CHAPTER 2

REVIEW OF LITERATURE

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In this Chapter, the literatures on the relevant aspects of the current research work *viz*., (i) characterization of PCM and its importance for selection vis-à-vis applications, (ii) Thermal stability: A critical parameter for selection of PCMs (iii) Compatibility of PCMs with construction material of storage device PCM based solar dryer, (iv) applications of PCMs in Solar air heater and solar dryer (v) modelling and simulation techniques used for design of SAH and (vi) economic and environmental analysis of solar dryer are presented.

2.1 Characterisation of PCM in relation to its selection

An increasing number of individuals are focusing their attention, at this point in time, to the use of PCM for the storage of solar energy. This is a direct result of increased energy consumption as well as concerns about the environment. In general, PCM is a material that has a high enthalpy of fusion; it is capable of absorbing, storing, and releasing a significant amount of heating energy while remaining at a constant temperature.The use of PCM for solar energy storage is the growing focus of the hour due to rising energy consumption and environmental issues. In general, PCM is a substance of high heat of fusion, it can absorb, store, and release a lot of thermal energy at constant temperature. PCM-TES systems overcomes solar energy's intermittency and streamlines the mismatch of energy demand and supply. The energy stored can be used for extended period operation, system efficiency enhancement and cost saving. A variety of PCM are available for TES application with a wide range of characteristics. Considering the merits of PCM materials for several prospective applications, several commercial manufacturers including Rubitherm, Cristopia, Teap, Doerken, Mitsubishi Chemical, Climator and EPS Ltd. have been producing and marketing more than 100 PCM products for industrial, domestic, and medical applications [1-5]. Table 2.1 represents a comprehensive overview of the wide ranges of PCM materials.

Table 2.1: Overview of some PCMs reported in literature

Types with example	Beneficial features	Issues requiring attention	Melting Temperature (ºC)	Latent heat of fusion (kJ/kg K)	Reference
Paraffin (straight chain n-alkanes CH_3–(CH_2)–CH_3) [6]	Higher heat of fusion [6] [7], chemically inert and stable below 500°C [8]	Low thermal conductivity, inflammability, low flash points, toxic, instability at high temperatures [8]	28-76	150-270	[6,7,8]
Non-paraffin (D-Lattic acid, Methyl palmitate, Camphenilone, Docasyl bromide, Caprylone, Phenol)	Wide range of PCM availability [7]	Flammable [7]	26-127.2	86-259	[7,8,9]
Fatty acids (Acetic acid, Polyethylene glycol 600, Capric acid, Eladic acid, Lauric acid, Pentadecanoic acid, Myristic acid, Palmatic acid, Stearic acid, Acetamide) [6]	Higher heat of fusion, reproducible melting and freezing behavior and freeze with no super cooling	Higher cost (~ 2–2.5 times greater than that of technical grade paraffin), corrosive.	16.7-102	146-242	[6,7,8,9]
Salt hydrates ($LiNO_3.2H_2O$, $Na_2S_2O_3.5H_2O$, $MgSO_4.7H_2O$, $CH_3COONa.3H_2O$, $NaOH.H_2O$, $Ba(OH)_2.8H_2O$, $MgCl_2.4H_2O$) [6]	Higher latent heat of fusion, relatively high thermal conductivity (almost double of the paraffin), small volume changes on melting, compatible with plastics, inexpensive [7]	Incongruent melting, slightly toxic	14-117	90-296	[6,7,8,9]

Types with example	Beneficial features	Issues requiring attention	Melting Temperature (°C)	Latent heat of fusion (kJ/kg K)	Reference
Metallics (Gallium–Gallium, Cerrolow eutectic, Bi–Cd–In eutectic, Bi–Pb–tin eutectic)	Higher heat of fusion, higher thermal conductivity	Higher specific weight tends to increase the overall system weight	29.8-72	-NA-	[8]
Eutectics ($CaCl_2.6H_2O$ + $CaBr_2.6H_2O$, $LiNO_3$ + NH_4NO_3 + NH_4Cl, CH_3CONH_2 + $C_{17}H_{35}COOH$)	Melts and freeze congruently and without segregation	-NA-	14.7-81.6	95-218	[8,9]

The different kinds of PCMs, together with their properties, advantages, and disadvantages, are outlined in Table 2.1. In order to ensure the desired performance, economical operations, and safer design of the system such as a latent heat thermal energy storage system (LHTESS), it is essential to take into consideration the beneficial features of a PCM before making a preliminary choice of a PCM for a specific application. These beneficial features include high enthalpy of fusion, superior thermal conductivity, availability, nontoxicity, and less price. In general, selection of PCM is based on some key factors *viz*., (i) thermophysical (melting temperature, latent heat), and chemical properties (non-toxic, compatible, and durable), (ii) kinetic features and (iii) economic and environmental considerations [10]. The intended use, operating conditions, and desired performance also influence the selection of PCM. Due to the diversity of the inherent properties, users are always confronted with a situation to select the optimum material which is governed by the above-mentioned factors. Thermal and physical properties include a phase-change temperature suitable for the range of acceptable temperatures for operation, high heat transfer efficiency and thermal conductivity, high enthalpy of fusion, superior density and specific heat, long-term thermal stability, consistent melting behaviour, equilibrium in a positive phase, no phase separation, little alteration in capacity during phase transition, and reduced vapour pressure at temperatures of use. Kinetic features include reduced liquid supercooling, high nucleation rate, and a quick rate of crystallisation. Chemical features include reversible melting and freezing, chemical stability after repeated cycles, compatibility with construction materials without corrosion, and non-explosiveness, non-flammability, and non-toxicity. The PCM's affordability, abundance, and accessibility make it economic. Environmental qualities include low embodied energy, materials isolation, recycling, low ecological effect, and non-polluting characteristics [11-15].

The heat transfer capacity of PCM is essentially regulated by its primary applications, which include thermal insulation or inertia and storage. Thermal insulation or inertia and storage are two major applications of PCM which are primarily governed by the thermal conductivity of the material. For instance, higher thermal conductivity is preferable for thermal storage to improve heat transfer, whereas low thermal conductivity is necessary for thermal insulation purposes. Characterization is essential for identifying an ideal PCM for successful LHTES application [10]. PCMs have numerous uses in a variety of industries such as heating, cooling, power generation, and cold storage with a temperature range of -50 to 200ºC [16,17]. Specifically, PCMs are used in building insulation and construction industry [18], textile industry [19], electronics industry [20], solar power plants [21], healthcare [22] and food storage [23]. PCMs should be selected that are the best suited for the respective applications. Due to wide range of characteristics and varied types of applications, selection of appropriate PCM has remained a matter of investigation. Table 2.2 summarises some of the approaches used for PCM selection that are documented in the literature.

Table 2.2: PCM selection methodology for some applications

Methodology for PCM selection	Application	Selected PCMs	Ref
Multi criteria decision approaches viz., (i) Analytic hierarchy process, (ii) Entropy method, (iii) TOPSIS method, (iv) VIKOR method and (v) EXPROM2 method	Domestic water heating	The best three PCMs are Sodium acetate trihydrate (90%) + graphite (10%), Stearic acid, and n-hexacosane out of 15 preselected PCMs	[24]
Fuzzy based hybrid multi criteria decision matrix viz., (i) Fuzzy analytic hierarchy process computations, (ii) TOPSIS computations, (iii) VIKOR computations and (iv)	Electronics cooling system	Out of 10 PCMs, the best PCM identified was RT-80	[25]

Methodology for PCM selection	Application	Selected PCMs	Ref
PROMETHEE computations			
Multiple Objective Decision-Matrix (MODM) and Multiple Attribute Decision-Matrix (MADM) approach viz., (i) Analytic hierarchy Process and (ii) TOPSIS	Passive thermal management in an automobile cabin	Gallium was recommended out of 26 pre-selected PCMs	[26]
Multi-criteria decision matrix viz., (i) Analytic hierarchy process, (ii) Entropy information method and (iii) TOPSIS	Ground source heat pump (GSHP) integrated with phase change thermal storage (PCTS) system	$Ba(OH)_2.8H_2O$ was found as best PCM material out of 8 PCMs	[27]
Multiple Attribute Decision-Matrix (MADM) viz., (i) TOPSIS, (ii) Fuzzy TOPSIS and (iii) Analytic hierarchy process	Solar domestic hot water system	Calcium chloride hexahydrate is preferred as best alternative out of 9 PCMs	[28]
Multiple Attribute Decision-Matrix based on TOPSIS and AHP	Solar air conditioning applications	Erythritol ranked first during ranking out of 10 PCMs	[29]
Qualitative decision matrix (QDM)	Building heating applications	The results showed that RT28HC has the best potential in this application in all scenarios with 78.3%, 80% and 73.3% in Scenario A, Scenario B and Scenario C out of 7 PCMs	[30]
Multi-attribute decision-matrix technique (i) The weight of the attributes needed for TOPSIS calculation is obtained by using AHP method. Two different models TOPSIS and fuzzy TOPSIS were employed	Thermal management of electronic devices	The optimum PCM for thermal control of electronic components was (RT)44HC out of 30 PCMs	[31]

As seen in Table 2.2, optimization techniques are used for selecting PCMs for a wide range of purposes using characteristics of PCMs (e.g., phase change temperature, latent heat, sensible heat, thermal conductivity, specific heat and density, melting point, volume change, vapour pressure, supercooling, incongruent melting, thermal stability, phase separation, recyclability, toxicity, compatibility, corrosion, flammability, maximum operating temperature, cost) as decision criteria to best the application conditions. In general, the identified PCMs are recommended for applications such as domestic water heating, electronics cooling system, passive thermal management in an automobile cabin, ground source heat pump, solar air conditioning and building heating.

2.1.1 Thermal stability: A critical parameter for selection of PCMs

In addition to the favourable melting temperature, absence of subcooling, lack of phase separation, and toxicity, thermal stability has also been identified as one of the important parameters. Thermal stability on repeated thermal cycles without losing inherent characteristics is desired for long term stability of PCM. Thermal cycling experiments of PCMs are designed to find out whether its thermal properties are impacted by the thermal exposure. As a result, the success of the LHTES is heavily reliant on the stability of the PCMs. Thermal stability of PCM can be determined by estimating the thermophysical characteristics of the PCM following a series of repeated heat cycles. To ensure the LHTESS's long-term functionality, a full understanding of the thermal stability of PCMs as a consequence of multiple repeated heat cycles is required [32-35]. There are two accelerated thermal cycling methods viz., pyramid and the dynamic methods mostly used to study about the thermal reliability of the PCM. In pyramid method, the PCM samples are heated and cooled repeatedly without any isothermal stages whereas in dynamic method PCM samples are subjected to isothermal stages before and after each heating and cooling cycle. Trends suggest the preferences for dynamic method of cycling over the pyramid method, however, no material specific recommendations are available [36]. Accelerated thermal cycle is performed to check the thermal stability with reference to key properties viz., phase transition temperature and latent heat of fusion using standard method (differential scanning calorimetry, DSC). The degree of deviation of phase change temperature and latent heat are estimated using relative percentage difference (RPD %) to understand thermal stability of the PCM [37]. Thermogravimetric analysis (TGA) is also amongst the prevalent technique to estimate degradation characteristics of PCM to be tested for long term storage performance [38].

2.1.2 Compatibility of PCMs with construction material of storage device

One of the reasons that prevented the widespread deployment of LHTESS is the lower usable life of PCM-container systems due to corrosion between the PCM and the container caused by long-term exposure and repeated heating and cooling cycles. PCM corrosion with the contact material reduces system life. PCM materials' corrosion characteristics in contact with container metal surfaces like aluminium, brass, copper, carbon steel, stainless steel, and Perspex have been studied for thermal comfort building, heating, cooling, and TES. The rate of corrosion, usually represented as loss of mass per unit of surface area per year, depends on the contact surfaces and PCM. While testing with several PCMs (inorganic mixture, ester, different fatty acid, eutectics, and certain commercial PCMs), aluminium, copper, carbon steel, stainless steel, brass, and Perspex showed a wide range of corrosion rates (mg/cm^2 year). Stainless steel generally resists corrosion. The permitted corrosion rate depends on the application [39-41]. The mass loss characteristic i.e., gravimetric analysis does not reflect the surface characteristics which is also matter of concern for many applications. Therefore, surface degradation behaviour has also been studied along with the gravimetric analysis using metallographic investigation such as microscopic imaging. There are standard methods to evaluate surface roughness using profilometer which can also be used to estimate corrosion induced surface roughness to understand the PCM and container material compatibility [42].

2.2 Applications of PCMs in Solar air heater and solar dryer

Solar thermal applications are drawing increasing attention in the solar energy field. The notable applications include process heating, space heating, refrigeration, air-conditioning, food, textiles, building and chemical industries [43-45].

2.2.1 PCM based SAH

PCMs have found application in solar heaters for various applications. PCMs used in different solar heating applications differ based on the type, configuration of the PCM integration and other influencing parameters such as melting temperature of PCM, air mass flow rate, desirable outlet temperature, energy and exergy performance. Table 2.3 represents an overview of various studies utilizing PCM based solar heating.

Table 2.3: A brief review of integration of PCMs in SAH

Configurations of PCM integration	**PCM (*Details*)**	**Salient findings**	**Ref**
Staggered set of tubes filled with storage PCM.	Paraffin wax (*Melting temperature: 61 °C, 51 °C, 43 °C, 32 °C*)	The best results were achieved with 51 °C and 43 °C. Mass flow rate of 0.01 kg/s gave rise to 8 ºC outlet temperature difference.	[46]
Cylindrical steel tank (11.6 m^3) insulated with glass wool (0.05 m) and steel plate (0.001 m) around the whole surface	Paraffin wax (*Quantity: 6000kg*)	Average net energy and exergy efficiencies were 40.4 % and 4.2 % respectively.	[47]
Cylindrical tubes (48 nos.) with height (0.75 m) and diameter (0.05 m).	Paraffin wax (*Quantity: 48 kg*)	Drying temperature maintained at range between 40 °C and 45 °C. The energy efficiency of the dryer was found to be 28.2 %.	[48]
Cylindrical acrylic vessel with diameter (0.10 m) and height (0.20 m). A copper tube through which heated heat transfer fluid flowed is attached with copper fins (18 nos.) with 0.01 m spacing between each fin.	Paraffin wax (*Melting point: 34 ºC - 54 ºC*)	Extractable energy per unit mass flow rate of inlet ambient air (1920 kJmin/kg and 1386 kJmin/kg) and energy savings (40% and 34%) with inlet air velocity of 1 m/s and 2 m/s.	[49]
Cylindrical plastic containers (2nos.) with height (0.3m) and inner radii (0.15m) filled with PCM and insulated from bottom and side.	Paraffin wax (*Melting point: 49 ºC*)	Drying air is 2.5 ºC – 7.5 ºC higher than ambient air after sunset for five hours.	[50]
A packed-bed absorber formed of spherical capsules containing PCM with a black coating fixed with steel matrix.	AC27 (*Melting point: 27 ºC*)	Daily average energy and exergy efficiency is 40% and 22% respectively.	[51]
PCM was inbuilt beneath the absorber plate. A copper pipe of 0.012m inner diameter and 1.35m long was embedded inside the PCM to carry the heat transfer fluid inside the collector.	Paraffin wax (*Melting point: 53.5 ºC*)	Discharging process took 2.75 hours for the drop of useful energy (160 W to 20 W) with 0.021 kg/m^2h mass flow rate.	[52]

Configurations of PCM integration	PCM (*Details*)	Salient findings	Ref
The heat exchanger made of PVC tube containing the PCM with diameter (40mm) and length (550mm)	Stearic acid (*Quantity: 400 g*) and (*Melting point: 65-69 ºC*)	Charge and discharge time, as well as heat release rates, are reasonable. Because of the impact of natural convection in the melted PCM, the melting front moves in radial and axial directions.	[53]
2 mm-thick hollow concentric aluminium cylinders (18cm and 25cm diameter, 8cm height). PCM filled the cylinder gaps. The PCM container can cook with a 17.5cm-diameter, 10-cm-tall cooking vessel.	Acetamide (*Melting point: 82 ºC*)	Solar energy storage has no effect on the performance of the solar cooker for noon cooking, and cooking with the current design will be possible even at night when PCM with melting temperature between 105 ºC and 108 ºC is employed.	[54]
Expanded metal mesh (EMM)	Salt hydrate (46 °C),	Aluminium EMM sheet created 90 % porosity. PCM melted 14 % faster with EMM. Simulation indicated that parallel, well-contacting EMM layers reduced melting time by 81 %.	[55]
Macro-encapsulation with spherical, tubular, cylindrical or rectangular container shape.	ClimSel	ClimSel-temperature-stable transport. ClimSel under an office building's ceiling in Stevenage, England, almost eliminated air conditioning. Soldiers, firefighters, foundry workers, and miners uses heat-absorbing PCM-integrated clothing. Desert substation electronic equipment temperature stabilisation.	[56]
PCM balls kept inside storage tank between two grid plates kept in the steel tank that provides support and also uniform distribution of air.	HS 58	Around 60 % of thermal efficiency is achieved.	[57]

The Table 2.3 presents an overview of various PCM integration techniques in different configurations and applications, including specific details such as PCM types with varying melting point and key findings in the process. These studies provide insight into the potential of PCMs for temperature regulation in a wide range of LHTESS. It has also been found that the incorporation of PCM with different configurations enhances the performance of the system, leading to increase in the temperature of the system's output as well as increases in the system's energy and exergy efficiency. Air input, air exit, absorber plate, glazing, insulation, and structural frame comprise the flat plate collector type SAH. SAH capture the solar radiation which is absorbed, converted into thermal energy, and transferred to flowing air, generating hot air up to 90 ºC and typical temperatures of 70 ºC can be used for process heat without a heat exchanger. SAH operation however face limitation due to thermal energy loss caused by low absorber plate and air stream heat transfer coefficients. Thermal efficiency is also reduced by air's low thermal capacity and density. Increasing the heat transfer coefficient between the absorber plate and moving air improves SAH performance [58-61]. Accordingly, there are now various design configurations of flat plate SAH, based on its mode of heat transfer (active, passive and hybrid) and geometric configuration (single channel, double channel, with glass and without glass) [62,63]. The focus for development of SAH is to maximise heat uptake while limiting heat loss which resulted in variety of design with a wide range of performances [64]. Some of the notable approaches for optimization to improve the SAH performance are improving the dimensions of the air heater construction elements, usage of extended surfaces with different shapes and dimensions, shape optimization of absorber, using rib-grooved artificial roughness, use of sensible and LHS media, use of concentrators to augment the available solar radiation and integrating photovoltaic elements with the SAH [65-69].

2.2.2 PCM based solar dryers

PCM-based solar dryers is the technology adopted for the current study. Performance of some of the PCM based solar dryers developed by various researchers, the findings of which laid the basis for the development of the PCM based solar dryer developed in the current study is summarized in Table 2.4.

Table 2.4: Performance of PCM based solar dryers

(Solar dryer types) and product dried	PCM used and its integration arrangement	Major findings	Ref
(Indirect Solar Dryer). Momordica charantia (bitter gourd)	Cans filled with paraffin wax and four thin aluminium strips enclosed in every can.	Thermal efficiency of 19.41 % achieved. Potential for improvement, waste energy ratio, and sustainability index average evaluated are 2.97, 3.89, and 1.74, respectively. Energy payback of 1.42-years, 35-year CO_2 emissions and mitigation are 23.88 kg/year and 20.128 tonnes. ISD earned \$100.642–\$402.569 in carbon credit.	[70]

(Solar dryer types) and product dried	PCM used and its integration arrangement	Major findings	Ref
(Solar tunnel dryer). Pineapple	A shell and tube heat exchanger filled with PCM (Acetamide)	Heat energy contribution from PCM is found to be 1,660 MJ. The developed model is preferred to be well utilised for solar drying applications for partial energy requirement during night hours.	[71]
(Forced convection flat plate solar dryer). Chilli	Paraffin wax-based shell and tube LHS unit	Two (SAH's) energy and exergy efficiencies are (32.4 % and 0.9 %) first and (14.1 % and 0.8 %) second respectively. The LHS unit has 43.6-49.8 % energy and 18.3-20.5 % exergy efficiency. Drying chamber average energy efficiency is 52.2 %. Chilli used 6.8 kWh per kilogramme of moisture and dried 10.8 %.	[72]
(Indirect mode natural convection solar dryer). Banana slices	PCM (paraffin wax) layer of 1 cm thickness placed between the bottom of the casing and absorber plate of the solar collector.	The moisture content reduced at a quicker rate for the lower tray with moisture ratio from 100 to 28 %. The maximum and average dryer and collector efficiencies are (9.88 and 2.98 %) and (85.46 and 66.32 %) respectively.	[73]
(Indirect mode forced convection solar dryer). seeded grapes.	Calcium chloride hexahydrate as PCM placed in the lower section of collector.	The swirl elements give the whirl effect to air flow in drying room helped in lowering the moisture value and lesser drying time. It is also observed that Midilli model provided the most appropriate results for each drying state in the seeded grape drying.	[74]
(Indirect solar dryer) potato slices.	Paraffin wax filled inside five small compartments attached beneath the absorber plate, each was capable to store 1 kg.	Following the sunshine period, the PCM inside the solar collector dramatically increased the dryer room inlet temperature for two hours. Thus, with the help of paraffin based PCM, the percentage weight of moisture removal from potato slices increased by 5.1 % each day.	[75]

In brief, the Table 2.4 provides an overview of a variety of solar dryer designs for drying of some products and the arrangement of PCM integration in the solar dryer. The research findings highlight the thermal efficiencies, energy contributions, drying efficiencies, and moisture removal rates attained utilising various PCM arrangement configurations. In a variety of agricultural and food drying applications, these studies indicated the potential for PCM integration in solar dryers to improve energy efficiency, shorten drying time, and enhance product quality. It has been found that PCM-based solar dryers differ in general dependent on the position of the PCM in the solar dryer, viz., (a) below the absorber surface, (b) in the heat exchanger, and (c) inside the drying chamber [76].

A PCM based solar dryer was developed with collector area of 0.64 m^2 and three trays each of 0.42 m^2 area in the drying chamber. A real-time data gathering system is included into the dryer to keep track of the temperature, humidity, and moisture loss. 20 kg of paraffin wax were also added to the collector to serve as a LHS medium for ongoing drying after sunlight. By drying fresh mint and coriander leaves with an initial moisture content of 82–86 % (wb), Its performance was compared to that of the developed dryer without PCM and shade drying, considering both the drying parameters and quality parameters of the dried herbs. Considerable change in drying rate is obtained [77]. The drying kinetics of food products were investigated using paraffin wax (melting temperature 54 ºC) in a sun drier. The study concluded that when the inlet air velocity is 1-2 m/s, the system can reduce the necessary thermal energy to dry sweet potato by approximately one-third [78]. HS 58 PCM having melting temperature 58 ºC was used in indirect solar dryer system. The system provided air temperature more than 50 ºC during the discharging period for 4 h when the mass flow rate is 0.0555 kg/s and the use of PCM improved the performance of the drying system [79]. Active and passive sun dryers with thermal energy storage systems (TESS) (sensible and latent) were tested for medicinal herbs. The PCM used was RT-42 paraffin. Exergy and energy analyses were used to evaluate drying performance, with solar collector exergy and energy efficiencies of 0.14 and 0.81 % without TESS and 9.8 and 26.10 % with TESS [80]. The greenhouse dryer was built using a hybrid drying strategy for drying bitter gourd, and the system's energy, economic, and environmental outcomes are examined. When compared to open sun drying, their recommended setup saved 8 hours to dry the sample product from 88.14 to 10.14 %(wb) [81]. The design and development of a solar dryer with a TESS included a solar flat plate, a packed PCM energy storage bed, a 12 kg fresh plant container, and a natural convection system. The heat energy stored by the PCM was sufficient for 5–6 h after sunset. The temperature of 6 ºC above the ambient temperature was maintained until midnight, and the thermal efficiency of this dryer was assessed to be 28.2 % [82].

2.3 Application of modelling and simulation software for SAH design

To develop a PCM based SAH system, a mathematical model of SAH helps in design, analysis of performance and optimization of the system. The net heat output of an exposed SAH array can be recreated at indoors employing numerical thermal performance evaluation methods. The outline of the steps involved in the mathematical modelling process:

(a) Define system parameters and considerations: Specify the key PCM-based solar air heater system parameters. This includes solar radiation intensity, collector area, PCM properties (melting point, latent heat of fusion), air flow rate, and inlet/outlet air temperatures. Optimise collector area, PCM characteristics, and operating circumstances using mathematical models to maximise heat transfer efficiency and minimise energy losses [83].

(b) Energy balance equations: Develop energy balance equations for the system's individual components. This includes considering the solar energy input, convective heat transfer between the collector and the air, energy storage and release in the PCM, and heat transfer to the surrounding environment. Consider both sensible and latent heat transfer processes in the energy balance equations [84].

(c) Heat transfer analysis: Model the heat transfer processes occurring within a system using the applicable heat transfer equations. This includes conduction within the PCM, convection between the PCM and the surrounding air, and radiative heat transfer. Incorporate relevant heat transfer coefficients and variations in temperature into the calculations [85].

(d) PCM phase change modelling: Utilise the appropriate mathematical models to include phase change phenomena in the PCM. Typically, this entails accounting for the solid-liquid phase transition and the resulting variations in heat storage/release. To model the PCM phase transition process, techniques such as the enthalpy-porosity technique may be used [86].

(e) Numerical solution: Utilise numerical methods such as finite difference, finite volume, or finite element methods to solve the system equations. Discretize the system domain and iteratively solve the equations to determine the system's temperature profiles and heat transfer rates [87].

(f) Model validation: Compare the results of the mathematical model to experimental data or published results for analogous systems in order to verify its accuracy. If required, adjust model parameters to improve the agreement between model predictions and experimental observations [88].

(g) Optimization and uncertainty analysis: Utilise the mathematical model to optimise and conduct uncertainty analysis. This involves altering system parameters within certain ranges to identify the optimal design configurations that maximise the system's performance. Uncertainty facilitates the comprehension of the effects of parameter variations on the system's behaviour, as it is an essential index for evaluating the precision of experiment testing results and is calculated based on the independent variables involved [89].

It is important to note that the mathematical modelling approach may differ depending on the specific PCM based solar air heater configuration and the level of complexity required for accurate representation. The modelling process should be validated and refined based on experimental data and system-specific considerations. Various mathematical models, primarily analysing the heat transfer process of SAH, have been studied. Various mathematical models have been developed by researchers to study the behaviour of SAHs. The overview of some of such models, the findings of which helped in formulation of the design of the SAH developed in the current study.

A mathematical model anticipated the thermal efficiency, heat gain, and outlet air temperature of a covered plate attic solar collector. This study simulates SAH behaviour using heat transfer concepts and correlations. An attic solar collector drying operation verified the model's outlet air temperatures and collector efficiency. The mathematical model examined the effect of air speed inside the collector and wind speed above the collector on the collector efficiency and concluded that 4–6 m/s was optimal [90].

SAH performance evaluation criteria such as thermal efficiency, exergy, heat transfer, heat loss, friction factor, and pressure drop have been specifically studied using modelling, and optimisation software tools viz., CFD, EnergyPLAN, energyPRO, 9Invert, LEAP, RETScreen, SIVAEL, WATSUN, POLYSUN, MATLAB-Simulink, SOLTHERM, EnergyPlus, COMSOL, and spreadsheets for solar heating systems [91].

The novel SAH idea was demonstrated and validated using Computational fluid dynamics (CFD) computation for implementing and testing. The device was recommended to maintain consistent ambient conditions for thermal comfort and minimal energy usage for interior spaces, greenhouses, passive homes, and buildings against thermal swings. SAH prototype operation tested for 350 days and found good agreement between the Open FOAM (an open source numerical CFD software) numerical simulation and experimental results [92]. COMSOL Multiphysics 3D model optimised PCM SAH exchanger setup for solar energy storage and ventilation pre-heating. The study found that 90 mm PCM plate depth and 6 mm air gap thickness were optimal for 6-h solar charging. Summer night cooling and winter solar energy storage employed the same arrangement. One charging phase released 93.31 MJ/m3 of latent heat [93].

2.4 Economic and environmental analysis of solar dryer

Solar dryers' viability as an alternative to conventional drying processes depends on the economic and environmental assessment. Through economic analysis, it has been demonstrated that the use of solar dryers significantly reduces the carbon footprint associated with the energy-intensive drying process. CO_2 mitigation is a tool for measuring climate change potential that provides the opportunity to reduce greenhouse gas emissions by capping total annual emissions and allowing the market to attribute a monetary value to any emissions shortfall through trading. Carbon credit is an instrument that represents any tradable certificate or permit that grants businesses or industries the right to emit one metric tonne of carbon or carbon dioxide equivalent. Carbon credits are essential for the implementation of an emission trading approach [94].

Utilising solar energy, specifically solar drying systems, typically necessitates a substantial initial investment compared to conventional energy conversion equipment. Consequently, economic analysis is the most important step in determining the system's usefulness in practise that is based on initial investment, operating, maintenance, and potential returns. Solar drying systems must be utilised continuously throughout the year to be economical in comparison with electricity, oil, and gas drying systems [95].

Four solar drying system economic indicators viz., (i) cost benefit ratio, (ii) internal rate of return, (iii) net present worth and (iv) payback period was suggested. To obtain the discount rate that made the incremental net benefit stream's net present worth zero, the internal rate of return was calculated by trial-and-error. A naturally ventilated solar greenhouse was used to grow cucumbers and tomatoes for economic feasibility. Cucumber's cost-benefit ratio was 2.17, higher than tomato's 1.77. The cost benefit ratio of the product was commercially viable if it exceeded one [96].

Hybrid PV thermal greenhouse solar dryer characteristics was tested and observed that it operated well in every weather since it used direct and diffused radiation. Compared to other systems, energy and exergy payback times were 1.23 years and 10 years, respectively. CO_2 mitigation and carbon credit obtained over 25 years were 81.75 tonnes and $817.50, respectively that ensured the system sustainability [97].

The benefits of solar drying were examined as an alternative to using fossil fuels and electricity for farm machinery in agriculture. Solar drying not only reduced greenhouse gas emissions but also decreased post-harvest food losses. The indirect solar dryer unit experimented drying of 2 kg of fenugreek leaves in each tray. Several environmental and economic parameters were evaluated, including the payback period, energy payback time, embodied energy, CO_2 emissions, and earned carbon credits. The total embodied energy of the system was calculated to be 1081.83 kWh. The energy payback time was determined to be 4.36 years, and the annual CO_2 emissions amounted to 391.52 kg. These findings highlighted the potential of solar drying as a sustainable and cost-effective solution for farmers, promoting energy efficiency and reducing carbon footprints [98].

2.5 Summary

Comprehensive overview of the thermophysical properties of a range PCM materials used for a variety of applications is presented in this Chapter. Optimum selection of PCM and its integration for TES depend upon the characteristics of PCM. Adequate research-based know-how concerning characteristics vis-à-vis selection of PCM have been generated, notable highlights, relevant to the current research are presented in this Chapter. Review concerning (i) thermal stability of PCM and (ii) compatibility of PCM with the container materials for long term storage have also been elaborated as current research has implication on these aspects. Applications of PCM based solar heaters claiming (i) efficient utilization of solar energy for heating purposes, (ii) contribution to energy conservation, and (iii) reducing reliance on conventional energy sources which have been cited in literature are also analysed in the context of the current research work. Reported literature on (i) various configurations of PCM integrated SAH and (ii) design of PCM integrated SAH using mathematical models and software are elaborated. The importance of parametric representation of the system and applications of energy balance vis-à-vis heat transfer analysis including PCM phase change modelling for designing are also elaborated. Overview of economic and environmental contexts in earlier research works on PCM integrated SAH are also presented. Finally, the review enabled to justify the identification of the research gaps and provided a comprehensive know-how to get support for refining the methodology and presenting the outcomes through proper discussion.

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