SOLAR STILL INTEGRATED WITH PHASE CHANGE MATERIALS: A REVIEW

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ABSTRACT:

The shortage of water especially drinkable has always been a major issue in many developing and even in developed countries. Water from various sources cannot be used for drinking purpose due to often brackish (i.e. contain dissolved salts) and/or contains harmful bacteria. In addition, there are many coastal areas where seawater is abundant but potable water is not available in sufficient quantity. Desalination, a technology that converts saline water into clean water, offers one of the most important solutions to these problems. Solar stills can provide a solution for those areas where solar energy is available in plenty but water quality is not good and hence can be used for producing drinking water. This paper reviews the development of latent heat thermal energy storage systems studied detailing various phase change materials (PCMs) including the nano particles based PCM investigated over the last three decades, the heat transfer and enhancement techniques employed in PCMs to effectively charge and discharge latent heat energy and the formulation of the phase change problem. Mathematical modelling for a single slope-single basin solar still with and without phase change material (PCM) under the basin liner of the still is presented. The exergy balance equation, the pure water productivity and exergy efficiency for each element of the desalination unit as well as for the PCM is formulated and shown here.

KEYWORDS: Productivity, Phase change material (PCM), solar still, thermal efficiency

1. INTRODUCTION

Water is a necessity of mankind that influences the development of any nation. Today, the availability of fresh drinking water is a serious problem to all developing & developed nations. Water from various sources cannot be used for drinking purpose due to often brackish (i.e. contain dissolved salts) and/or contains harmful bacteria (Montgomery 2001). In addition, there are many coastal areas where seawater is abundant but potable water is not available in sufficient quantity. Pure water is not only used for drinking purpose but also useful for health and industrial purposes such as hospitals, schools and batteries etc. Almost 90% of the health problems in rural areas are due to the contaminated drinking water (Myers 2000). Fresh water resources are becoming scarce due to ever increasing population and pollution due to industrial waste. Out of approx 50 litres per capita per day (lpcd) of water requirement for domestic consumption, only 2 lpcd is the drinking water. For drinking and cooking purposes amount of 5–10 lpcd water is needed and thus, it is only this quantity of water that needs to meet the stringent quality standards of portability prescribed by W.H.O. or other similar installations, whereas the remaining amount of water needed for washing and cleaning can be of intermediate quality. Therefore, for an efficient water management system, it is important to supply water at appropriate level of quality, which is suitable enough for the kind of use for which it is meant (Nafey 2002, Sarı A 2003, Shukla SK 2005). A huge number of people are without clean drinking water and approximately 2.3 billion people (41% of the world population) live in regions with water shortages (Service 2006). Desalination, a technology that converts saline water into clean water, offers one of the most important solutions to these problems (Gleick 2008). Fresh water may be
treated when it is containing less than 1000 mg/L of salts or total dissolved solids (TDS) (Sandia 2003). Presently, the total global desalination capacity is around 66.4 million m$^3$/d and it is expected to reach about 100 million m$^3$/d by 2015 (GWI 2009). The five world leading countries by desalination capacity are Saudi Arabia (17.4%), USA (16.2%), the United Arab Emirates (14.7%), Spain (6.4%), and Kuwait (5.8%) (Khawaji et al. 2008). Solar stills can provide a solution for those areas where solar energy is available in plenty but water quality is not good and hence can be used for producing drinking water. Solar stills are cheap and having low maintenance cost but the problem of solar still is the low productivity (Duffie 1991). It can be used for low capacity and self - dependence water supplying systems because it produces drinking water by solar energy only, and do not need other energy sources such as fuel or electricity.

There are many methods for converting brackish water in to potable water (Sukhamte 1987). Some of the water distillation ways are described as: In desalination thermal energy is used to evaporate the brackish or saline water, and resulting steam is collected and condensed as final product. Vapour compression is the process of purifying of liquid in which water vapour from boiling water is compressed adiabatically and vapour gets superheated. This superheated vapour is first cooled to saturation temperature and then condensed at constant pressure and these pressures are derived by mechanical energy. Reverse osmosis is the process in which saline water is pushed at high pressure through a special membrane which allows water molecules to pass selectively and do not allow to pass dissolved salts. In electrolysis method, water is passed through a pair of special membranes, perpendicular to which there is an electric field. Water does not pass through the membranes while dissolved salts pass selectively.

2. **CLASSIFICATIONS OF SOLAR STILL**

For large interest in water purification due to high demand, several types of solar still have been invented. They stills are divided into two groups on the basis of energy supply: active solar stills & passive solar stills. Among active and passive systems, passive solar system is preferred because it is cheaper compared to active solar still. Some of them are single or multiple wick stills, the multistage flash distillation stills, solar film covered stills, and solar concentrator stills. Only the basin type stills using single effect distillation have been used for the supply of large quantities of water for isolated communities or for small supplies of water such as for battery charging and analytical purposes.

2.1 **SINGLE BASIN SOLAR STILL**

Single basin solar still consists of a black basin (tray) in which the saline water is kept. The basin has a transparent cover that may be clear glass or hard plastic. There are various designs depending on the shape of the cover. The transparent covers can be slanting either upwards (Figure 1) or downwards (Figures 2 and 3).
Simple single basin solar stills are easy to construct and can have a lifetime of more than 20 years (Hinnawi 1981). The design can be made portable or fixed at one place. In cases of large water masses, cascading the single basin still to form several stills is possible. These are called multiple basin stills (Daniels 1964). Solar still has a thin layer of water on its basin, a transparent glass cover over the water and channel for collecting the distillate water from solar still. The glass transmits the sun rays through it and saline water in the basin or solar still is heated by solar radiation which passes through the glass cover and absorbed by the bottom of the solar still. In a solar still, the temperature difference between the water and glass cover is the drinking force of the pure water yield Vapor flows upwards from the hot water and condensate. This condensate water is collected through a channel. There are several minor variations in the geometric configuration of single basin stills. The Classifications of solar stills is shown in fig 4.
3. ADVANCEMENT IN SOLAR STILL DESIGN & PROCESS

Solar still technology was first developed in 1872 by Carlos Wilson. In 1920, Kaush used metal concentrators to focus solar energy on brackish water to improve the performance of the still. An efficiency of 50% was achieved, and these results were later confirmed by Pasteur in 1928 (Sodha 1983). In 1930, Abbot used cylindrical parabolic reflectors for focusing solar energy onto tubes containing polluted water. The system worked with an efficiency of 80% (Daniels 1964). Lof, in 1961, investigated the performance of single basin stills with respect to variations in solar radiation, ambient temperature, area of cover, wind velocity, and water depth (Sodha et al. 1983) and his investigations revealed that productivity increased with increased solar radiation and that productivity also increased with increased ambient temperature. Direct variation between solar radiation and the performance of solar stills was later confirmed by Akinsete et al., in 1969 (Sodha et al. 1983). However, Akinsete et al., in their research of 1969, proposed that the effect of energy losses from the still is less significant at higher ambient temperatures. (Cooper 1969) studied the effect of water depth on productivity of solar stills and found out that productivity decreases with increased depth. This is in agreement with Lof’s results of 1961. However, there is no mention of optimum depths needed for the still to function most efficiently. Bloemer investigated the effect of angle of inclination of the cover on still productivity in 1965 and found out that the still’s performance was the same at inclinations of 10° and 45° (Alawi 1986). (Salam et al. 1986) reported that productivity of stills is much higher at low angles of inclination and that it decreases with increasing inclination.

Another method used to improve the productivity of solar stills is by using storage systems it can be in the form of either sensible or latent heat systems which utilizes the heat dissipated from the bottom of the still. The latent heat thermal energy storage systems have many advantages over sensible heat storage systems including a large energy storage capacity per unit volume and almost constant temperature for charging and discharging (Fath 1998). Recently, many researcher has given focus on concerning the use of PCM as storage media integrated with some solar-thermal energy systems; such as domestic hot water systems (Talmatsky 2008), solar cookers [Chen 2008 and Hussein 2008 ], and greenhouses (Najjar 2008) in order to fulfil the gap between supply and demand of solar energy.

The integration of a thin layer of PCM under the basin liner of a solar still, results in the storage of considerable amount of heat within the PCM during sunshine hours instead of wasting it to surroundings. When the basin liner temperature becomes higher than that of the PCM, heat is first stored as a sensible heat till the PCM reaches its melting point. By time, the PCM starts to melt and after complete melting of the PCM, the heat will be stored in the melted PCM as a sensible heat. Afternoon, when the solar radiation decreases, the still components starts to cool down, the liquid PCM transfers heat to the basin liner and from the latter to the basin water until the PCM completely solidified. In other words, the PCM will behave as heat source for the basin water during low intensity solar radiation periods as well as during the night; consequently, the still continues to produce fresh water after sunset even with thin layers of basin water which results in enhancement of the still productivity especially during the night period.

3.1 PHASE CHANGE MATERIAL

Thermal energy can be stored as sensible or latent energy by heating or cooling a bulk of material and becomes available when the reverse process is applied. The storage of thermal energy by using the latent heat of the material is called latent heat storage. Latent heat defined as the amount of heat absorbed or released during the material phase change from one phase to another phase. There are two known types of latent heat which are latent heat of fusion and latent heat of vaporization.
Phase change materials (PCM) are widely used to store thermal energy at a fixed temperature by taking advantage of their latent heat (heat of fusion) during phase change. The melting temperature varies over a wide range for different PCM, e.g., paraffins, fatty acids, sugar alcohols, salt hydrates, etc. A number of review articles (Abhat 1983, Kamimoto 1987, Hasnain 1998, Zalba 2003, Farid 2004 and Sharma 2005) discussed candidate PCM, their thermophysical/transport properties, encapsulation, heat transfer enhancement and system-related issues. In view of this observed shortcoming and based on the greater importance of thermal energy storage and associated developments in related fields, the present review of literature with a focus on thermal conductivity promotion of PCM was prepared. The classification of energy storage materials is shown in fig. 5 (Abhat 1983).

![Fig. 5 Classification of energy storage materials](image)

### 3.2 INTEGRATION OF PHASE CHANGE MATERIAL WITH SOLAR STILL

(Mona et al. 2002) had constructed a single stage solar still that made use of phase change energy storage mixer. They found that the use of an energy storage material led to a larger productivity of distilled water and that the larger the concentration of the saline water, lower the productivity. Also higher flow rate and high inlet saline water temperature improved the still efficiency (Mona et al. 2002). (Radhwan 2004) presented a transient performance of a steeped solar still with built-in latent heat thermal energy storage for heating and humidification of agricultural green house. He investigated the effect of thickness of paraffin wax as a PCM and mass flow rate of air on the system performance. His results indicated that decreasing the air flow rate has a significant influence on the still yield, while the green house heat load experiences a decrease. A total yield of about 4.6 L/m² with an efficiency of 57% has been obtained.

(Nijmeh et al. 2005), experimentally studied a single basin solar still using various absorbing materials like violet dye, charcoal, potassium permanganate (KMnO4) and potassium dichromate (K2Cr2O7). The best result obtained by violet dye i.e. 29%. (Eman-Bellah 2007) carried out experiments to investigate a method to improve the thermal conductivity of paraffin wax by embedding aluminum powder in it. The size of the aluminum powder particles is 80 μm. Results showed that the value of the average heat transfer coefficient is greater for composite than for pure paraffin and charging time decreased by 60% for composite than that for pure paraffin wax. Useful heat gained increases with the addition of aluminum powder to the paraffin wax.
(Sebaii 2009) et al, studied the performance of solar still with and without the stearic acid as PCM on summer and winter days by computer simulation. Results reveals that after sunset, the stearic acid (PCM) as a heat source for the basin water until sun rise in the early morning hours of the next day. At lower masses of basin water PCM becomes more effective during the winter. On a summer day, the daily productivity of the still is higher with PCM.

(Tabrizi et al. 2010) studied two cascade solar stills with latent heat thermal energy storage system (LHTESS) and without LHTESS. Both stills had the optimum inclination through the year for Zahedan, Iran. The total productivity of still without LHTESS is slightly higher than the still with LHTESS.

(Hamadani et al. 2011) conducted experimental investigations on a solar still with lauric acid as phase change material (PCM). Results reveal that daily productivity and the efficiency of solar still increases by using higher mass of PCM with lower mass of water. The distillate productivity at night and on day for solar still without PCM 30% to 35% and with PCM increased by 127%. (Swetha 2011), used Lauric Acid as a phase change material on his study on a single slope single basin solar still. They observed that 13% increment when the still is used with sand as heat reservoir and 36% increment when the still is used with Lauric Acid as PCM.

The utility of the LTES system is limited for wide range of applications due to low thermal conductivity of the PCMs. The low thermal conductivity of the PCM would reduce the energy storage capacity and increase the time required for complete melting and solidification processes (Sari 2008 and Dolado 2012) as it causes less heat transfer rate from heat transfer fluid (HTF) to PCM and vice versa. In order to accelerate the heat transfer rate of the PCMs many researchers had focused their interests and as a result several new methods were proposed. Metal fins, metal screens and other metal structures were embedded with the PCMs for enhancing the heat transfer performance [Ismail 2001, Castell 2010 and Fan 2013].

An evolution of the nanotechnology has introduced the new technique called “Nanofluid”, which comprises of a base fluid and solid Nanoparticles (NPs), whose sizes range from 1 nm to 100 nm. In LTES systems, nanofluids (nanomaterials embedded PCMs) consist of base PCMs and solid NPs (supporting materials). Also, nanofluid is also known as composite PCM since two and more dissimilar materials (PCMs and solid NPs) are mixed together as single material. Unlike nanofluids flowing in the pipe line of the heat exchanging systems, they do not tend to flow in the LTES system as they filled in the spherical or cylindrical encapsulation are kept in the storage tank (Wang et al. 2012).

Several researchers used nano technology to increase the thermal conductivity of PCM material. (Jana et al 2007) investigated the thermal conductivity enhancement of single nanofluids containing CNTs, AuNPs and CuNPs added into water and hybrid nanofluids containing nanoparticles of CNT-AuNP and CNT-CuNP with water. Results reveal that nanofluid with CuNPs showed the 74% enhancement of thermal conductivity.

(Wu et al. 2009) prepared Al₂O₃-H₂O nanofluids and found that by adding 0.2wt% Al₂O₃ nanoparticles into water, the maximum enhancement of thermal conductivity was increased by 10.5%. (Liu et al 2009) reported that TiO₂ nanoparticles dispersed into saturated BaCl₂ aqueous solution increased thermal conductivity considerably compared to the base material and in turn the cool storage and supply rate, and the cool storage and supply capacity all increased greatly.

4. MATHEMATICAL MODELLING OF A SOLAR STILL

The energy balance equations for the single slope-single basin solar still elements (with and/or without the PCM) are as follow:
4.1 THE STILL WITH THE PCM (CHARGING MODE)

Glass Cover:

\[ I_\alpha_g + h_2(T_w - T_g) = h_{cgs}(T_g - T_a) + h_{eys}(T_y - T_a), \]

Where

\[ h_2 = h_{cws} + h_{ews} \]

is the total internal heat transfer coefficient. The radiative \( h_{rws} \), convective \( h_{cws} \) and evaporative \( h_{ews} \) heat transfer coefficients are calculated using Dunkle’s correlations (Dunkle et al. 1961)

Basin water:

\[ I_\tau_g \alpha_w + h_1(T_p - T_w) = h_2(T_w - T_g) + (m_w c_w / A_p)(dT_w / dt), \]

Where \( h_1 \) is the convective heat transfer coefficient from the basin liner to the basin water.

Basin liner:

\[ I_\tau_g \tau_w \alpha_p = h_1(T_p - T_w) + (k_p / x_p)(T_p - T_{pcm}) , \]

Where \( k_p \) and \( x_p \) are the thermal conductivity and thickness of the basin liner.

Phase change material (PCM):

\[ (k_p / x_p)(T_p - T_{pcm}) = (M_{equ} / A_p)(dT_{pcm} / dt) + U_b(T_{pcm} - T_a), \]

Where \( U_b = k_{ins} / x_{ins} \) is the back loss coefficient and \( M_{equ} \) is the equivalent heat capacity of the PCM, expressed as (Radhwan 2004).

4.2 THE STILL WITH THE PCM (DISCHARGING MODE)

The energy balance equations for the various elements of the still during off-sunshine hours (discharging mode), may be written as follows:

Phase change material (PCM):

For a selected time interval \( \Delta t \), the energy balance equation for the PCM may be written as

\[ m_{pcm} L_{pcm} / A_p \Delta t = h'_{b}(T_{pcm} - T_p) + U_b(T_{pcm} - T_a) \]

\[ h'_{b} = k_{pcm} / x_{pcm} \]

is the conductive heat transfer coefficient from the PCM to the basin liner.

Basin liner:

\[ h'_{b}(T_{pcm} - T_p) = h_1(T_p - T_w) \]

Basin water

\[ h_1(T_p - T_w) = h_2(T_w - T_g) + (m_w c_w / A_p)(dT_w / dt), \]
Glass cover

\[ h_2(T_w - T_g) = h_{rgs}(T_g - T_s) + h_{cga}(T_g - T_a), \]

The above equation is solved analytically using the method of separation of variables and the following expression has been obtained for the basin water temperature \( T_w \) PCM temperature \( T_{pcm} \) during the discharging mode:

### 4.3 The Still Without the PCM

The energy balance equations for the basin liner, basin water and glass cover can be written, respectively, as follows:

\[
I_{\tau p} \alpha_p = h_1(T_p - T_w) + U_b(T_p - T_a),
\]

\[
I_{\tau g} \alpha_w + h_1(T_p - T_w) = h_2(T_w - T_g) + (m_w c_w / A_p)(dT_w / dt),
\]

\[
I \alpha_g + h_2(T_w - T_g) = h_{rgs}(T_g - T_s) + h_{cga}(T_g - T_a).
\]

The above equations are solved using the same method described previously for the still with the PCM. The following analytical formulas have been obtained for basin liner, glass cover and basin water temperatures, respectively (Sharma and Mallick 1998).

### 4.4 Productivity and Efficiency of the Still

The hourly productivity \( P_h \) is calculated using the following Eq.

\[ P_h = h_{ewg} (T_w - T_g) \times 3600 / L_w \]

The daily productivity \( P_d \) and efficiency \( \eta_d \) are calculated using the following formulas (Sebaii et al. 2009).

\[ P_d = \Sigma P_h, \]

\[ \eta_d = \frac{P_d L_{wav} \times 100(\%)}{A_p \Sigma I \Delta t} \]

Where \( L_{wav} \) is the daily average of the latent heat of vaporization of water and \( \Delta t \) is time interval during which the solar radiation is measured.

### 4.5 Exergy Evaluation

It should be noted that the form of exergy involved in the passive solar still has been only considered here. So, the exergy of heat (\( Ex_Q \)) associated with the heat transfer (\( Q \)) is expressed as follows (Dinçer and Rosen 2011)

\[ Ex_Q = Q(1 - T_{amb}) T \]

### 4.6 Exergy Balance Equations

Generally, the exergy balance may be written as (Dinçer and Rosen, 2011).

\[ Ex_{acc} = Ex_{in} + Ex_{gen} - Ex_{out} - Ex_d \]

Where,
Ex\text{in} and Ex\text{out} are respectively exergy quantities entering and exiting (useful and/or losses) through system boundaries;

Ex\text{gen} and Ex\text{d} refer respectively to the produced exergy within the system and the destroyed (or consumed) exergy quantity;

Ex\text{acc} is the build-up of the exergy (or the exergy accumulation) in the system.

If the quasi-steady state assumption has been adopted, the exergy balance becomes:

\[ Ex_d = Ex_{in} + Ex_{gen} - Ex_{out} \]

This last relationship will be applied to every component of the passive solar still. The notations and schematic diagrams used in the references (Ranjan et al. 2013) showing the exergy transfers in the each component of this device, are also undertaken.

5. CONCLUSION

The abundantly & free of cost available Solar energy is the best alternative thermal energy source. It is clean and freely available in almost all parts of the world. Solar stills intrinsic simplicity, its capability to supply fresh water to remote areas where no fresh water is available, and its environmental responsiveness makes it a technology that is grown for much wider use. This review paper is focused on the available thermal energy storage technology with PCMs with different types of solar still. This paper presents the transient mathematical models for a single slope-single basin solar still with and without phase change material (PCM) under the basin liner of the still. This environment friendly technology is very beneficial for the humans and as well as for the energy conservation. It also includes the study of, thermal and heat transfer characteristics of the newly prepared nanomaterials embedded PCMs (nanofluid PCMs or composite PCMs) in order to suggest for heat and cool thermal storage systems. Oleic acid, water-glycerol mixture, stearic acid, palmitic acid, paraffin, and LA/SA mixture were considered as the base materials (PCMs) and CuO, TiO2, and ZnO NPs were regarded as the supporting materials. We may therefore conclude that the use of solar water distillation promises to improve the quality of life and to improve health standards in arid areas.

REFERENCES


