the incorporation of honeycomb with PCM decreases the charging and discharging time. Raj et al. (2020) analyzed the relationship between efficiency of solar air heater enriched PCM with significant parameters like wax quantity, heat input, melting temperature and flow velocity. Kabeel et al. (2016) investigated the two typical absorber plates such as conventional flat and v-corrugated of SAH incorporated along with PCM and LHTES, where the PCM material is paraffin wax. The result shows that the v-corrugated plate with PCM is more significant in the improvisation of SAH performance, and there is an increase in daily efficiency by 12% than the v-corrugated plate without PCM. Raul et al. (2018) focused the performance and thermal analysis of packed bed LHTES filled with encapsulated PCM. During discharging and charging period, the enhancement of HTF flow rate results in more energy. The enhanced thermal efficiency is from 62 to 64 %, enhancing the HTF flow rate from 7.1 to 9.3 lpm. BA. SunilRaj and Eswaramoorthy (2020) conducted an experimental study for drying of capsicum at outdoor conditions by SAH with thermal energy storage. On

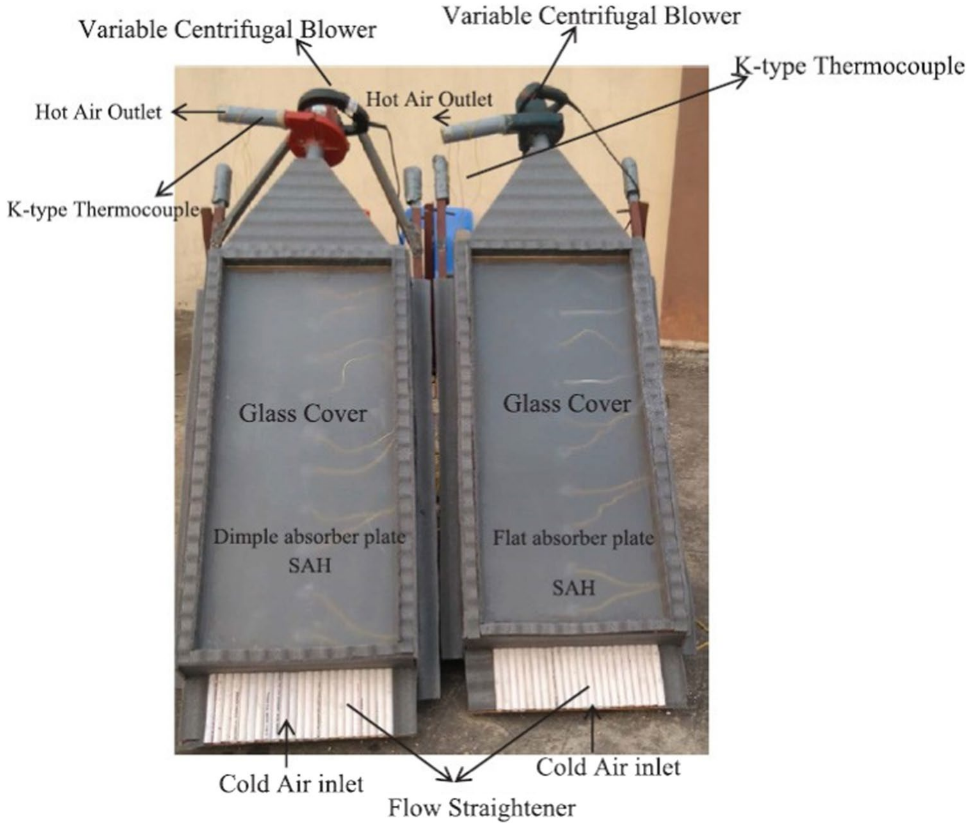


Fig. 19 Experimental setup of SDPSAH and FPSAH Perwez and Kumar (2019)

the hourly basis results of experimental test value, the thermal efficiency of SAH varies from 12% to 65%, with a ratio of 0.90. Wadhawan et al. (2018) manufactured the TESD and incorporated it with the SAH to enhance the performance of the SAH. The output temperature and the pressure drop are estimated by the comparison of SAH with and without TESD. The result shows that the output air temperature reduces from 8.67 to 4 K with enhancement in mass flow rate of air from 0.02 to 0.035 kg/s.

Air phase change material heat energy exchanger

Heat transfer between two or more fluids in a system is termed a PCM heat exchanger. PCM heat exchangers are utilized in both heating and cooling and cycles. A strong wall might isolate the liquids to direct contact. Jmal and Baccar (2018) numerically investigated the solidification of the horizontally arranged rectangular module with vertical fins. During the destocking phase, the use of RT27 paraffin composites suits best instead of paraffin C18 in the transfer of heat. Mohamed Dardiret al Dardir et al. (2019) suggested the development of the numerical model, which contains four sub-models: namely, thermal storage in PCM, thermal radiation, conduction and convection. The result reveals that the system promotes an increased cooling charging potential under an insufficiently lower temperature. Garg et al. (2018) analyzed the characteristics of the encapsulated PCM based heat exchanger for the management of building in Indian conditions. The schematic of encapsulated PCM based heat exchanger cooling system and its placement in the test chamber is shown in Fig. 20. It is found that encapsulated PCM-based heat exchanger meant reducing heat gain by approximately 50% and mean air temperature by more than 6°C. Gholamibozanjani and Farid (2019) depicted the dynamic air-PCM heat exchanger unit planned to employ a scientific show created in this work. The show was executed in MATLAB computer program, applying two-dimensional express limited contrast strategy. It comes about an extraordinary assertion between the show and test estimations, with a standard deviation of less than 8% and the test estimations affirmed the potential of the outlined unit to fulfil the heating request of a private building at power cost crest and move it to off-peak hours. Morovat et al. (2019) focused the primary portion of the paper on the plan of the PCM-HX. A few plan arrangements are assessed and examined the parameters which were incorporated in the PCM-HX measurements. The part portion of the paper declares the distinctive control procedures pointed at diminishing crest request and the estimation of the HVAC system. The utilization of dynamic PCM-HX and appropriate control methodologies may well be a viable arrangement to upgrade vitality and adaptability in buildings that diminish HVAC units' measurement. The

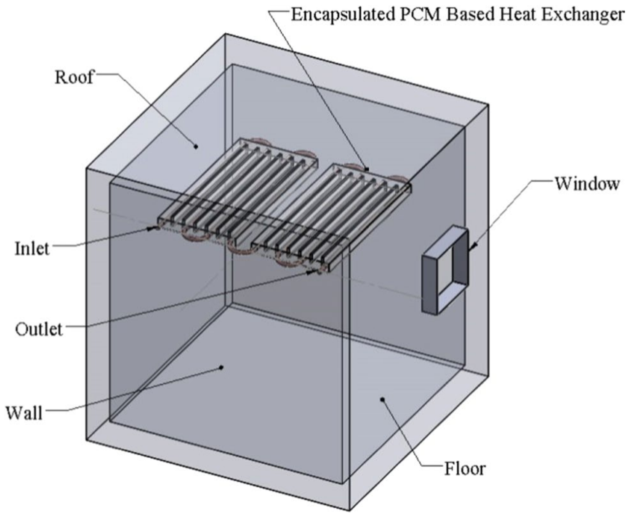
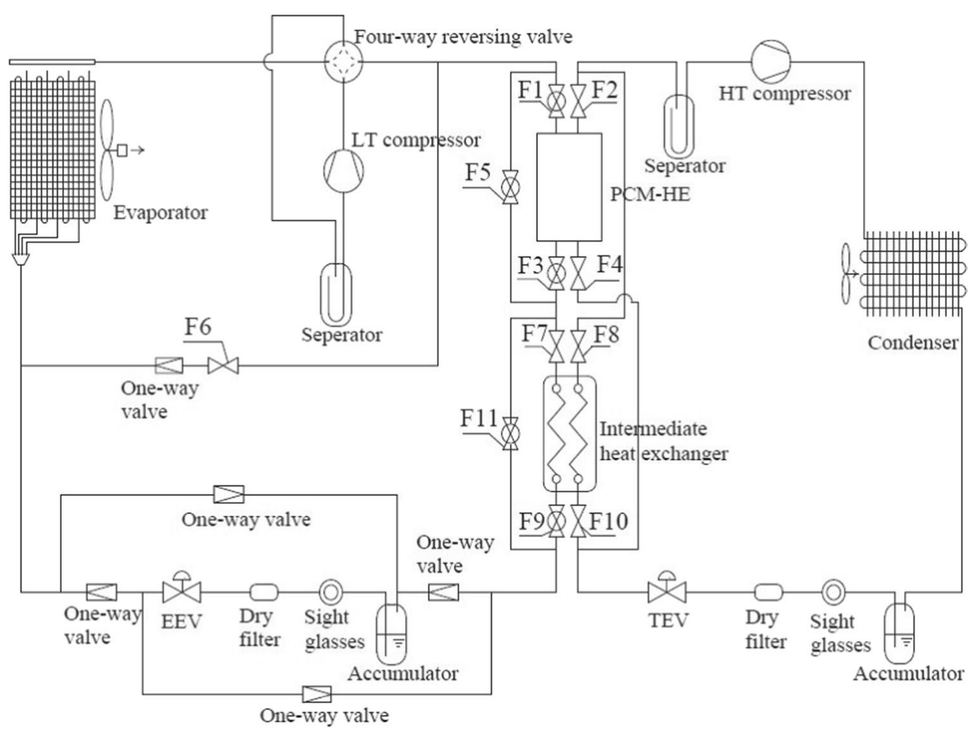


Fig. 20 Schematic of encapsulated PCM based heat exchanger cooling system and its placement in the test chamber Garg et al. (2018)

plan arrangement and accomplishment is to reserve funds both in initial capital costs and system operation costs. Ousegui et al. (2019) proclaimed the conversion strategy for assessing wind stream rate in phase change materials exchanger was introduced here. The previously mentioned strategy was applied to free cooling for two diverse stream rate esteems in a releasing and charging measure. The model was contrasted with trial information; approval of mathematical outcomes shows the strength and the consistency of this technique. Qu et al. (2019) The multi-mode heat release cycle of the finned-tube heat storage unit utilizes RT 10 as the stage change material under icing states of 12 °C and 85% RH. The schematic diagram of the prototype CASHP unit is shown in Fig. 21. It is recommended that the heat conversion scale to LT cycle was more significant than that to HT cycle and brought about by higher temperature qualification between LT cycle and PCM and LT refrigerant flow rate. During the TES based switch cycle defrosting, the working shows, for example, the pull pressure/temperature, refrigerant flow rate, in HT and LT cycle were assorted. In this way, the heat delivery qualities of the PCM were different in HT and LT cycles. Santos et al. (2019) assessed the trial work of thermal execution of new plan board to epitomize PCM and consolidated inside a PCM-Air heat exchanger system. The current heat battery has 9 rather than 7 boards, addressed trade territory 28% greater than the new heat battery. This decrease in boards per battery module will address a decrease in expense and support for the MVS. Stathopoulos et al. (2017) determined the daily peak power and renewable energy intermittence associated with the electrical heating of the PCM-Air heat exchanger by experimenting with a prototype of a PCM air-heat exchanger, and the experimental setup is shown in Fig. 22. The result proposed the demonstrations were gone up against with exploratory characterization information at diverse focuses of the unit and for different wind current rates and the most point of the demonstrate is, to begin with serving as an instrument for an optimization study of the unit and after that to propose

Fig. 21 Schematic diagram of the prototype CASHP unit Qu et al. (2019)



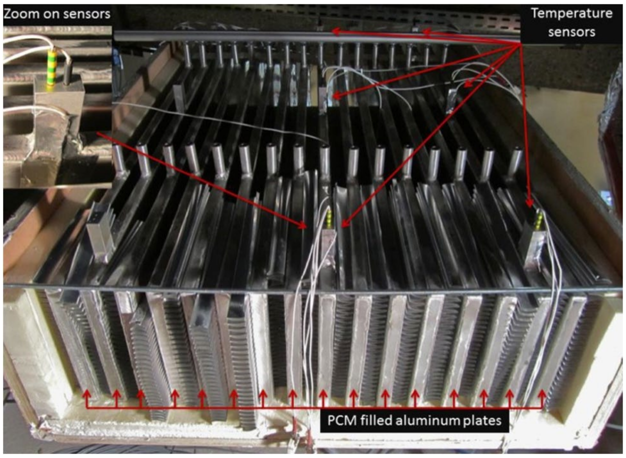


Fig. 22 The heat exchanger during construction: PCM filled aluminium plates and temperature sensors in PCM and on the surface of the plates Stathopoulos et al. (2017)

control methodologies when coupled with a building recreation program. Wu et al. (2018a) analyzed the performance of an all-encompassing graphite paraffin stage PCM heat exchanger functioning as a condenser in a transient source heat siphon water heater. EGPHEs can show up at the standards recorded in GB/T 23137-2008 by equivalent interfacing five16-L EGPHEs.

Solar water heater

The system comprises of solar water heater heat storage unit filled by PCM. Using a latent heat storage system using PCM is an efficient method in the solar water heater. Several methods are used in solar water heaters, such as flat plate solar collector integrated with built-in TES, ICSSWH using a PCM layer, solar storage tank integrating PCM modules for solar hot water production, SWHS and heat transfer the PCM module. Al-Kayiem and Lin (2014) analyzed the thermal characteristics of solar water heater incorporated with TES utilizing conducting the experimental setup at different inclination angles like 30°, 20°, and 10°. The schematic diagram & experimental setup of the integrated solar collector-TES water heater is shown in Figs. 23 and 24. The result shows that the efficiency of the solar concentrator was improved with the inclusion of TES Cu-PCM nanocomposite and paraffin wax. Allouhi et al. (2018) focused on the melting and solidification process of PCM for the storage technique. The flow rate of water, phase change material, its masses and external climate were the primary data to analyze the system's output. The output signifies PCM with the thickness of $1*10^{-2}$m, mass flow rate of 0.0015 kg/s and temperature at 313 K is the effective condition to obtain higher system performance. Chaabane et al. (2014) studied the integrated collector storage solar water heater and developed two numerical models: SHSU and LHSU. The result shows that the latent heat storage provides a better result than sensible heat storage when myristic acid is used as the PCM during day time. Bouhal et al. (2018b) designed

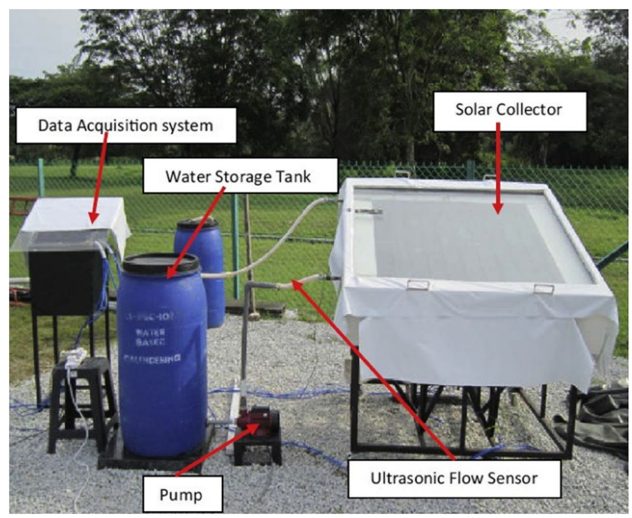
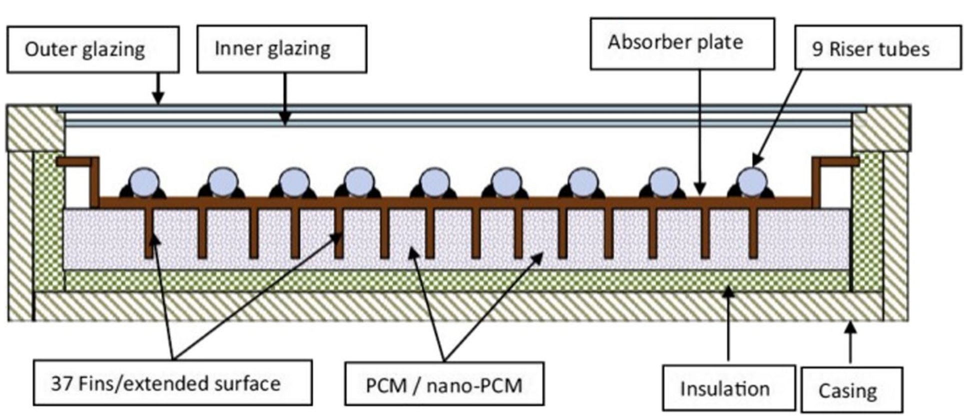


Fig. 24 The experimental setup of the integrated solar collector-TES water heater Al-Kayiem and Lin (2014)

Fig. 23 Schematic view of the solar-TES integrated collector Al-Kayiem and Lin (2014)



the solar water heater incorporated with the heat storage unit. The Schematic of the hot water system with PCM is shown in Fig. 25. The result shows that nearly 2.5H requires the complete melting process inside the storage tank, and heat losses to surrounding in dynamic mode get increased, melting velocity decreased with the increase in PCM. Wu et al. (2018b) reduced the effect of solar radiation intensity fluctuations and improved the performance by adding PCM in storage with insertion of the oscillating heat pipe. The schematic diagram of the energy storage solar collector with inserted oscillating heat pipe is depicted in Fig. 26. The experimental result shows that PCM collecting efficiency fluctuations have 30% less than without using PCM. Xue (2016) investigated the performance of a domestic SWHS with solar collector coupled PCM. The transfer of heat in the PCM module is suppressed due to the maximum viscosity and low K value of PCM. The result shows that the system performance is dependent on initial water temperature and radiation.

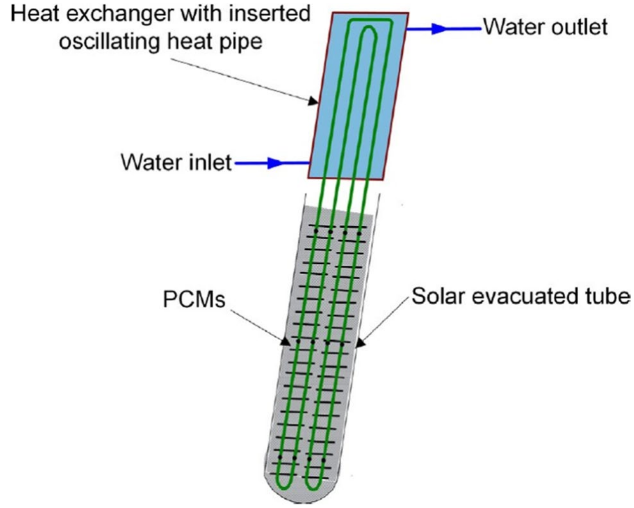


Fig. 26 Energy storage solar collector with inserted oscillating heat pipe Wu et al. (2018b)

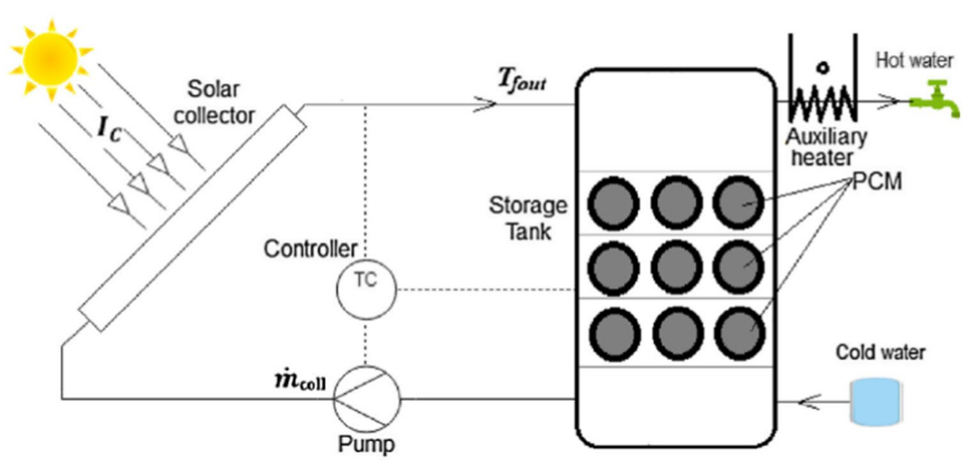
Phase change material filled cavities

Blended convection in a PCM filled square pit under the impact of a turning chamber was mathematically examined. Methods of PCM filled in cavities such as centred around portraying the heat exchange in a cavity loaded up with air and blended convection in a PCM. Moreno et al. (2020) performed an analysis on the heat transfer in a cavity filled with air which consists of a vertical wall with a PCM. The result shows a reduction in heat transfer rate to air when the PCM is used, and there is also a reduction of Nusselt numbers between 66.80% and 75.47% without using PCM. Bouhal et al. (2018a) performed the numerical two-dimensional CFD model to simulate the melting process of the PCMs filled into the cylindrical cavity with the specific heat source. The result shows that adding a cylindrical cavity with the addition of four fins at the heating source enhances the melting rate from 18.35 to 13.35 min at the temperature of 40 °C. Selimefendigil et al. (2020) numerically investigated the impact of rotating cylinder with mixed convection of phase change material filled with a square cavity. It was found that the rotation of the cylinder can regulate the heat transfer and melting process in the cavity. The result shows that the Nusselt number enhances 10% by rotating the cylinder in clockwise and using a larger cylinder instead of a smaller one. Ye et al. (2012) analyzed the impact of several volume fractions of cavities, heat exchange and fluid flow of latent heat storage system incorporated with PCM.

Phase change material selection

PCM possess a significant part in the dynamic heat and dampness buffering process. Whereas PCM selections have

Fig. 25 Schematic of the hot water systemwith PCM Bouhal et al. (2018b)



different models such as DSG, a new database for PCM selection, commercial Phase Change Materials using the AHP method, applications, sun-facing walls of solar passive curing buildings. Ruiz-Cabañas et al. (2017) One of the predominant solutions for TES indirect steam generation is the phase change material, and it should possess properties like energy delivering/storing at constant temperature and high energy density. Consequently, LiOH-KOH peritectic mixture was chosen as the PCM for DSG because it possesses the above properties with the change in enthalpy of 535 kJ/kg and with a melting point of 315 °C. Barreneche et al. (2014) established that TES can improvise the gap between energy consumption and energy supply and it. It was found that nearly 300 plus PCMs were used as the PCM. The result shows a reduction in their standardization of the evaluation of thermophysical properties of phase change materials. Bashir et al. (2020) There must be a need for low power production for rural areas, less than 100 KW, by using a dish-micro gas turbine system. Using ANSYS fluent 19.1 the 3D CFD model was designed to analyze the charging and discharging ability of PCMs. The concept diagram of the PCM integrated solar receiver is shown in Fig. 27. The output indicates that the discharge phase time is nearly 20–30 min for the outlet air temperature above 800 °C. Socaciu et al. (2016) analyzed the problem of selecting a suitable method to choose a specific phase change material for an engineering application. AHP method was chosen for the ranking of ten commercial PCM considering the technical specification of the materials. Yang et al. (2018) explored the phase change material in several applications for the enhancement of energy efficiency and economy. The result shows that the GSHP incorporated with the PCTS system possesses a high-cost effectual output compared with the GSHP system and the suitable material for GSHP and the PCTS system is $Ba(OH)_2.8H_2O$. Yu et al. (2020) analyzed the thermal process parameter in thermal process and PC curing process of phase change materials and developed the conceptual design of solar passive PC steam curing buildings with the incorporation of PCM on-wall heat storage. The result shows that there is a reduction in annual steam consumption by 4.7%.

Solar photovoltaic system

PCM with photovoltaic cell to frame a PV/PCM system is a suitable method to use the photovoltaic system with increased performance. The temperature of PV cells is as high as 80°C if there should arise an occurrence of enhanced solar radiation forces that initiate the coordinated carrier to focus in the photovoltaic cells to make a prompt higher immersion and to bring down voltage of the photovoltaic cells Mazer (1997). The temperature enhancement significantly increases the current and reduces the voltage that produces a total reduction in the force yield of the photovoltaic cell Radziemska and Klugman (2002). A common integration of the photovoltaic in to the structures provides an enhancement in the photovoltaic working temperature to a significant point that it reported for a 9.3% reduced force yield as compared to the conventional system Krauter et al. (1999). This demands the need for an effective temperature regulation of accomplishing integrated photovoltaic cells. Several temperature dissipation techniques are used to maintain the photovoltaic cells at low temperature. Among these techniques, strong liquid phase change materials have been utilized as temperature regulators in specific applications Lu (2000) & Wang et al. (2007). Various researchers have carried out several investigations in incorporating paraffin wax, combination of paraffin wax with various nanofluids, RT 25 HC, RT 22 HC, organic based RT44, pork fat, hydrated, macro-encapsulated, composite oil and capric acid PCM with photovoltaic cells to attain a significant increase in the performance of PV cells.

Elsheniti et al. (2020) proposed a one dimensional mathematical model to optimize the seasonal inclination angle

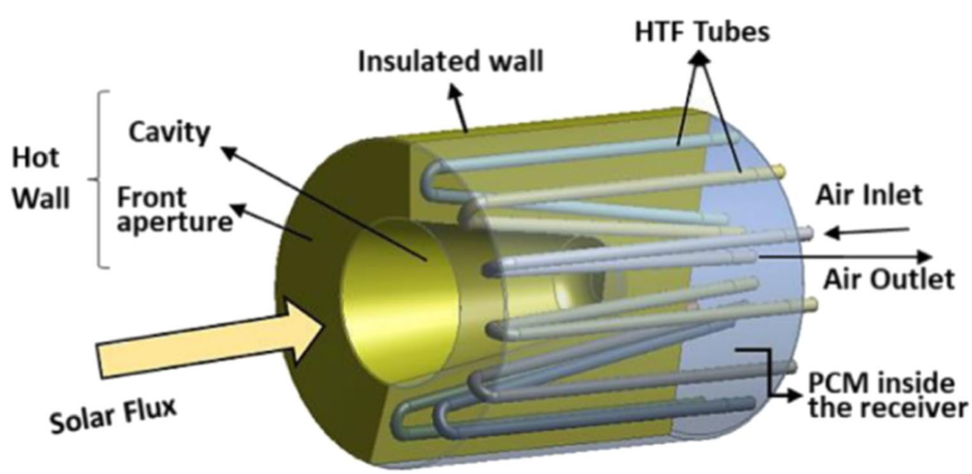


Fig. 27 PCM integrated solar receiver Bashir et al. (2020)

of the PV/PCM in Alexandria, Egypt which enumerates the temperature of the PV which is in contact with the RT 25 HC Paraffin based PCM. The PCM domain aspect ratio, inclination angles, PCM thickness, melting temperature are resulted to be 2 to 8, 0° to 90°, 10–40 mm and 25 and 26.6 °C. Results indicates that PCM thickness of 30 mm provides the maximum efficiency under the given conditions. Elarga et al. (2016) investigated the efficiency of a system that integrates a photovoltaic layer and a phase change material layer in a double skin façade. Results indicate that the integration of a paraffin wax based phase change material layer in the double skin façade with a semi-transparent photovoltaic layer leads to a minimisation of energy utilization by 30%. Hasan et al. (2017) investigated a photovoltaic paraffin based phase change material system in significantly high temperature conditions of the United Arab Emirates to analyze the energy saving factor. The schematic diagram of the energy flow in the PV–PCM system is shown in Fig. 28. Results reveal that the photovoltaic annual electrical energy yield enhanced by 6% in the high temperature conditions. Lari and Sahin (2018) to meet the electrical and thermal demands of a residential building in Dhahran, Saudi Arabia, the researchers developed a nanofluid-cooled photovoltaic/thermal system with a octadecane paraffin based phase change material in thermal battery. The proposed system indicates an 11.8% enhancement in its electrical performance over an uncooled photovoltaic system. Preet et al. (2017) conducted an experimental study in three different systems, such as traditional PV panel, water based PV/T with double absorber plate and water based photovoltaic/thermal system with paraffin wax based phase change material. Result signifies that the electrical efficiency of water based PV/T-PCM and water based PV/T is higher than that of traditional photovoltaic panel. Maximum enhancement in electrical efficiency is 12.7 with water based PV/T-PCM and 10.7 with water based PV/T. Senthil Kumar et al. (2020) made an experimental study on copper, silicon carbide, paraffin wax PCM to investigate the effect on the thermal behavior and electrical performance of a PV panel. Two prototypes were prepared to compare the performance of the photovoltaic panel. Prototype 1 consists of a platform, a PV panel and an electrical circuit with a known charge. Prototype 2 are fabricated with a vessel added on each photovoltaic panel's rear side which holds an integrated phase change material. The results indicate that when using combined PCM the electrical efficiency of the photovoltaic panels were increased by 4.3% on an average.

Abdelrazik et al. (2020) investigated numerically the performance of the combined photovoltaic thermal system with the phase change material. The Schematic diagram for a typical PV/T/nano PCM system is shown in Fig. 29. Numerical results indicate that the addition of Graphene nanoplatelets (GNP) in the Paraffin wax (PW)

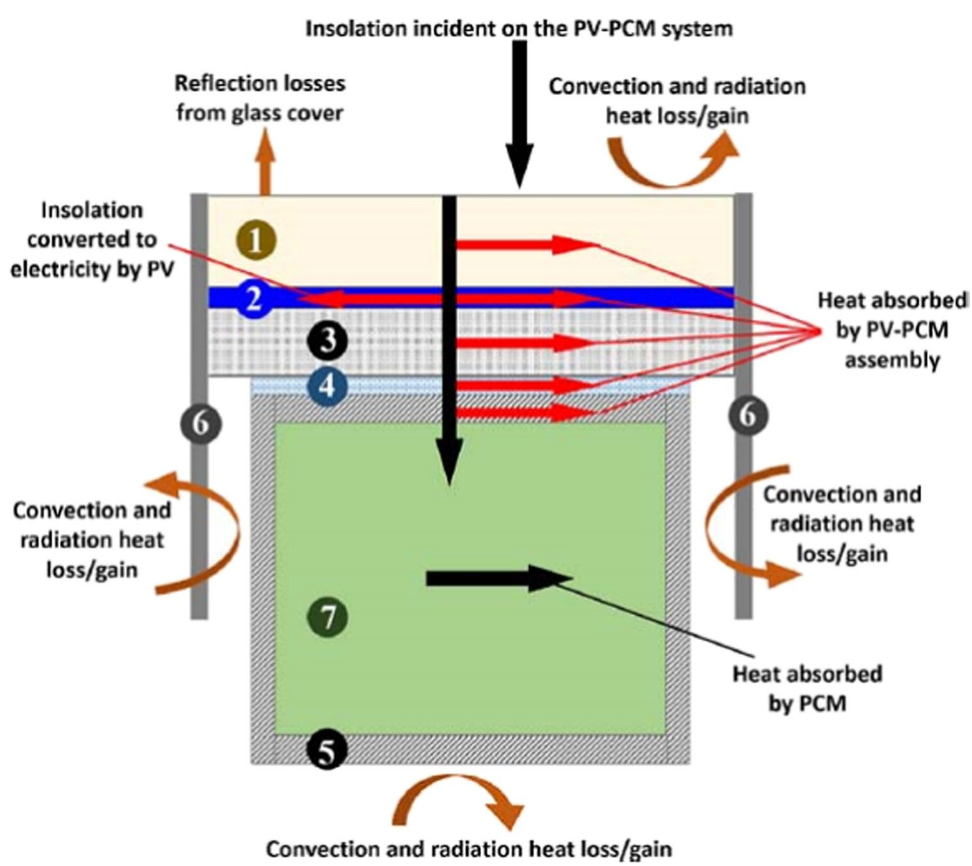


Fig. 28 The schematic diagram of the energy flow in the PV–PCM system with labels 1 – glass cover, 2 – PV cell, 3 – PV back sheet, 4 – layer of epoxy glue as interface between PV and PCM container, 5 – PCM container wall, 6 – PV frame and 7 – PCM layer. Hasan et al. (2017)

phase change material enriches electrical efficiency and cooling of the PV panel. Results also signifies that there would be an increase in electrical efficiency and drop in PV panel temperature as the nanoparticles loading-percentage is increased. Nada et al. (2018) investigated the concept of efficiency enhancement of PV-building integrated system using paraffin wax based phase change materials (PCM) and Al_2O_3 nanoparticles. The investigation mainly sketches the inspection of three different PV modules combined with building wall, pure PCM and PCM/Al_2O_3 nanoparticles compound at the same time span and location. Among these modifications, integrating the PV with pure PCM and enhanced PCM by nanoparticles can reduce the temperature of the modules by 8.1 and 10.6 °C and increase its efficiency by 5.7 and 13.2%. Al-Waeli et al. (2018) proposed three types of cooling systems such as tank filled with water and water flows through the cooling pipes, tank filled with PCM and water flows through the cooling pipes, and tank filled with PCM/nano-SiC and nanofluid (water-SiC) flows through the cooling pipes. Results indicate that nano-PCM and nanofluid improves the electrical efficiency from 8.1% to 13.3% and electrical current from 3.7 A to 4.1 A compared with conventional photovoltaic panels. Yazdanifard et al. (2020) put forward a numerical dynamic approach for a concentrating photovoltaic/thermal system with a hybrid spectral splitter of phase change material Ag/water nanofluids. A simulation was carried to test the impact of the nanofluids in both solid and liquid phase and its was sensed that when the phase change material is pointed below the nanofluid channel, high energy and exergy efficiencies of 2.4% and 9.3% was attained when using S27 as compared to RT25 PCM. The results also indicate that the energy and exergy efficiency was enhanced to 11% and 7% respectively.

Sourav Khanna et al. (2018) analyzed the thermal performance of PV, PV-RT 25 HC PCM and Finned-PV-RT 25 HC PCM systems. This study enumerates that the most suitable depth of PCM container is 4.6 cm for $\sum IT = 5$ kWh/m2 /day and 2.8 cm for $\sum IT = 3$ kWh/m2/ day for the selected variables. The most suitable depth of PCM container is 3.9 cm for $\sum IT = 5$ kWh/m2 /day and 2.3 cm for $\sum IT = 3$ kWh/m2 /day for a PV-PCM system. Soares et al. (2020) conducted experimental investigation to analyze the performance of 250 W STC-rated commercial polycrystalline silicon PV panels which could be efficiently enriched by positioning movable thermal energy storage (TES) units filled with the free-form PCM RT 22 HC on the panels' back and the paper also significantly plots an outline on the usage of PCMs on the thermal regulation of photovoltaic (PV) devices. It was deduced that a PCM with a higher phase change temperature must be chosen for Mediterranean climate and the movable TES units have a negative impact on the performance of the PV/PCM systems. Waqasa and Ji (2017) designed mathematically the model of a PV panel combined with Organic based RT44 PCM. The model emphasized that the conventional PV panel temperature neglecting the phase change material could be as large as 64 °C which could be conventionally deduced to 42 °C. Under hot humid climatic conditions efficiency can be improved up to 9% during peak summer season. A theorified technique for intensifying the performance of the solar PV panel with the phase change material and the aluminium sheet as thermal conductivity enhancers was suggested by Rajvikram et al. (2019) inventively confirmed that the conversion efficiency of the panel is improved by an average of 24.5% when the PV-Organic PCM is positioned with an aluminium sheet at the backside of the panel. The current efficiency of the panel is increased 2%, when there is an average decrease in temperature of 10 °C. Nižetić et al. (2017) considered the pork fat as a

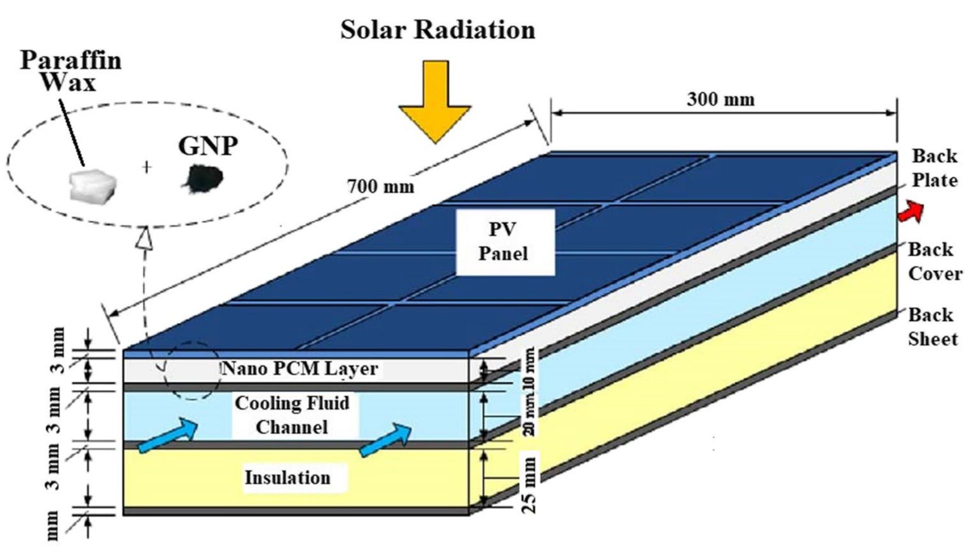


Fig. 29 Schematic diagram for a typical PV/T/nano PCM system. Abdelrazik et al. (2020)

considerable phase change material for photovoltaic applications and proposed a simple numerical plot considering two photovoltaic phase change material configurations such as conventional PV-PCM system (organic PCM) and the other was a PV-pork fat system. It is more certainly validated that the pork fat is a very efficient PCM material other than economical aspects.

Akshayveer et al. (2020) elucidated the extraction of heat from the panel has been done by integrating natural convection phenomena with phase change materials (PCM) beneath the PV panel. Results indicate that the reduction of PV cell temperature by 25% and 35% for PV/PCM system and air PV-T/PCM system. Results also signifies that the electrical efficiency is enhanced to 14% and 20% for PV/PCM system and air PV-T/PCM system. Yao et al. (2020) developed a combined model of PV/T module with heat pump evaporator for direct expansion of solar PV/T heat pump in high latitude area. This combination effectively achieves the stable residential heating demand. Results indicate that the temperature of underfloor heating which using integrated Hydrated PCM heat storage can reach 31 °C after 39 hours when the circulating water is 40 °C which is steady and appropriate for domestic temperature raise. Modjinou et al. (2018) made a comparative study of macro-encapsulated phase change material (PCM) based solar photovoltaic thermal (PV/T) system and micro-channel heat pipes (MCHP) PV/T with a conventional PV/T. Results indicate that the encapsulated PCM, MCHP and conventional PV/T systems possess 36.71%, 35.53% and 31.78% of electrical efficiency. Nasrin Abdollahi and Rahimi (2020) This paper includes a plot for natural cooling water circulation along with a newly built photovoltaic module passive cooling systems. Results reveal that adding Boehmite nanopowder to the composite oil reduces the photovoltaic panel temperature in comparison with the setup of no cooling and using the composite oil as PCM. To enrich the Photo voltaic performance Darkwa et al. (2019) invented a concept of integrating thermoelectric PCM system in photovoltaic system. Conceptual investigations under natural convection conditions resulted that the thermoelectric generators (TEGs) had small power output due to small temperature difference. In order to reduce its insulation effect on the TEG and PV layers high PCM conductivity for a thick PCM layer is integrated. Final results reveal that the PV/TEG/PCM produces an enhanced thermal performance with a phase change temperature of 45 °C, thermal conductivity of 5 W/m K and PCM layer of 50 mm thick. Yang et al. (2017) conducted a solar radiation experiments to improvise the energy generation capacity of a PV/T-Capric acid PCM module and to differentiate the overall energy performance of the PV/T-PCM and PV/T systems. It was evaluated that the PV/T-PCM module and the PV/T module under solar irradiation reduces the increase in backplane temperature of the PV plate on the application of the PCM layers and it was also proved that the PV/T module has lower power output than the PV/T-PCM module. It was observed that there would be 42.4 and 40.3 °C temperature in the water storage tanks of the PV/T and PV/T-PCM systems.

Solar dryer

The phase change material (PCM) has the capability to retain maximum capacity of surplus thermal energy during its melting stage and benefit of it under static temperature later, makes it superior device to increase efficiency of the solar drying system. Bhardwaj et al. (2017) studied the time taken to complete the drying process of a certain herb using Phase change material (Paraffin RT – 42) based solar dryer. The schematic diagram of experimental setup is shown in Fig. 30. At the end of study, it is inferred that the amount of moisture got reduced from 89 to 9% in 5 days when the solar dryer is integrated with PCM. Agarwala and Sarviya (2017) conducted experimental analysis to predict the thermal properties of paraffin wax as PCM in solar dryer. Few parameters were measured using Differential scanning calorimetry and the thermal conductivity is determined by using Hot Disk Thermal Constant Analyzer TPS 2500. The obtained result signifies that the paraffin wax as PCM is a suitable material for solar drying applications. Rabha and Muthukumar (2017) studied the drying parameters of a paraffin wax PCM-based solar dryer with a latent heat storage unit made of shells and tubes at a temperature of 36 to 60°C. Results indicates that the amount of moisture present in chilli got reduced from 73.5 to 9.7% in 4 days of time with the utilization of paraffin wax as PCM in solar dryer. Aymen El Khadraoui et al. (2017) investigated the feasibility of paraffin wax PCM based solar dryer. The storing and discharging capacity of the latent heat storage unit is noted and it is found that energy accumulation can be completed at an energy efficiency of 33.9% and at 8.5% of exergy efficiency. Shalabya et al. (2020) studied the quality of the basil leaves which is dried in the soalr dryer attached with the paraffin wax as thermal storage material. The impact on volatile compounds were studied with the help of gas chromatography and mass spectrometry. It is inferred that the leaves got dried in 31 h while placed on dryer and took 60h when dried in natural air. Alimohammadi et al. (2020) investigated how the working fluid affects the thermal performance of a parabolic Trough collector at a fixed air flow rate of 0.025kg/s when integrated with paraffin wax based PCM as thermal energy storage medium. Results inferred that the various working fluids along with the PCM does not have any undesired effect on quality of the dried material. Ananno et al. (2020) investigated a hybrid geothermal Solar collector which is assisted with the paraffin wax based Phase Change material and can be used for food drying.

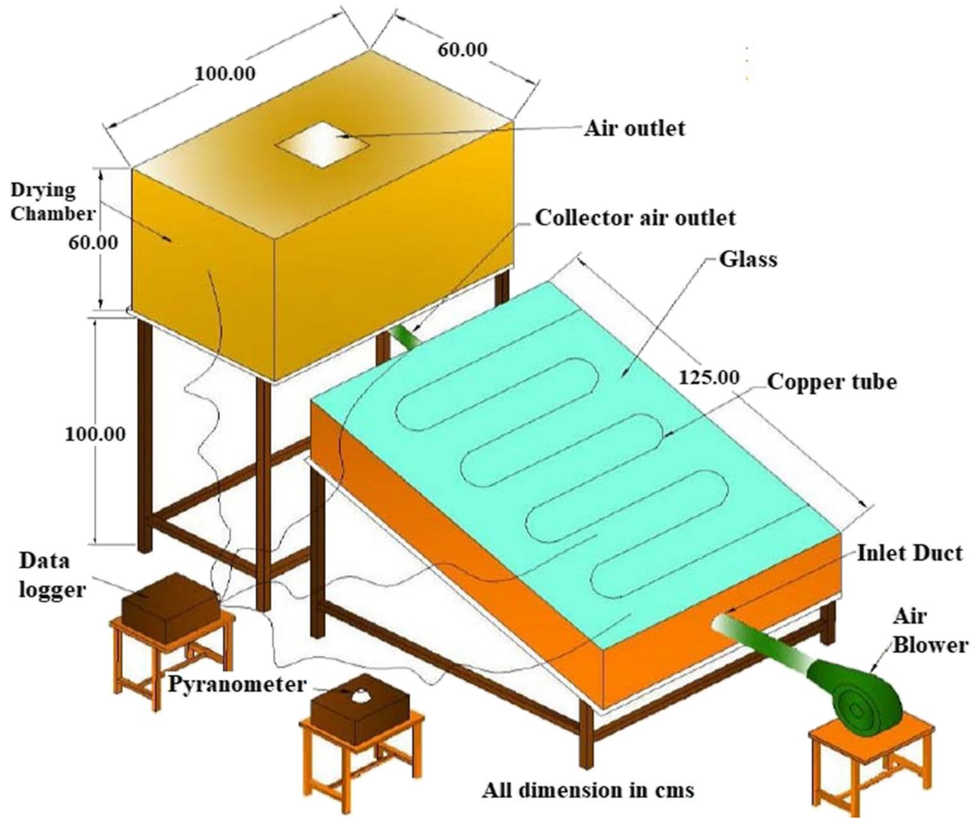


Fig. 30 Schematic diagram of experimental setup Bhardwaj et al. (2017)

It is inferred that the efficiency of the hybrid geothermal solar collector is 20.5% efficient than the conventional solar collector. The authors believe that integration of this technology with food processing industries paves way in attaining Sustainable development goals. Bhardwaj et al. (2020) described that performance of solar dyer with combination of sensible heat storage (SHS) and paraffin wax PCM for drying chillies. Experimental investigation of sensible heat storage medium in solar air collector (SAC) is carried out in this paper. Results shown that reduction of dehydrating time by 78.12% and 86.00%. based on the drying system many sensible parameters were identified.

Sharma et al. (2020) suggested the utilization of renewable energy sources by the requirement of green house gas. improvement of air heating and drying by solar air heating applications. Latent heat storage is utilized by PCM. The main disadvantage revealed that fluctuation in availability of solar radiation. Many techniques based on heat transfer like encapsulation, extended surfaces and conductive particle dispersion with integration of PCM have significant effect in the thermal performance of solar dryer. Madhankumar et al. (2021) found that the exergy performance is effectively increases with increase in duration of drying due to utilization of paraffin wax as PCM with a variation about 8.69 to 79.02%. The analysis resulted that the Indirect Solar Dryer (ISD) is used effectively, as sustainable alternative development and farming community due to its cost effectiveness. Ebrahimi et al. (2021) investigated the total drying efficiency and thermal performance of flat plate collector incorporated with the paraffin wax phase change materials. The result revealed that the thermal efficiency of the collector could be found with high accuracy ($R2 > 0.9432$) and the overall performance lies in between 21.92% and 25.72 %. Sharma et al. (2021) examined the performance characteristics of indirect type solar dryer which is incorporated with the paraffin wax phase change materials. The result showed that the performance of the solar dryer is significantly high due to inclusion of PCM and CO_2 mitigation among the different drying units. Atalay and Cankurtaran (2020) presented a large solar dryer and analyzed the exergoeconomic, exergo-environment assessments along with the performance characteristics. The result described that the solar dryer with paraffin wax PCM has a very much effective output in industrial drying process both in terms of environmental sustainability and the performance characteristics.

Bhardwaj et al. (2021) discussed elaborately about to maintain the thermal fluctuations during the day-night drying process, solar air collector was used to sensible heat storage medium, while drying paraffin RT-42 was included in thermal energy storage medium. 3.7 to 75.15 % is the efficiency of drying unit has evaluated with 30.28% of mean value.11.33kwh/kg moisture is the specific energy consumption of the rhizomes and 10.53% is the overall efficiency of rhizomes. Vigneshkumar et al. (2021) elucidated that the solar dryers are assuming as a vital part in the food businesses for protecting consumable things like grains, vegetables, fish, and so forth, through the expulsion of dampness content from them. Their moisture evacuation rate is high and the quality of the final result would likewise be improved by them. Indirect type single-pass forced convection by solar dryer is envisaged to increase the efficiency of solar dryer by using paraffin wax as PCM. Results indicate that the percentage weight of moisture elimination from potato was increased by 5% per day with the inclusion of paraffin wax based PCM. Swami et al. (2018) studied about the drying time taken by the organic PCM based air dryer which is to be used for the purpose of Fish drying. The results showed that time taken for drying process got reduced to a reasonable value and consequently the drying process is improved significantly due to utilization of organic PCM. Karaagac et al. (2021) studied this paper, nano-enhanced PCM $A1_2O_3$ – paraffin wax was used by enriched photovoltaic-thermal solar dryer. Steps to be taken for a stable $A1_2O_3$ nano-PCM sample is shown in Fig. 31. First and second laws discussed about the complete thermodynamic analysis of the system. Results signifies that mushrooms are dried initial to final moisture content as 17.45 to 0.0515 g water/g.

Solar still

In modern years, various investigations were led to increase the production rate of solar stills. One of the methods were the incorporation of phase change materials in the traditional solar stills to prolong the water production capability after the sunlight periods. Researchers conducted several experimental analyses in conventional and modified single and double slope solar still with different PCM such as paraffin wax, sodium acetate trihydrate, sodium thiosulfate pentahydrate, paraffin C18 & trimethylolethane material, stearic acid, shape stabilized phase change material, nanoparticles incorporated PCM, palmitic acid and salt hydrate PCM.

Vigneswaran et al. (2019) determined the enhancement of productivity of solar still. This study revealed that thermal performance of three same sized passive solar still with and without incorporation of paraffin wax PCM. The schematic diagram of Solar still with single PCM is shown in Fig. 32. Analyzation of thermal performance was done in terms of hourly yield per day and exergy efficiency. The increase in production rate of still with double phase change material, still with single phase change material and conventional still were found to be 4.4 L/m^2/day, 4.1 L/m^2/day, and 3.7 L/m^2/day respectively. Mazraeh et al. (2018) proclaimed that new solar still system cumulated with semitransparent photovoltaic, evacuated tube collectors and phase change materials. Investigation of effects of various PCM-PV modules, basin water depth and tube numbers on the system thermal and electrical performance were done. Presence of paraffin wax based PCM has improved the energy efficiency significantly, however had negligible effect on the exergy efficiency.

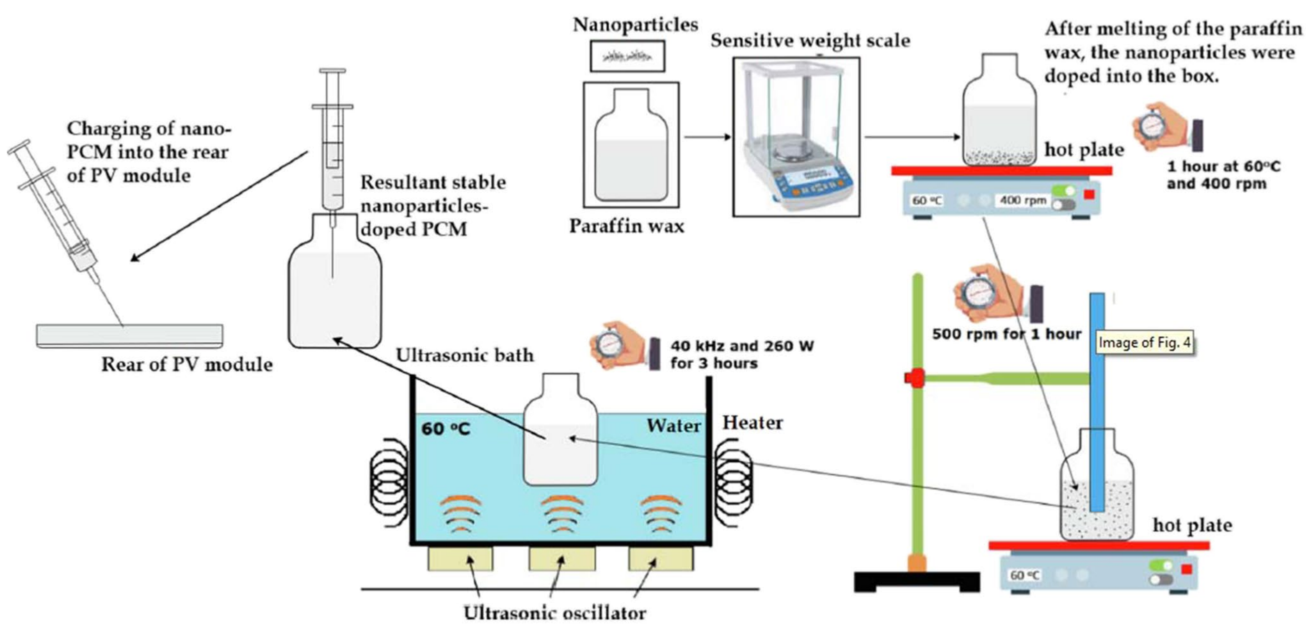


Fig. 31 Steps to be taken for a stable $A1_2O_3$ nano-PCM sample. Karaagac et al. (2021)

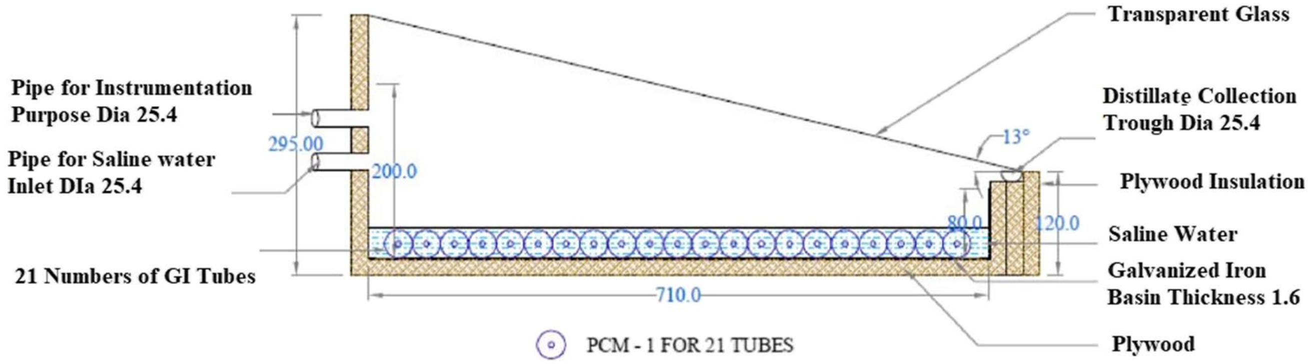


Fig. 32 Schematic diagram of Solar still with single PCM. V.S. Vigneswaran et al. (2019)

Yousef et al. (2019) stated the improvement of heat transfer characteristics of PCM storage unit which is applicable to solar still system by using hollow cylindrical pin fins embedded in paraffin based PCM. The performance analysis was carried out on three cases under the same climate conditions such as conventional solar still, solar still with PCM and solar still with pin fins incorporated in the PCM. The conclusion revealed that the cumulative production rate of the solar still with pin fins incorporated in the PCM was greater than that of conventional solar still and solar still with PCM by 17% and 7% respectively. Sarhaddi et al. (2017) explained the study of energy and exergy performance of two weir type cascade solar stills with and without paraffin based PCM storage. The effect of different parameters based on energy and exergy efficiencies of both solar still were investigated. It is identified that exergy efficiency of both weir-type cascade solar still is much lower than its energy efficiency. The solar still with PCM storage is preferred for semi-cloudy days due to its better energy and exergy performance. Kamara (2019) described the analyzation of solar stills by two necessary factors such as rate of distillate and temperatures. The working of stills with better efficiency and effectiveness in terms of distillate yield is done by temperature data set and distillate output with paraffin was PCM. Kabeel and Mohamed (2016) suggested the performance of solar still through increasing the productivity of fresh water by incorporating paraffin was PCM acts as a heat storage medium. The daily distillate yield was approximately reached 7.5 L/m^2. The percentage of daily distillate yield is 67 % which is higher than the conventional solar still without PCM. Khalilmoghadam et al. (2020) conducted analysis in integration of latent heat storage and built in condenser with solar still. The heat dissipation kept the condenser temperature low. Using pulsating heat pipes (PHPs) the heat stored in paraffin wax PCM was transferred to the saline water. the amount of daily fresh water production and its cost per liter were 6.3 kg/m^2 and 0.0093$/1/m^2, respectively. Asbik et al. (2016) explained the determination of magnitude of exergy losses during the heat storage on passive solar still combined with heat storage system such as paraffin wax based PCM. Drying up phenomenon can appear for some brackish water depth. The latent heat storage increases the water productivity and reduces the exergy efficiency. Benhammou and Sahli (2020) described the investigation of single slope solar still coupled with a separated heat storage system consisting of double glazing solar collector. It showed that daily irreversibility decreases slightly with increasing the water mass and slope angle of collector. The conclusion revealed that increasing the mass of saline water in the solar still with paraffin wax PCM has negative effect on the production rate. Mohamed et al. (2021) investigated the performance of solar still by using square and circular hollow fins with paraffin wax PCM. The array of copper hollow fins was fitted with absorber tube. The improved productivity of hollow circular fins is 6.2 L/m^2/day with 47% of enhancement. The conventional tubular still provided an average accumulated productivity of 4.2 L/m^2 per day. The inclusion of paraffin wax based PCM in the solar still enhances the yield of tubular still by 33%.

Gnanavel et al. (2020) elucidated the improvement of solar still by using aluminium basin with phase change material Paraffin C18 & Trimethylolethane material and without phase change materials. It was concluded that Paraffin C18 material only gives the high distillate yield and high volume fraction of water in solar still applications. Abu-Arabi et al. (2020) conducted the performance analysis in modified solar still by the following cases: solar still with glass cooling (SC), SC connected to an external collector (SCC) and SC with phase change material (SCCP). Three different PCMs such as sodium acetate trihydrate, sodium thiosulfate pentahydrate, and paraffin wax with various parameters were investigated. It concluded that addition of external collector and PCM in the basin, increased the distillate yield by a factor of 2.4.

Shanmugan et al. (2017) discussed that inclusion of Al_2O_3 nanoparticles in wick materials of solar still with stearic acid PCM. The process employed that drip button to decant saline water drop by drop on absorbing material in the basin. Vitality equilibrium equation is needed to get instantaneous efficiency of the anticipated structure. The result shows that solar still have been charity in PCM and nano particles for random heat progresses slightly sophisticated storage density and isothermal nature process of whole efficiency of the structure. Behura and Gupta (2020) described that nano particles embedded with phase change material improves productivity. Performance of solar distiller with PCM as a heat storage material placed at bottom of solar still covered with v-corrugated plate and with nano particles embedded with PCM is carried out. The experiment carried out with different weight fraction of CuO nano particles with paraffin wax PCM. Results reveal that the distillate yield enhances by 63% due to CuO nano particles with paraffin wax PCM in solar still. Kumar et al. (2020) conducted performance analysis in conventional single slope passive solar still (CSS) under the influence of paraffin wax based PCM and nano based PCM with respect to fresh water production per day. Photographic view of experimented solar stills is shown in Fig. 33. Results indicate that the inclusion of paraffin wax PCM and n-PCM improved the fresh water production by 51% and 67% as compared to conventional single slope solar still.

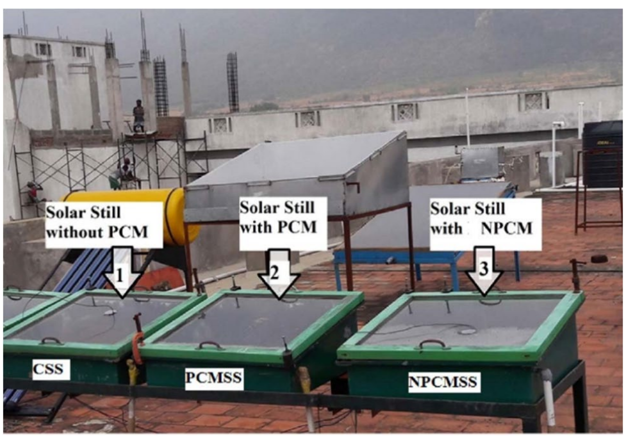
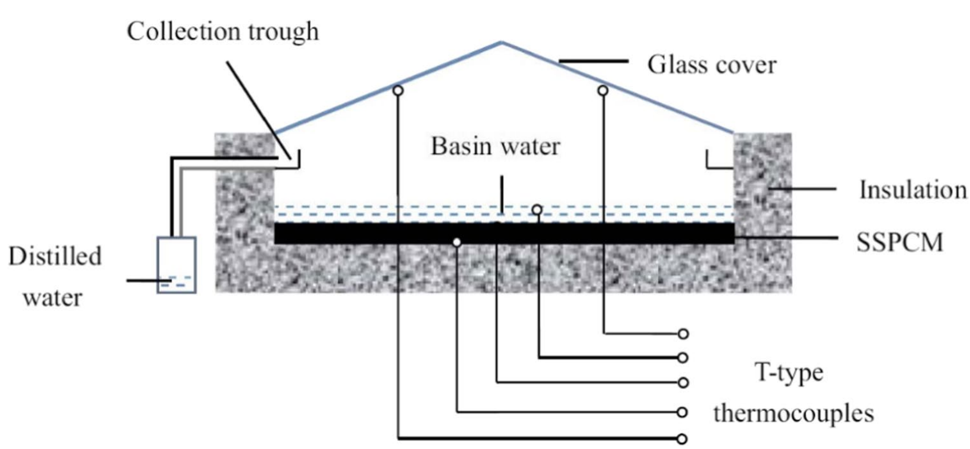


Fig. 33 Photographic view of experimented solar stills. Kumar et al. (2021)

Cheng et al. (2019) explained the performance of solar still by applying a new shape stabilized phase change material (SSPCM). Schematic diagram of the pyramid solar still with SSPCM is shown in Fig. 34. The considered characterization of (SSPCM) were stable shape, high thermal conductivity and solar absorption. The result concluded that daily distillate yield enhanced from 42 to 53% compared with that of conventional solar still.

Toosi et al. (2021) conducted experimental analysis with four different conditions in stepped solar still such as single stepped solar still, stepped solar still with an external condenser, stepped solar still with stearic acid PCM and stepped solar still with external condenser and stearic acid PCM. The purpose of this investigation is to improve the distillate of the stepped solar still through additional techniques. These four cases reveal the necessity of using an external condenser and PCM in stepped solar still. The results show that the increase in distillate yield of stepped solar still with external condenser and stearic acid PCM is 104%, as compared to single stepped solar still without PCM. Kateshia and Lakhera (2021) determined the analysis of single basin solar still using palmitic acid PCM with and without pin fins as absorbing material. It is considered that the usage of solar still using the PCM material along with pin fin is a cost effective option. The total accumulated productivity is high when compared to conventional solar still. Jahanpanah et al. (2021) proclaimed the usage of salt hydrate low temperature phase change material in single-slope solar still. Three test cases of similar PCM under different weight is carried out. It was concluded low temperature PCM improves the overall efficiency by 36%.

Fig. 34 Schematic diagram of the pyramid solar still with SSPCM. Cheng et al. (2019)



Economic analysis of solar energy system

Elfeky et al. (2020a, 2020b) examined the volume fraction and phase change materials in TES tank arrangement used in CSP plants along with the impact on economic and thermal performance of TRI-layer thermocline TES. The result described that the lowermost paraffin wax PCM layer has the highest volume fraction and it is the most effective option which is relatively lower cost and enhanced efficiency. Liu et al. (2021) found that, by using a higher temperature with supercritical CO_2 Brayton power cycle, the cost of the CSP plant is reduced reliably. The analysis reports that the total cost of 5-PCM635 storage is \$21.82/kWht and \$28.066/kWht and the hybrid PCM is most reliable and cost effective which is nearly \$26.96/kWht and \$21.49/kWht for charging temperature of 720°C and 750°C. Pourmoghadam et al. (2021) examined the economic performance of solar power plant and found that the effective economic performance is achieved by combination of Dimethylol and R245fa/R500 as the phase change material thermal storage. The sensitivity result shows that the PTC is least sensitive to the cost and NPV is extremely sensitive to the carrier of energies. Prieto and Cabeza (2021) established that the levelled and initial cost of the plant is much reliable, when using the tube and shell type heat exchangers for phase change material storage and showed that, the improvisation of thermal properties by performing modification, encapsulation of PCM and enhancement of thermal conductivity were helps to reduce further cost of the solar power plants.

Sohani et al. (2020) found that the solar still is one of the cost effective process for eradication of salts from impure water. In this process the evaporation of water is done by the sufficient radiation from the sun and the pure water is collected in the small dent, which is provided in the top layer, then the salty water is deposited in the basin.

Arunachala and Kundapur (2020) listed the effective low cost solar cookers in large group, particularly the funnel and panel types of solar cooker which works satisfactorily, simple to fabricate and cost effective. The result shows that the performance of cooker panel is around 60 -70%, which means that the performance is nearly the performance of box type solar cooker (70-75%) at fraction of cost. Edmonds (2018) described the cost effective solar cooker with traditional style pan, cooking at high temperature. Considered the safety purpose the focussed sunlight is to be surrounded inside the system and the pan is located at a suitable fixed height overhead the ground. And the concentrator is made by forming the eight flat, cost effective reflecting panels, which is easy to manufacture.

Raj et al. (2019) analyzed the cost effective, simple, and easy integration process of designed and constructed DPSAHS. The phase change material which is used in this system is paraffin, due to its cost effectiveness, availability, easier to handle and has an effective chemical stability. Lamrani et al. (2021) numerically investigated the solar wood dryer's (conventional) energy and economic feasibilities, incorporated with the solar air heater and the heat recovery unit. The investigation could results in HRU is more constructive in both the climates along with the maximum payback limit of nearly 2years, but on summer days the payback period is around 3.5years, with the help of PVT collector which is applicable only for wood dryers.

Pandey et al. (2021) reviewed the comprehensive variability of work on the exergy, energy, enviroeconomic and exergyeconomic (4E) methodology along with and without paraffin wax based phase change materials incorporated with the solar water heater systems for constructions and further applications in latest years and to report the technical encounters with solar water heater systems. Chargui and Tashtoush (2021) studied the feasible economic performance of solar water heater integrated with PCM. Based on the selling price nearly is 0.180 DT (Tunisian Dinar) (about 0.065 \$) of I kWh of electricity the annual system savings were calculated. The result shows that the system lifespan is nearly 25 years and the payback period of TSWH system is around 3.6 years and total annual savings is corresponding to 8,532 DT.

Nian et al. (2021) studied the annual economic analysis of the shape-stabilised phase change material due to running of the desalination plants for long-term. The analysis results that the payback period of SSPCM solar still was the least which is around 7years with the cost of water is 0.2 ¥/L and the SSPCM solar still acquires the least TAC nearly 0.123 ¥/L at the first year. Vigneswaran et al. (2021) described that the phase change material is used to serve the heat for the water in the basin of stills, during at the night time. Thus, higher temperature difference is achieved between the water surface and inner glazing surface with the help of the paraffin PCM. And the price of per litre water produced by GIBSS, ABSS and CSS was nearly ₹1.09, ₹1.23 and ₹0.67 respectively. Hossain et al. (2018) postulated a research work to validate the energy and economic performance of a designed and developed photovoltaic / thermal phase change materials system under typical malaysian weather condition. At 2 LPM the highest thermal efficiency is encountered as 88% and electrical efficiency of the PV and PV with PCM is 10% and 11% at 4 LPM. Results indicate that the photovoltaic/thermal-phase change materials have a maximum energy efficiency of 7% and 12% at 0.5 LPM. Results also signifies that the PV/T-PCM systems are more cost efficient than the long run solar PV system, thus the developed system is preferred dominantly for the household families with a standard lifespan of 5 years.

Conclusion

Phase change materials can be applied to various solar energy systems for prolonged heat energy storage, which is relatively sound as the solar energy is discontinuous and is inaccessible during the night period. The review article shows a detailed study on the classification of Phase change materials, performance, and applications. The review paper exposes the applications of PCM in solar thermal power plants, solar desalination, solar cooker, solar air heater and solar water heater. The main aim of these applications in PCM is to enhance the economically viable efficiency of PCM in solar thermal energy utilization. The following are the most important findings of this review article:

- Inorganic phase change materials, a considerable quantity of latent heat is retained and discharged during the phase change process. It is more reliable in the food drying process, and the microencapsulation process prevents the leakage of organic PCM.
- In paraffin type PCM, the temperature range depends on both the maximum composition and heating rate and found that the phase change process takes place in a specific temperature range for the binary mixture. The thermal conductivity of the PCM is get enhanced by the encapsulation of expanded graphite.
- The inorganic PCM has huge melting enthalpy, high thermal energy storage capacity, and they are inflammable. Crystal hydrated salt PCM is used to apply heat storage due to its steady thermal properties and high latent heat of phase change, and the Salt hydrate PCM is used for the solar energy storage in the ICS system.
- In metallic PCM, the hydrogen is fully absorbed by the MH at the proportion generated by electrolyser and by the demand of fuel cell, the absorbed hydrogen gets desorbed. The eutectic Na_2SO_4-NaCl salt is used for the solar TES. Specific development is made on the eutectic Na_2SO_4-NaCl salt/ceramic composites to resist corrosion due to the high-temperature range in TES for STPP.
- The NPCM has several enhancements than the phase change materials. The experimental results show that nearly 35% enhancements in productivity when the solar still combines copper oxide nanoparticles and phase change materials. Inevitable development is made on the eutectic Na_2SO_4-NaCl salt/ceramic composites to resist corrosion due to the high range of temperature in thermal energy storage for STPP.
- A parabolic concentrated TES unit is employed to retain the heat using phase change material for the effective storage medium. Comparison is made on the standard insulated tank of PCM loaded non-finned tank with newly designed PCM-loaded finned cell-based tank in PC thermal storage unit, and the results show that it is more advantageous in-tank efficiency and tank water temperature when the tank is enhanced with phase change material.
- The concentrated solar power system generates electric power at huge rates by storing the heat energy and converting it into electric power. The direct steam parabolic trough solar power plant incorporated with TES, which is made of phase change material, increases in output stream quality from 0.2 to 0.5 and decrease in charging time, and there is an enhancement in thermal conductivity of PCM from 0.5 to 5 W. The properties and the enhancement of solar unit along with PCM as the storage unit were discussed.
- The parabolic dish collector whose working temperature is in the range of low or medium is most preferable for industries, and the results show that the performance of the cavity covered receiver is increased by 20% compared to a flat plate receiver with minimal working temperature. The reduction of temperature is higher than 450 °C at the receiver. Solar cooker with PCM using parabolic dish collector whose diameter is 0.9 m whose mean exergy and energy efficiencies were found to be 2.6% and 22%, respectively.
- Solar still incorporated with sodium thiosulfate pentahydrate as PCM results in increased productivity with an increase in the flow rate of cooling water from 6 to 10 ml/s, but the enhancement of the flow rate to 15 ml/s decreases the productivity slightly, causing a negative effect.
- The production rate of solar still is getting enriched with the addition of paraffin wax as a PCM, and a parabolic solar concentrator was incorporated to improve the quantity of solar irradiance, which is absorbed by the still. The experiments reduced salinity from 3000 to 500 ppm and proven that energy efficiency is maximum than the expected value during sunny days.
- Regeneration air was preheated before the entry to the desiccant wheel, and the best value of distillate water for an air mass flow rate of 0.78 kg/s were about 0.411 and 4.9l/h, respectively. Then, the Exergoeconomic analysis is performed with dynamic modelling of PCM, and the output result indicates that the exergy efficiency is about 21.19%.
- The impact of the candle wax as a PCM on the amount of fresh water by using solar units was analyzed, and the results indicate that the melting of PCM reveals the first zone appearance, and the solidification of PCM reveals the second zone appearance. The optimum preheating flow rates of the salty water is studied under meteorological conditions, and the results reveal that the energy efficiency of the solar desalination system is 8.2%, 13% and 20%, respectively.
- The impacts of upper cycle temperature on thermal behavior in galactitol in bulk thermal cycling were studied. Galactitol is a medium temperature latent heat storage PCM of solar cooker, and the bulk samples have the most significant influence on the rate of change of degree of subcooling. The result shows that the amount of latent

heat discharge is reduced substantially by the bulk galactitol, which has the degree of subcooling that falls within the 25.0–40.0 °C range.

- Several reflectors were delivered to enhance the performance of the box-type solar cooker, and the experimental result shows that the accuracy and the thermal efficiency of the solar cooker are 10% and 6.9%, respectively.
- For the preserving process of renewable energy, OPCM combines with a thermal energy storage system. Due to low thermal conductivity and leakage during phase change, the properties of OPCM are not significantly considered. The jacket sand around the cooking pot improves the cooking performance.
- Phase change material acted as a storage media for cooking during the daytime. Moreover, two concentric cylindrical vessels were constructed with 2 cm gaps and the gap was filled by PCM called stearic acid, which results in enhancement of overall efficiency, which is 82%.
- The solar cooker performance is improved by the applications of phase change material (PCM) as a TES medium, and the influence of thermal and geometric behaviour are discussed. Under the testing modification of the solar box cooker, a cylindrical copper tube is infused with TES. The efficiency of the solar cooker is enhanced by using the parallel shape pipe, and a single booster mirror is used along with the inclination of an optimally inclined box type solar cooker, especially in winter.
- In Quonset solar cooker (QSC) kind of solar cookers, the efficiencies of water and glycerin vary from 6 to 35% and from 9 to 92%, respectively. The comparison of a PCM storage unit with a standard solar cooker was studied, and hence, the conclusion reveals that a solar cooker with a PCM storage unit has better thermal performance characteristics.
- The efficiency of a double-walled cooking unit appropriate for an indirect type solar cooking application incorporated with TES was 152 °C, and it has very little time consuming, i.e., 15 min relatively less than conformist liquefied petroleum gas stove. The cooking rate is more effective in the solar cooker having the intermediate temperature (120–240 °C), and it has a variant range of cooking options, which minimizes the time of cooking with a higher range of thermal losses. At a higher level of solar radiation, the constant temperature method results in greater exergy efficiency.
- The efficiency of the solar air heater can be enhanced by using an improved model (SAH-C) integrated with a specific mixture of granular carbon powder and paraffin wax PCM filled inside the helical tubes.
- A double-pass solar air heater with paraffin wax PCM filled in multiple rectangular capsules leads to lagging in the melting period and reduction in melting temperature. Double pass solar air heater system equipped with cylindrical and rectangular macro-encapsulates filled with paraffin PCM has to encapsulate an efficiency of 67 % and 47 %.
- Solar air heater with pinned blade filled and paraffin wax PCM on the absorber surface significantly increases exergy efficiency.
- Solar air heaters with V-corrugated plates and PCM possess an enhancement in daily efficiency of 12% compared with V-corrugated plates without PCM. Packed bed LHTES filled with encapsulated PCM enhances the thermal efficiency from 62% to 64%, enhancing the HTF flow rate from 7.1 pm to 9.3 lpm.
- Using a latent heat storage system with PCM is an effective method in the solar water heater. Several methods are used in the solar water heater to enhance productivity, such as flat plate solar collector integrated with built-in TES, ICSSWH using a PCM layer, solar storage tank integrating PCM modules for solar hot water production, SWHS and heat transfer in the PCM module. The modification associated with the incorporation of PCM significantly enhances the production rate of the solar water heater.
- PCM with photovoltaic cell to frame a PV/PCM system is a suitable method to use the photovoltaic system with increased performance. The temperature of PV cells is as high as 80°C if there should arise an occurrence of enhanced solar radiation forces that initiate the coordinated carrier to focus in the photovoltaic cells to make a prompt higher immersion and to bring down voltage of the photovoltaic cells.
- The phase change material (PCM) has the capability to retain maximum capacity of surplus thermal energy during its melting stage and benefit of it under static temperature later, makes it superior device to increase efficiency of the solar drying system.
- Researchers conducted several experimental analyses in conventional and modified single and double slope solar still with different PCM such as paraffin wax, sodium acetate trihydrate, sodium thiosulfate pentahydrate, paraffin C18 & trimethylolethane material, stearic acid, shape stabilized phase change material, nanoparticles incorporated PCM, palmitic acid and salt hydrate PCM. The result signifies that the addition of PCM in solar still enahcnes the distillate yield by a maximum of 67%.

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