Mechanical Analysis Carried out to a Single Basin Solar Still Integrated with Nano-Composite PCM

Ganesh E. Kondhalkar¹, Kashinath H. Munde¹, Dattatray P. Kamble¹, Dhanashree S. Ware¹, Mahesh P. Kumbhare¹
¹Anantrao Pawar College of Engineering and Research, Pune, Maharashtra

Abstract
In this article, thermal modeling of a single basin solar still coupled with an evacuated tube solar collector under natural circulation mode has been carried out on the basis energy balance equations. The expressions of inner surface of glass cover, outer surface of glass cover, basin liner, and water mass have been derived for the numerical computation. The experiments were conducted under various meteorological conditions for 0.05 m water depth. This experimental setup has been installed at Solar Energy Park, Tamilnadu College of Engineering, Coimbatore, India (Latitude: 11°N; Longitude: 77°E; and an altitude of 409 m above sea level). Observation revealed that there was a considerable increase in the average daily yield of solar still when integrated with an evacuated tube solar collector. For all the cases, the correlation of coefficients (r) between theoretical and experimental values have been verified and they showed good agreement with 0.98 < r < 0.99 and root mean square present deviation of 10.26 < e < 39.7%.

Keywords- Modal analysis of lathe, vibration monitoring of machine tool.

1. Introduction
The severe shortage of fresh drinking water in remote and urban areas in the world, it is need to distillate the available saline water to compensate the shortage. The uncertainties of grid supply, the peoples are unable to use existing popular desalination devices to get fresh water. The utilization of solar energy for desalination shall be the best solution for rural as well as urban areas while exploitation of fossil fuels to run the existing desalination devices. The use of solar energy is a promising option for desalination of saline water because it locally available and zero energy cost (Tiwari, 2010).

The evaluation of energy efficiency and distillate output of any solar stills is primarily done by energy analysis, which is based on the first law of thermodynamics. It considers only the quantitative aspect of the energy transfer. The quality of energy or exergy, defined by the second law of thermodynamics is usually ignored. The technique of exergy analysis is proved to be the most effective thermodynamic tool for achieving the goal of more efficient resource use, as it enables the locations, types and true magnitudes of waste and loss to be determined. It has been successfully applied in the optimization of the entire system or specific variables in a single component of thermal systems, such as steam power plants, solar thermal power plants, steam or gas turbine, boiler, etc. This knowledge can also be used to design a solar still, to reduce the sources of inefficiency and irreversibility in the existing processes and
components of the solar still. It may prove to be very useful to achieve higher cost-effective efficiency and productivity.

Mona Naim et al. (2002) signed a still with PCM like paraffin wax and paraffin oil as energy storage medium to store excess solar energy at noon with its latent heat of fusion, which could be utilized during the off shine hours for production of distillate. Tiwari et al. (1985) investigated the effect of water flow. Tiwari et al. (2009) have investigated the effect of the number of collectors and water depth on exergy and thermal efficiency of the active solar still. Kumar and Tiwari (2011) have analyzed the energy and exergy efficiency of a shallow basin passive solar still. It is found that with decrease in absorptivity (0.9–0.6) with time, the energetic and exergetic efficiencies decrease by 21.8% and 36.7%, respectively. The effect of glass cover tilt is found to be insignificant, and the respective efficiencies decrease by 0.75 and 0.47% per degree increase in tilt. These efficiencies increase rapidly up to a wind velocity of 2 m/s. Kianifar et al. (2012) have conducted an exergy analysis to show the effect of a small fan on the exergy efficiency in a pyramid-shaped solar still. The effect of seasonal change on exergy efficiency has also been reported here. Theoretical overall instantaneous exergy efficiency of a passive solar still having 308 tilt angle of glass cover and water depth of 0.04 m on a typical day in June was evaluated by Kaushik et al. (2013). They have found it in the range of 0.06–5.9% for the variation in experimental results of overall instantaneous energy efficiency from 8 to 87.2%. The daily energy and exergy efficiency of the solar still is 20.7 and 1.31%, respectively. The interest of the exergy analysis is to locate and characterize the causes of exergy destruction or exergy losses, as well as to quantify the corresponding rates. The concept of exergy destruction or rate of irreversibility is widely used for the exergy analysis of thermal systems. But its application in the analysis of passive solar still is a few. The objective of this study is to analysis the exergy efficiency of solar still integrated with nano composite phase change materials with different weight ratio of materials on phase change materials for the given design and operating parameters.

2. Description of the System

A schematic diagram of the investigated solar still with built-in PCM as a storage medium is shown in Figure 1. It consists of three main components: (i) metallic basin-liner, (ii) saline water body and (iii) glass cover and (iv) Thermal energy storage. It operates on the basic principal of heating, evaporation and condensation similar to the phenomenon of natural raining but within a confined space. It relies on the distillation process to remove fresh water from saline or brackish water. The schematic diagram of single slope solar still incorporated with nano-composite phase change materials is considered for an investigation is shown in figure 1. It shows the major energy transfer mechanisms of the solar still producing potable water. The operating and climatic parameters of the selected passive solar distillation system are mentioned in Table 1 and Table 2.
The solar radiation transmitted through the glass cover and basin water is absorbed by the basin liner; hence, its temperature increases, part of thermal energy is transmitted by convection to the basin water and other will transferred by conduction to the PCM under the basin liner. When the basin linear temperature becomes higher than that of PCM, heat will be stored in the melted PCM as latent heat. When the solar radiation decreases, the still components starts cool down, latent heat PCM transfer heat to the basin liner and from the latter to the basin water until the PCM completely solidified. The still continues to produce the fresh water after sunset even with thin layer of basin water. Basin water transfers heat to the bottom surface of the glass cover by radiation, convection and evaporation. The heat is conducted through the glass cover and then transfer to surroundings by radiation to the sky and by convection to ambient air.

**Table 1.**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific heat of saline water ( c_m )</td>
<td>4190 J/kgK</td>
</tr>
<tr>
<td>Latent heat of vaporization, ( h_{fg} )</td>
<td>2260103 J/kg</td>
</tr>
<tr>
<td>Thermal conductivity of water ( k_w )</td>
<td>0.590 W/m K</td>
</tr>
<tr>
<td>Depth of saline water in the basin, ( X_w )</td>
<td>0.04 m s</td>
</tr>
<tr>
<td>Emissivity of glass</td>
<td>0.94</td>
</tr>
<tr>
<td>Time interval, ( \Delta t )</td>
<td>3600 s</td>
</tr>
<tr>
<td>Area of basin-liner, ( A_b )</td>
<td>1mX1m</td>
</tr>
<tr>
<td>Thermal conductivity of glass cover, ( K_g )</td>
<td>0.78 W/m K</td>
</tr>
<tr>
<td>Thermal conductivity of insulating material, ( K_i )</td>
<td>0.35 W/m K</td>
</tr>
<tr>
<td>Thickness of glass cover, ( X_g )</td>
<td>0.003 m</td>
</tr>
<tr>
<td>Thickness of insulation, ( X_i )</td>
<td>0.005 m</td>
</tr>
<tr>
<td>Effective absorptance of basin-liner ( \alpha )</td>
<td>0.5814</td>
</tr>
</tbody>
</table>
3. Thermodynamic Modeling

The components of basin-liner, saline water, glass cover and thermal energy storage materials of the solar still integrated with thermal energy storage are modeled based on first and second law of thermodynamics. The following assumptions have been considered.

(i). The conduction heat transfer mode between PCM and basin liner.

(ii). The temperature gradients across the basin-liner, saline water depth and PCM are negligible.

(iii). The heat capacity of the basin-liner, glass cover and insulating materials are negligible compared to those for the basin water and PCM.

(iv). The system is vapor tight and the side losses are negligible;

(v). The PCM is in good contact with the basin liner

(vi). The heat transfer coefficients are temperature dependent.

(vii). The inside and outside glass cover temperatures are different \( i.e. T_{gi} \neq T_{go} \).

(viii). The side heat loss from the solar still is negligible because of very small area of side wall of the still as compared with basin-liner area.

(ix). The selected nano-composite phase change materials are homogenous and its thermophysical properties are constant

(x). All properties of saline water are assumed to be similar to that of water for simplicity

3.1 Energy Analysis

3.1.2 nano Phase Change Materials

The thermophysical properties of paraffin wax and Al₂O₃ are listed in Table 2. The difference in solid and liquid temperature defines the transition from solid to liquid phase during the melting of PCM. The density, specific heat capacity, latent heat of nano PCM, dynamic viscosity and thermal conductivity are computed from the following correlations (Chow and Zhong, 1996)

\[
\rho_{n-pcm} = \phi \rho_{np} + (1- \phi) \rho_{pcm} \tag{1}
\]

\[
c_{p,n-pcm} = \frac{\phi (\rho c_p)_{np} + (1- \phi) (\rho c_p)_{pcm}}{\rho_{n-pcm}} \tag{2}
\]

\[
L_{n-pcm} = \frac{(1- \phi)(\rho L)_{pcm}}{\rho_{n-pcm}} \tag{3}
\]
\[ \mu_{n PCM} = 0.983e^{12.959\phi} \mu_{pcm} \] (4)

\[ K_{n PCM} = \frac{K_{np} + 2K_{pcm} - 2(K_{pcm} - K_{np})\phi}{K_{np} + 2K_{pcm} + (K_{pcm} - K_{np})\phi} K_{pcm} + 5 \times 10^3 \beta_k \zeta \phi \rho_{pcm} c_{pcm} \sqrt{BT \rho_{np} d_{np}} f(T, \phi) \] (5)

The effect of thermal conductivity of the nano PCM which includes the effects of particle size, particle volume fraction and temperature dependence as well as properties of the base PCM and the particle subject to Brownian motion. Where \( B \) Boltzeman constant \( 1.381 \times 10^{-23} \) J/K and

\[ \beta_k = 8.4407(100\phi)^{-1.07304} \] (6)

\[ f(T, \phi) = (2.8217 \times 10^{-2} \phi + 3.917 \times 10^{-3}) \frac{T}{T_{ref}} + (-3.0669 \times 10^{-2} \phi - 3.91123 \times 10^{-3}) \] (7)

Where \( T_{ref} \) is the reference temperature \( 273 \) K. The first part \( K_{n PCM} \) is obtained from the directly the Maxwell model while the second par accounts for Brownian motion. Which causes the temperature dependence of the effective thermal conductivity. Note that there is a correction factor \( \zeta \) in the Brownian motion term, since there should be no Brownian motion in solid phase.

**Table 2**

<table>
<thead>
<tr>
<th>Property</th>
<th>Paraffin wax</th>
<th>Al(_2)O(_3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density ((kg/m(^3)))</td>
<td>750/((0.001(T-319.15)+1)</td>
<td>3600</td>
</tr>
<tr>
<td>Specific heat (J/kgK)</td>
<td>2890</td>
<td>765</td>
</tr>
<tr>
<td>Thermal conductivity (W/mK)</td>
<td>0.21 if T &lt; T(_{solidus})</td>
<td>36</td>
</tr>
<tr>
<td></td>
<td>0.12 if T &gt; T(_{liquidus})</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.001 exp (-4.25+1790/T)</td>
<td></td>
</tr>
<tr>
<td>Viscosity (Ns/m(^2))</td>
<td>4.25+1790/T</td>
<td>-</td>
</tr>
<tr>
<td>Latent heat (J/kg)</td>
<td>173400</td>
<td>-</td>
</tr>
<tr>
<td>Solidus</td>
<td>319</td>
<td>-</td>
</tr>
</tbody>
</table>
The amount of thermal energy stored and delivered during the charging and discharging period are computed from the following correlations:

\[ E_{\text{stored}} = m_{n-pcm} c_s (T_m - T_{in}) + m_{n-pcm} L_{n-pcm} + m_{pcm} c_i (T_{out} - T_m) \]  
\[ E_{\text{delivered}} = m_{n-pcm} c_s (T_m - T_{out}) + m_{n-pcm} L_{n-pcm} + m_{n-pcm} c_i (T_{in} - T_m) \]  

Energy efficiency of thermal energy storage material is

\[ \eta_{I,n-pcm} = \frac{E_{\text{delivered}}}{E_{\text{stored}}} \]  

**3.1.2 Energy efficiency of basin liner**

It is defined as the ratio of thermal energy transfered to the water to thermal energy absorbed in the basin liner as mathmatically expressed as

\[ \eta_{I,\text{basin/liner}} = \frac{m_s c_{pw} (T_{wo} - T_{wi})}{\tau_g \tau_w \alpha_y G_s} \]  

**3.1.3 Solar Still**

The theoretical overall instantaneous energy efficiency of a solar still with nano composite material at any time defined as the ratio of heat transfer rate in the still by evaporation – condensation \((q_{e,w-g})\) to the rate of incident solar radiation \((G_s)\) on the glass cover of solar still (Sampathkumar et al., 2010), i.e.

\[ \eta_{I,\text{stll}} = \frac{q_{e,w-g}}{G_s} = \frac{h_{e,w-g} (T_{w} - T_{g})}{G_s} \]  

The expression for the hourly distillate output \((m_{wo})\) from the solar still \((\text{kg/m}^2 \text{h})\) is calculated using the following Eq.

\[ m_{wo} = \frac{h_{e,w-g} (T_{w} - T_{gl})}{h_{fg}} \times 3600 \]  

Where \(h_{e,w-g}\) is evaporative heat transfer coefficient between saline water and glass cover \((\text{kg/m}^2 \text{h})\), and \(h_{fg}\) is the latent heat of vaporization of water \((\text{J/kg})\).

The daily productivity and daily energy efficiency of a solar still with nano-composite material PCM is calculated as follows;

\[ m_{wo,\text{daily}} = \sum_{24 \text{hours}} m_{wo} \]
\[ \eta_{\text{daily}} = \frac{\sum m_{w.o} \times h_{\text{fg}}}{\sum G_i \times 3600} \]  

(15)

### 3.2 Exergy Analysis

The exergy (work potential) of heat or exergy transfer accompanying heat, \( Ex_q \) (in W/m²) connected to internal and external heat transfer of passive solar stills through conduction, convection or evaporation (i.e. excluding radiation) is expressed as follows (Moran and Shapiro, 2010)

\[ Ex_q = q \left( 1 - \frac{T_a}{T} \right) \]  

(16)

The exergy transfer associated with blackbody radiation \( Ex_{\text{radiation}} \) (Petala, 2010) at surface temperature \( T \), i.e. thermal radiation \( q_r \) from the component of the solar still, with reference to a reference temperature \( T_{\text{r}} \), is expressed similar to the solar exergy described in the next section:

\[ Ex_{\text{radiation}} = q_r \left[ 1 + \frac{1}{3} \left( \frac{T_a}{T} \right)^4 - 4 \left( \frac{T_a}{T} \right)^3 \right] \]  

(17)

### 3.3 nano Composite Phase Change Materials

The mass of nano composite materials is fixed and conduction heat transfer process, the exergy transfer during input, stored, delivered and exergy efficiency of the nano composite phase change materials are expressed as follows (Rezaei, 2013)

\[ Ex_{\text{input}} = m_{n-pcm} c_{n-pcm} \left[ (T_{n-pcm,in} - T_{n-pcm,out}) - T_o \ln \left( \frac{T_{n-pcm,in}}{T_{n-pcm,out}} \right) \right] \]  

(18)

\[ Ex_{\text{output}} = m_{n-pcm} c_{n-pcm} \left[ (T_{n-pcm,out} - T_{n-pcm,in}) - T_o \ln \left( \frac{T_{n-pcm,out}}{T_{n-pcm,in}} \right) \right] \]  

(19)

\[ Ex_{\text{stored}} = m_{n-pcm} c_{n-pcm} (T_{n-pcm,in} - T_{n-pcm,out}) \left( 1 - \frac{T_o}{T_m} \right) \]  

(20)

\[ \eta_{II,n-pcm} = \frac{Ex_{\text{output}}}{Ex_{\text{input}}} \times 100 \]  

(21)

### 3.3.3 Glass cover

\[ Ex_{d,g} = \alpha_g Ex_{w-g} - Ex_{r,g-a} \]  

(22)
where $\alpha_g$ is the absorptivity of glass cover and $Ex_{t,g-a}$ is the exergy loss associated with heat losses from glass cover to the atmosphere owing to radiation $Ex_{r,g-a}$ and convection $Ex_{c,g-a}$ and is given as:

$$Ex_{t,g-a} = Ex_{r,g-a} + Ex_{c,g-a}$$ (23)

The glass cover can be assumed to work as a performing useful work by helping in the condensation of the distillate by rejecting heat to the atmosphere. therefore, exergy efficiency of the glass cover can be expressed as the ratio of exergy in the distillate yield and the maximum possible work obtainable from the total heat gained by glass cover (Energy efficiency), hence, the exergy efficiency of the glass cover may be given as:

$$\eta_{ex, glass cover} = \frac{m_{w0} \Delta h_{fg} \left(1 - \frac{T_a}{T_w}\right)}{\alpha_g Ex_{sun} + Ex_{t,w,g}}$$ (24)

$$\eta_{ex, glass cover} = \frac{Ex_{c,w-g}}{\alpha_g Ex_{sun} + Ex_{t,w-g}}$$ (25)

Exergy efficiency on saline water

$$\eta_{ex, salinewater} = \frac{Ex_{t,w-g}}{\left(\tau_g \alpha_w\right)Ex_{sun} + Ex_w}$$ (26)

3.3.4 Basin-liner

Exergy of the solar radiation on the solar still per unit area, $Ex_{sun}$ (in W/m²), is given as:

$$Ex_{sun} = G_s \left[1 + \frac{1}{3} \left(\frac{T_a}{T_s}\right) - \frac{4}{3} \left(\frac{T_a}{T_s}\right)^2\right]$$ (27)

Exergy efficiency on basin–liner

$$\eta_{ex} = \frac{Ex_w}{\left(\tau_g \tau_w \alpha_b\right)Ex_{sun}}$$ (28)

3.3.5 Exergetic Efficiency

The overall instantaneous exergy efficiency of the solar still with composite PCM is defined as the ratio of exergy output of solar still to the exergy of the incident solar radiation, i.e. Exergy output of the solar still with composite PCM is the useful exergy associated with heat
transfer through evaporation, i.e. $Ex_{e,w-g}$, which is responsible for the transportation of the water vapor from saline water surface to the glass cover and distillate is produced after condensation. Hence,

$$\eta_{ex} = \frac{Ex_{e,w-g}}{Ex_{sun}}$$  \hspace{1cm} (29)

$$q_{e,w-g} (1 - \frac{T_a}{T_w})$$

$$\eta_{ex} = \frac{Ex_{e,w-g}}{Ex_{sun}}$$  \hspace{1cm} (30)

$$\eta_{ex,solar.still} = 1 - \left[ \frac{Ex_{d,b} + Ex_{d,w} + Ex_{d,g}}{Ex_{sun}} \right]$$  \hspace{1cm} (31)

4. Numerical Results and Discussion
Thermophysical properties of Al$_2$O$_3$ nano materials dispersed in melted paraffin wax with 2% weight and 4% weight is computed for the different temperature based on the equations mentioned in thermal modeling section. The Figure 1 shows the variation of density of nano composite phase change materials with temperature. It decreases slowly to increase in temperature for the different weight ratio of Al$_2$O$_3$ and paraffin wax alone.

![Figure 1 Variation of density with respect to temperature and weight ratio of nano particles](image-url)
The Figure 2 shows the specific heat value of nano composite phase change materials for 2% and 4% weight ratio and it decreases slowly for increase in temperature. The Figure 3 shows the variation of latent heat value of nano composite phase change materials with temperature and it decrease while increase in it temperature.
The Figure 4 shows the dynamic viscosity variation with temperature for 2%wt and 4%wt Al₂O₃ and paraffin wax alone. The dynamic viscosity values are decrease for increase in temperature and its value differences are minimum at higher temperature compared to minimum temperature.

![Figure 4 Variation of dynamic viscosity with respect to temperature and weight ratio of nano particles](image)

![Figure 5 Variation of thermal conductivity with respect to temperature and weight ratio of nano particles](image)
The Figure 5 illustrates the variation of the thermal conductivity with respect to temperature and weight ratio of nano particles. Values are high at solid state when compared to liquid state.

**Figure 6** Variation of heat transfer co-efficient with respect to basin liner temperature

**Figure 7** Variation of heat transfer co-efficient with respect to basin liner temperature
The Figure 6 and Figure 7 shows the evaporative heat transfer co-efficient, radiative heat transfer co-efficient and convective heat transfer co-efficient value between the different temperature of basin liner and a values of inner glass cover temperature. The evaporative heat transfer co-efficient is dominant factor compared to convective and radiative heat transfer co-efficient values for both cases.

![Figure 8 Variation of mass of distillate for basin liner temperature](image)

**Figure 8 Variation of mass of distillate for basin liner temperature**

![Figure 9 Exergy efficiency on various components of solar still](image)

**Figure 9 Exergy efficiency on various components of solar still**
The exergy efficiency of the various component of solar still are computed from the available correlation in section 3. The Figure 9 shows the exergy efficiency of sub components of solar still basin liner, saline water, glass cover and phase change materials. The glass cover gives maximum exergy efficiency of 34.3% and minimum exergy efficiency value of 19.8% at basin liner. It shows maximum exergy losses occurs in basin liner compared to glass cover.

![Figure 9 Exergy Efficiency of Solar Still Components](image)

**Figure 9 Exergy Efficiency of Solar Still Components**

The Figure 10 shows the exergy efficiency of solar still integrated with nano composite phase change materials for PCM, 2% weight Al2O3 represented by Nano PCM-1 and 4% weight of Al2O3 represented by Nano PCM-2. The higher weight ratio of Al2O3 gives maximum exergy efficiency value of 27% compared Nano PCM-1 and PCM alone.

![Figure 10 Exergy Efficiency on Different Nano PCM](image)

**Figure 10 Exergy Efficiency on Different Nano PCM**

The higher weight ratio of Al2O3 gives maximum exergy efficiency value of 27% compared Nano PCM-1 and PCM alone.

![Figure 11 Comparison of Energy and Exergy Efficiency of Solar Still](image)

**Figure 11 Comparison of Energy and Exergy Efficiency of Solar Still**
The Figure 11 shows the comparative analysis of energy and exergy efficiency of solar still by PCM, Nano PCM-1 and Nano PCM-2 for set of operating parameters mentioned in the Table 1 and Table 2. The Nano PCM-2 shows the higher energy efficiency of 72% and exergy efficiency of 45% than Nano PCM-1 based solar still having the energy efficiency of 65% and exergy efficiency of 39% and PCM based solar still having energy efficiency of 58% and exergy efficiency of 34%. It is recommended for the higher weight ratio Al2O3 based solar still gives better performance and thermo-economic study will helps the financial feasibility in the further study.

Conclusion
An exergy analysis was carried out to a single basin solar still integrated with nano-composite phase change materials for the given design and selected operating parameters. The subsystems like basin liner, thermal energy storage, glass cover were considered along with different weight ratio of nano materials and paraffin wax. The causes, factors and exact locations responsible for lower energy and exergy efficiency and ultimately less productivity of the passive solar still are ascertain. Some concluding remarks from this study are as follows:

1) Thermo physical properties of nano-composite phase change material are increased with increases in temperature.
2) The maximum instantaneous overall energy and exergy efficiency and hourly yield are 49.29%, 9.48% and 0.69 l/m2, respectively.
3) Daily average energy efficiency, exergy efficiency and productivity are found to be 30.42%, 4.93% and 4.17 l/day, respectively.
4) Low exergy efficiency obtained in the basin-liner than water body and glass cover.
5) It is observed exergy efficiency increases with increases in weight fraction of nano particle.

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References


