Chapter 2

Literature review

2.1 Introduction

Now-a-days the provision of pure drinking water is becoming a challenging issue in many areas of the world. In urban and sub-urban regions, drinking water is very scarce, and living of a human being in these areas strongly depends on how much water can be made available. Solar energy can be considered as the most prominent clean and renewable resource (El-Sebaii and El-Bialy, 2015). Solar distillation has been in practice for a long time. In 15th century solar radiation was exposed to water heating, evaporate and condensate (Nebbia and Menozzi, 1968). In the 16th century, Arab Alchemists carried out the first documented work on solar still (Mouchot, 1869). Solar still is a frugal technology which is economically viable and has potential in decontaminating water and thus, it became popular especially in resource limited settings where there is scarcity in drinking water. Distillation of contaminated water utilizing solar energy is admitted as solar distillation and the system used for solar distillation is known as a solar still (El-Sebaii and El-Bialy, 2015). In 1870, the first American patent on solar still was granted for experimental work (Wheeler, 1870). After two years in 1872, Carlos Wilson, an engineer from Sweden, designed and built the first large scale solar distillation plant in Las Salinas, Chile, for large-scale distilled water production (Talbert, 1970). In 1970, Talbert et al. (Talbert, 1970) presented the historical background of solar distillation and Bloemer et al. (Bloemer et al., 1965) reviewed the major plant of solar still around the world in 1965. Sharshir et al. (Sharshir et al., 2017) mentioned that the solar stills were mainly categorized as passive and active systems. The most commonly used solar still is a simple passive still, where the heat collection and distillation processes occur within the same system. The active solar still accommodates an auxiliary source (like flat solar collectors, solar ponds, waste thermal energy from industries and power plants) to supply excess heat to the contaminated water in the basin to enhance its evaporation rate for maximum production of distillate. In line with the development of passive solar still, Taghvaei at al. (Taghvaei et al., 2014) concluded that the main drawback of solar still was its low productivity. Many researchers worldwide have conducted multiple studies on the improvements of productivity of solar still. Most of them found that the performance of solar still highly depends on absorption area, tilt angle, heat transfer, water depth, evaporation area, heat loss (mainly side and bottom walls) and glass cover temperature. During the recent years, the major development in the field of solar distillation has been found in using thermal energy storage medium other than water to increase the efficiency of the distillation unit. The thermal energy storage medium helps in stocking the thermal energy in the form of sensible heat or latent heat or both, which can be utilized at a later time for industrial, building heating and cooling applications, and solar distillation purposes (Sarbu and Sebarchievici, 2018). The main advantages related to thermal energy storage include an increment in overall efficiency, better economics, lower running cost and increased reliability. However, solar energy (in rainy season) and wind energy are not always available at time of need. To overcome this problem, phase change materials can be used for energy storage. Latent heat is achieved by using phase change materials while conducting the solar distillation experiment in the beneath of the water basin and, we found that distillate and efficiency increases both (Radhwan, 2005). Ansari et al. (Ansari et al., 2013) has also confirmed that PCM position (paraffin wax) beneath the water basin and conclude the efficiency and productivity was about 61% and 4.9 L/m^2, respectively, in the stepped solar still. Therefore, the possible use of phase change materials (PCMs) as a thermal energy storage medium in solar system applications are worth investigating.

2.2 Thermal energy storage

It can be stored as a sensible heat and latent heat or a change in the internal energy of materials as a collection of these. A general sketch of major techniques of solar energy heat storage is shown in Fig. 2.1.

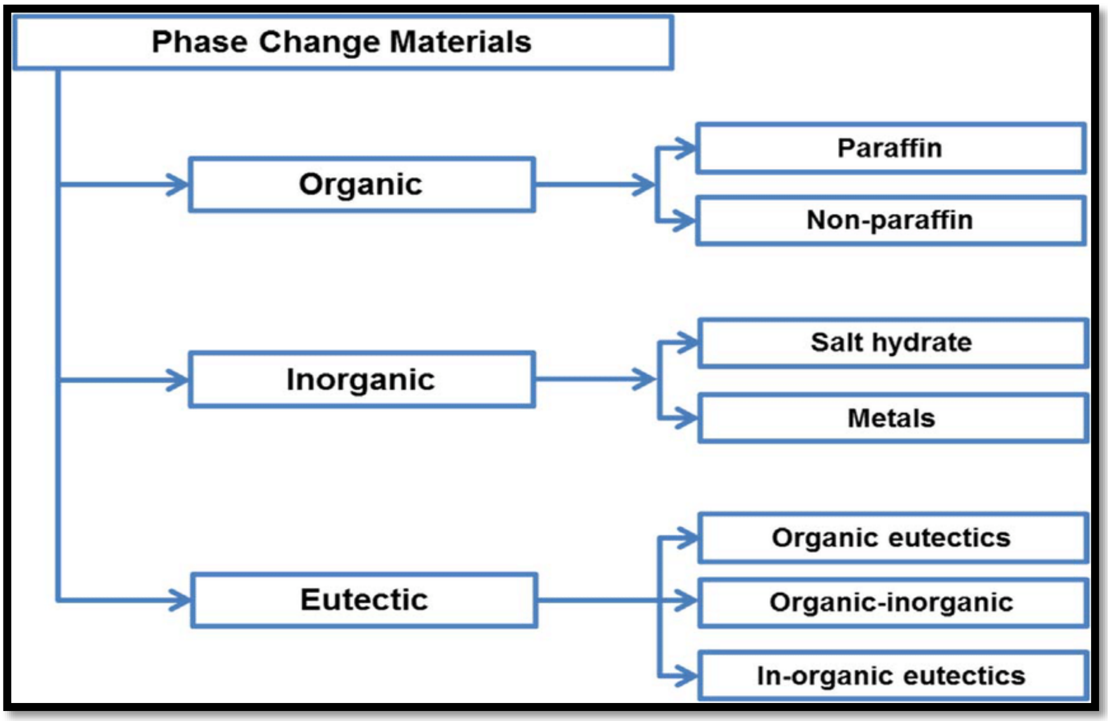

Fig. 2.1 Classification of phase change materials (Kant et al., 2016c)

2.2.1 Sensible heat storage

Solar radiation in sensible heat storage is stored by increasing the temperature of a solid or liquid. In this process the heat capacity and change of material are used during the process of changing and discharging mode. The amount of heat stored depends on the specific heat of the medium, the temperature change, and the amount of storage materials in the process is given by (Sharma et al., 2009) in Eqs. (2.1) and (2.2):

$$Q = \int_{T_i}^{T_f} mC_p \mathrm{dT} \tag{2.1}$$

$$Q = mC_p(T_f - T_i) \tag{2.2}$$

Also, water can absorb solar energy only in the form of sensible heat (no phase transformation occurs), and hence, no energy can be obtained once light intensity becomes zero after sunset. However, the solar still integrated with PCM (shown in Fig. 2.2) stores solar energy in form of sensible heat and latent heat due to its phase change phenomenon.

2.2.2 Latent heat storage

Absorbing and releasing heat in latent heat storage are based on the storage materials, when phase change occurs in the storage materials from solid to liquid or liquid to gas or vice versa. The storage capacity of the latent heat storage system with PCM is given by Sharma et al. (Sharma et al., 2009) in Eqs. (2.3) and (2.4):

$$Q = \int_{T_i}^{T_m} mC_p dT + ma_m \Delta h_m + \int_{T_m}^{T_f} mC_p \, dT \tag{2.3}$$

$$Q = m[C_p(T_m - T_i) + a_m \Delta h_{m+} C_p(T_{f-} T_m)] \tag{2.4}$$

In the middle of the above thermal heat storage methods, the latent heat thermal energy storage is surprisingly attractive due to its ability to provide high energy storage density and its characteristics for storing heat at constant pressure corresponding to the phase transition temperature of PCM. Overall, these transitions have smaller latent heat and small volume changes than solid to liquid transitions. The volume changes of PCMs upon melting will also attract the special volume design of containers to all PCMs. Several experimental as well the theoretical studies were carried out to investigate the influence of PCM on the performance and thereby, productivity of a solar still.

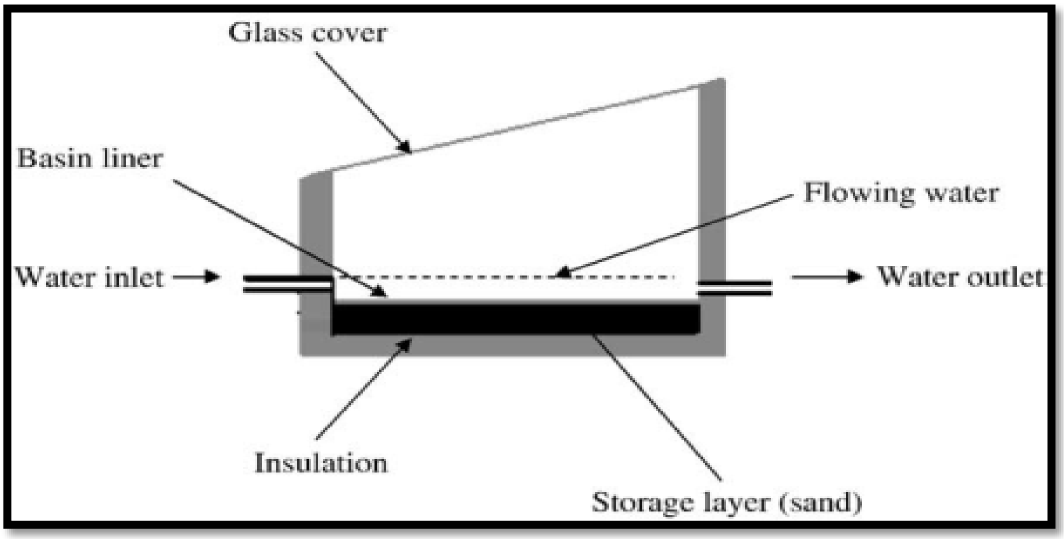

Fig. 2.2 A schematic diagram of the single basin solar still with heat storage material (Tiwari, 2013)

Sharma et al. (Sharma et al., 2009) also mentioned that PCM can absorb 5-14 times more heat per unit volume as compared to sensible heat storing capacity of water, rock, or masonry. El-Sebaii et al. (El-Sebaii et al., 2009a) mentioned the appreciable increase in daily productivity from 0.64 (kg/m^2-day) to 2.38 (kg/m^2-day) for solar still coupled with PCM (stearic acid) as compared to a system without PCM. The main advantages associated with PCM are its low cost, easy availability, suitable phase transforming temperature range, high latent heat of transformation with long term chemical stability, and improved performance in terms of heat transfer and daily productivity. Sarhaddi et al. (Sarhaddi et al., 2017) experimentally analysed two weir-cascade basin solar stills with and without paraffin wax, which have been founded to have energy and exergy efficiencies as 76.69% and 8.59% with paraffin wax. Yousef et al. (Yousef et al., 2019) reported the results for the performance of a single slope solar still with paraffin wax where during sunshine hours productivity has been increased by 7%, and during sunset hours productivity has been increased by 400%, compared to traditional solar still. Yousef et al. (Yousef and Hassan, 2019) performed the comparative study for the single slope solar still with paraffin wax and steel wood fibre where total productivity were 17% and 7%

higher than that of conventional solar still, respectively. They also reported that for a solar still integrated with both steel wood fibre, and paraffin wax increased daylight productivity by 14% and overnight productivity by 80% compared to a solar still coupled with only paraffin wax. Kabeel et al. (Kabeel and Abdelgaied, 2017) examined the impression of a cylindrical concentrator on a solar still with paraffin wax present under the basin of still increased the daily distillate productivity of the solar still by 140.40%. Kabeel et al. (Kabeel et al., 2017) showed experimentally that the use of paraffin wax increases the productivity of freshwater by 67.18%, compared to conventional solar still.

Phase change materials are also known as latent heat storage materials, which can be used for thermal energy storage, building heating and cooling applications (Kant et al., 2016c; Kant et al., 2016b; Sharma et al., 2013; Tyagi and Buddhi, 2007), crops dying (Bal et al., 2010; Bal et al., 2011), cooling of photovoltaic (Biwole et al., 2013; Huang et al., 2006; Kant et al., 2016b), electronics cooling and solar greenhouse (Kandasamy et al., 2008; Shukla et al., 2016; Tan and Tso, 2004). According to (Kalogirou, 1997), in the earliest experimental works, various types of processes that are analysed, the multi-effect boiling system, and multi-effect stack type evaporator are the most suitable for solar energy utilization. Ibrahim et al. (Ibrahim et al., 2015) studied a single and double basin type solar still, which is the most widely used for distillation through solar energy. Kumar and Tiwari (Kumar and Tiwari, 1996) found experimentally a single effect active solar still with water flow over the glass cover, which produced the highest distillate. Kabeel et al. (Kabeel, 2009) modified the new design for better productivity based on the local climatic condition and operating condition that is a concave wick type evaporation surface. The comprehensive reviews of the solar desalination technique were reported by Tiwari et al. (Tiwari et al., 2003b). The simple solar still is the most widely used. However, the main disadvantages of the simple solar still are low productivity and difficulty to fulfil daily demand for freshwater. Arunkumar et al. (Arunkumar et al., 2013) studied the solar still with concentrator-coupled hemisphere basin with and without PCM to enhance the productivity due to heat source of PCM after the sunset and found that PCM became more effective in the low sunshine hours at the low mass of water in the basin. El-Sebaii et al. (El-Sebaii et al., 2009a) achieved the high distillate overnight with a thin layer of stearic acid beneath the basin liner. Moreover, he found PCM to be more effective at a low level of water in the solar still basin. Arunkumar et al. (Arunkumar et al., 2013) used spherical copper balls to store PCM in the distillation process. However, for the given volume, the total surface area of a sphere is approximately 14.5% lesser as compared to that of a cylinder. However, in terms of fabrication, achieving a precise dimension for a sphere is difficult as compared to a cylinder made of copper sheet having shallow thickness. The operation of the solar distillation unit mounted with a solar concentrator becomes difficult to operate for the user, as the concentrator has to be adjusted in a regular interval. Tabrizi et al. (Tabrizi et al., 2010) and (Shukla et al., 2016) used an absorber plate and solar concentrator, respectively, to increase the distillate. Nonetheless, these extra mountings increase the cost of the solar distillation unit, whereas in this study, we have used a simple solar distillation unit with copper cylinders filled with PCM to improve the performance along with making it both user friendly and economically viable. One such application was investigated by Li et al. (Li et al., 2019) where laminated composite PCM blind system was developed, and its performance was measured in a double skin facade (DSF) building. The results revealed that the integrated PCM blind system in DSF kept average air temperature below 35 ^{o}C and reduced the inner skin surface temperature of DSF by 2.9 ^{o}C, thus reducing heat transfer into the building. Su et al. (Su et al., 2015) reviewed the various types of PCMs in thermal storage applications, and the study revealed that organic PCMs have more advantages in terms of lesser segregation, less super cooling, and broader temperature range application as compared to inorganic PCMs. However, organic PCMs possess some disadvantages, such as lower thermal conductivity, being flammable, and lower density as compared to inorganic PCMs. Su et al. (Su et al., 2017) developed a microencapsulated PCMs, and the results showed better thermal conductivity and higher thermal energy storage density than most of the conventional PCMs when tested for solar assisted hot water storage system. Su et al. (Su et al., 2020) also investigated the possible use of microencapsulated PCMs for energy storage applications in buildings. The simulation results showed that laminated microencapsulated PCMs drywall performed better as compared to conventional walls over a period of time, with about 12% increase in a number of hours when the indoor air temperature was in the range of 21–28 ^{o}C. Thermal conductivity is an important thermodynamic factor in faster thermal response. Thermodynamic properties of PCM play a crucial role in the selection criteria for a particular PCM however, economical aspects also becomes one the most important criteria for its selection. PCMs are still used in solar still to store solar energy, but low thermal conductivity leads to high charging and discharge time. The duration of charging and discharging of PCMs solely depends on the thermal conductivity of the absorbed material and hence, the duration can be reduced by enhancing the thermal conductivity of PCMs which instigate us embedding high conductive materials with PCMs. In order to overcome the limitations of PCM in terms of thermal properties, nanomaterial can be used to enhance the latent heat, thermal conductivity, solidification, and melting temperature of various types of PCMs in different applications. However, the dispersed nanoparticles into the PCMs is a new concept to improve the physical properties of PCMs. The doping of nanoparticles in PCM reduces the melting and freezing time of PCM. Though introduction of nanoparticles is a proven technology to enhance heat transfer rate, the same was rarely applied to enhance the output of solar distillation. Either the application of PCM or nanoparticle alone is insufficient to explain the optimization of the distillation output.

Kibria et al. (Kibria et al., 2015) reported that when nanoparticles were doped in PCM it helped in overcoming the problems such as its low thermal conductivity and low heat release. Biswas et al. (Biswas et al., 2014) conducted an experiment incorporating PCM with nanoparticle and concluded that a reduction of 15% was observed in the melting duration of NPCM compared to pure PCM. Lovedeep et al. (Sahota and Tiwari, 2016) conducted an experiment and claimed that the solar still renders the productivity enhanced by 12.2% when Al_2O_3 nanoparticles were incorporated with latent heat storage materials. Omara et al. (Omara et al., 2015) obtained 25.5% higher productivity while using Al_2O_3 nanoparticle under the vacuum conditions. Mahian et al. (Mahian et al., 2017) used nanoparticles and found that there was a notable increase in the thermal performance of the heat exchanger. PCMs are materials used for heat absorption, storage and recovery and often employed in renewable energy system due to the intermittent and unpredictable nature. They are analogous to heat batteries and contribute to the applied system for rationalizing and uniformly spreading the use of energy over a period of time (Kant et al., 2016a; Sharma et al., 2009).

2.3 Design guidelines for PCM

The first property to consider when deciding on a suitable material for any given application is melting temperature. However, solid and liquid phase change materials have been employed in a broad range of application including space craft thermal management and solar energy storage. Thermal energy storage (TES) has been occurred in the PCM when they undergo a solid- liquid phase transition. When designing PCM thermal control system for the specific application, a number of factors other than the heat of fusion and melting point with the latent heat of capacity of all heat storage materials used in distillation process for heat source must be considered as given in Tables 2.1 and Table 2.2. Sharma et al. (Sharma et al., 2009) also finds the effects of thermo-physical properties on heat exchanger materials on the thermal performance of the energy storage system. Materials used for phase change in the application of TES storage must have a large latent heat capacity and high thermal conductivity. They must have a melting temperature that is in practical range of operation, melt completely with minimal sub cooling and be chemically stable, low in cost, nontoxic and non-corrosive.

The materials that have been studied over the past 40 years are hydrated salts, paraffin wax, fatty acids, and eutectics of organic and non-organic compounds. Depending on the applications, PCMs must be selected based on their melting temperature. Materials melting below 15 ^{o}C are used for cold storage in air conditioning applications, while materials melting above 90 ^{o}C are used for absorption refrigeration (Farid and Husian, 1990; Kant et al., 2016b; Lane, G.A., 1975; Sharma et al., 2009). These materials represent the class of materials that have been studied most. A comprehensive list of most likely materials that can be used for latent heat storage is tabulated in Table 2.2.

Table 2.1 Parameters considers of phase change materials while using in solar distillation process (Garg, 1985; Kant et al., 2016a)

Properties or characteristics	**Desirable value or tendency**
Vapor pressure	low
Surface tension	low
Latent heat of fusion	high
Density	high
Volume change while phase transform	very low
Specific heat	high
Thermal conductivity	high
Melting and freezing behavior	dependable and reversible
Availability	readily acquirable
Cost	low
Compatibility	harmonious with container and filler materials
Toxicity	Non-poisonous
Hazardous behavior	not exhibited
Property data	easily available and well documented

In the selection criteria of PCM for a specific application, the most salient feature is the operational temperature limit of the component to be secured. The PCM should have a melting point temperature well within the range to ensure that unintentional undercooling or overheating will not damage the component. The latent heat must be as high as possible, especially to continue the process of evaporation during night hours. High thermal conductivity will aid in charging and discharging energy storage. Consequently, the PCMs included thermodynamics properties, heat transfer mechanism, and function of fillers, containment, and combination of all when selecting PCMs. It must suffer from degradation due to water loss hydration, chemical decomposition, or incompatibility with the materials of construction of the storage unit (Alawadhi, 2015; Barako et al., 2018; Ben Romdhane et al., 2020; Cárdenas-Ramírez et al., 2020).

Table 2.2 Melting point and latent heat capacity of PCM used in solar distillation process (Lane, G.A., D. N. Glew, 1975; Sharma et al., 2009)

Sr. No.	PCM	Chemical formula	Melting temp. (ºC)	Latent heat (kJ/kg)
1	Lauric acid	$CH_3(CH_2)_{10}COOH$	38-42	179
2	Polyethylene glycol 600	$HO(C_2H_4O)_nH$	19-24	144
3	Capric acid	$CH_3(CH_2)_8COOH$	35.5	153
4	Eladic acid	$C_8H_7C_9H_{16}COOH$	46	217
5	Acetic acid	CH_3COOH	17.2	183
6	Pentadecanoic acid	$CH_3(CH_2)_{13}COOH$	51.5	179
7	Paraffin wax	$C_{31}H_{64}$	44-67	167.7
8	Myristic acid	$CH_3(CH_2)_{12}COOH$	56	200
9	Palmatic acid	$CH_3(CH_2)_{14}COOH$	54	164
10	Stearic acid	$CH_3(CH_2)_{16}COOH$	54-62	201
11	Acetamide	CH_3CONH_2	80	243
12	Methyl fumarate	$(CHCONH_3)_2$	103	240
13	Tristearin	$C_{17}H_{35}COOC_3H_5$	55	190

PCMs used in solar energy applications have higher fusion heat than paraffin wax. Most PCMs used in the solar distillation purposes are known by fatty acid describe in Table 2.2 that shows a dependence on melting and freezing behaviour and freeze with no super cooling and mild corrosive. The general formula showing all the fatty acid is given in Table 2.2. Some fatty acids are used in low temperatures for latent heat energy storage applications (Lane, G.A., D. N. Glew, 1975).

2.4 Effects of climate and operating parameters

In most of cases, two kinds of factors affect the solar distillation processes are climate conditions and operating parameters. Climatic condition mainly depends on temperature of ambient, solar intensity, and the wind velocity, while operating parameters are the inclination angle, water depth, absorbing materials placed in the basin to stored energy, the temperature difference between water and covering material, insulation of solar still etc. The distillate of solar still increases with solar intensity for higher solar intensity increases temperature of water placed in the basin, which regulates the evaporation process faster. Furthermore, the solar still basin area coated by black paint, which uplifts the temperature of contaminated water that result in vaporization of water, is helpful in increasing production rate of solar stills (El-Sebaii, 2004; Singh and Tiwari, 2004; Taghvaei et al., 2014; Tiwari et al., 2003a; Tripathi and Tiwari, 2006).

2.5 Research gap

From the above literature it has been found that only few literatures are available on nanoparticle doped in PCM to enhance the performance of solar stills. Hence, the present study uses a novel approach of storing nanoparticle doped in PCM (paraffin wax), which is stored in a copper cylinder to increase the thermal conductivity, heat transfer rate, and daily productivity. However, based on literature review the following research gaps have been identified.

- There is a legacy of using PCM in passive solar still so that distillation output can be obtained beyond sunshine hours. It may also be noted that the thermal conductivity of

PCM is tremendously low, though its storage in copper cylinder enhances heat transfer rate.

- On the other hand, using nanoparticles for enhancing thermal conductivity is a proven technology. However, integration of PCM and nanoparticles as a new generation of the energy storage device rendering appreciable improvement of thermal conductivity was rarely studied though this combination would enhance the distillation output drastically.
- Though solar distillation is also an established technology, due to low distillation output, this technology has limited usage in those resource-limited settings where there is water scarcity. Efforts were made to improve distillation output leading to complicated design and thus, it obviously incurs higher cost. Hence, frugal disruptive technology of solar distillation in the resource-limited settings is the need of the hour.

Hence based on these research gap the present thesis makes an attempt to fulfil these in subsequent chapters based on an experimental analysis.