THEORETICAL PERFORMANCE COMPARISON OF SOLAR STILL USING DIFFERENT PCM

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ABSTRACT

In the present work, theoretical performance comparison of conventional solar still using different phase change materials (PCM) as a thermal storage material is performed. Three phase change materials are used to choose the best one. The solar still daily productivity for each PCM is studied. It is found that using phase change materials increase solar still productivity and system working time. The system productivity is increased by about 120 to 198% while the system working time increased to 2 to 3 h. This increase are mainly depends on the PCM melting temperature, specific heat, thermal conductivity and latent heat of fashion. Finally a good agreement between the present theoretical work and previous experimental results has been obtained.

Keywords: phase change materials, solar still

1 INTRODUCTION

Phase change material (PCM) is a substance with a high heat of fusion which, melting and solidifying at a certain temperature, is capable of storing and releasing large amounts of energy. Heat is absorbed or released when the material changes from solid to liquid and vice versa; thus, PCMs are classified as latent heat storage units. PCM in the last years have been employed in the heat transfer and energy storage applications in many fields such as heat exchangers and solar energy storage systems (Gunasekara et al , 2017), (Huang et al, 2017), (Ke, 2017) and (Mahdi and Nsofor, 2017). The PCM thermal properties have been augmented by nanoparticles (Colla et. Al, 2017), (Elbahjaoui, 2017), (Karaipekli et. Al, 2017), and (Haillot et. Al, 2017).

The performance of stepped solar still with a latent heat thermal energy storage system was studied (Radhwan, 2005). The system efficiency was 57%, and the entire daily return was about 4.6 Liters per square meter. The performance of single slope still utilizing stearic acid as PCM was simulated (El-Sebaii et al., 2009). The results indicated that the PCM was effective for lighter masses on winter months. The effect of latent heat thermal energy storage system on cascade solar still performance was studied (Tabrizi et al., 2010). The results revealed that the peak productivity was obtained at the lowest flow rate. Cascade solar still coupled with latent heat thermal energy storage system was considered experimentally (Dashtban and Tabrizi, 2011). The results displayed that an enhancement by 31% in the productivity due to PCM utilization. The performance of passive solar still with a heat energy storage system PCMs was simulated (Ansari et al., 2013). it was found that the selection of the phase change material (PCM) depends strictly on the brackish water maximum temperature. The performance enhancement of the concentrator-coupled hemispherical basin solar still via a phase change material (PCM) was studied experimentally (Arunkumar et al., 2013). It was found that the productivity significantly increased due to the PCM addition. The performance of the solar still via three different PCM was presented experimentally (Gugulothu et al., 2015). The PCMs were Potassium Dichromate, Sodium Sulphate, and Sodium Acetate. The performance of solar still by PCM was studied (Shashikanth et al., 2015). Also, wiper that drives water to the collecting dish was also integrated. An exergy analysis of a passive solar still employing PCM as a heat storage system was performed (Asbik et al., 2016). It was found that remarkable increasing in the water productivity was attained due to the PCM usage. The performance of a solar still. PCM was used in the solar still as a storage medium was studied experimentally (Kabeel and Abdelgaied, 2016). The results displayed that, the freshwater productivity was improved up to 68.8% due to PCM.

All previous works studied the effect of using an specific PCM. In the present work, theoretical performance comparison of conventional solar still using different phase change materials (PCM) as a thermal storage material is performed to obtain the best one to use. Two objective functions are used as a point of selection which are the daily productivity and pay back period. Four common different in properties PCM's are used, which are paraffin wax, capric-palmitic, Stearic acid and CaCl2·6H2O. The physical properties of the used PCM materails are summerized in Table (1).

Table 1. Physical properties of the used PCM materails.

Item		paraffin wax	Stearic acid	capric-palmitic	$CaCl_2{\cdot}6H_2O$
Melting temperature (°C)		56	52	22.5	29.8
Specific heat (J/kg K)	solid	2950	1590	2000	1400
	Liquid	2510		2300	2160
Density (kg/m3)	solid	818	965	870	1710
	Liquid	760	847	790	1560
Thermal conductivity (W/m °C)	solid	0.24	0.29	0.14	1.08
	Liquid	0.24		0.14	0.56
Heat of fusion (J/kg)		226000	169000	173000	191000
Price, $/kg		6.50	1.43−1.56		

2 MATHEMATICAL MODEL

In the present model energy balance for the conventional solar still will be applied on basin or absorber plate, hot saline water, glass cover and PCM materail. The temperature of basin plate, saline water, glass cover, and PCM can be evaluated at every instant. In the present study, it is assumed steady state conditions, glass cover is assumed to be thin and solar still is vapour leakage proof.

Energy balance for the basin plate (Velmurugan et al., 2009):

$$m_{bp}Cp_{bp}\frac{dt_{bp}}{d\tau} = (\alpha_{bp})A_{bp}I - Q_{b-sw} - Q_{b-PCM} \tag{1}$$

The convective heat transfer between basin and water, $Q_{b\text{-}sw}$, may obtained as follow (Velmurugan et al., 2008) and (Velmurugan et al., 2009b)

$$Q_{b-sw} = h_{b-sw}\, A_{bp}(t_{bp} - t_{sw}) \tag{2}$$

The convective heat transfer coefficient between basin and water, $h_{b\text{-}sw}$ is given by (Velmurugan et al., 2008) :

$$h_{b-sw} = 0.54\,\frac{K_{sw}}{x'}\,[Gr\;Pr]^{0.25} \tag{3}$$

$$Gr = \left[\frac{\rho_{sw}^2 g\;\beta_{sw}\,(T_{bp}-T_{sw})[x']^3}{\mu_{sw}^2}\right] \tag{4}$$

$$Pr = \left[\frac{C_p\,\mu}{K}\right]_{sw}$$

Energy balance for the saline water (Velmurugan et al., 2009) and (Murugavel et al., 2010) ,

$$m_{sw}Cp_{sw}\frac{dt_{sw}}{d\tau} = (\alpha_{sw})A_{sw}I + Q_{b-sw} - Q_{wg} - Q_{c(sw-g)} - Q_{evap} - Q_{mw} \tag{5}$$

The convective heat transfer between saline water and the glass cover , $Q_{c(sw-g)}$, is given by (Velmurugan et al., 2008) and (Velmurugan et al., 2009b) .

$$Q_{c(sw-g)} = h_{c(sw-g)}\,A_{sw}(t_{sw} - t_g) \tag{6}$$

The convective heat transfer coefficient between saline water and glass cover, $h_{c(sw-g)}$, is given by (Yousef and Mousa, 2004)

$$h_{c(sw-g)} = 0.884\left[t_{sw} - t_g + \frac{(p_{sw}-p_g)(t_{sw}+273)}{268900-p_{sw}}\right]^{1/3} \tag{7}$$

Where $$p_{sw} = e^{\left(25.317-\frac{5144}{t_{sw}+273}\right)} \tag{8}$$

$$p_g = e^{\left(25.317-\frac{5144}{t_g+273}\right)} \tag{9}$$

The radiation heat transfer from the basin to glass cover, Q_{wg}, is given by:

$$Q_{wg} = \frac{\sigma\left[(t_{sw}+273)^4-(t_g+273)^4\right]}{\left(\frac{1-\varepsilon_w}{A_{sw}\varepsilon_{sw}}\right)+\left(\frac{1}{A_g F_{gw}}\right)+\left(\frac{1-\varepsilon_g}{A_g\varepsilon_g}\right)} \tag{10}$$

The radiation shape factor between the glass cover and saline water for the conventional solar still may be assumed to be unity.

The evaporative heat transfer between saline water and the glass is given by (Velmurugan et al., 2008) and (Velmurugan et al., 2009b)

$$Q_{evap} = (16.237\times10^{-3})h_{c(sw-g)}\,A_{sw}(p_{sw} - p_g) \tag{11}$$

The energy needed to heat the makeup water, Q_{mw}, is given as follows:

$$Q_{mw} = m_{prod}\,(Cp_{sw}t_{sw} - Cp_a t_a) \tag{12}$$

Energy balance for the glass cover (Velmurugan et al., 2009) and (Bassam, 1996):

$$m_g Cp_g\frac{dt_g}{d\tau} = (\alpha_g)A_g I + Q_{wg} + Q_{c(sw-g)} + Q_{evap} - Q_{c(g-a)} - Q_{r(g-a)} \tag{13}$$

The radiative heat transfer between the glass and the sky is given by (Velmurugan et al., 2008) and (Velmurugan et al., 2009b) ,

$$Q_{r(g-a)} = \varepsilon_g A_g\sigma\left[(t_g+273)^4 - (t_{sky}+273)^4\right] \tag{14}$$

The sky temperature is given by (Velmurugan et al., 2009b)

$$t_{sky} = t_a - 6.0 \tag{15}$$

The convective heat transfer between the glass and the sky is given by (Yousef and Mousa, 2004) ,

$$Q_{c(g-a)} = h_{c(g-a)}\,A_g(t_g - t_{sky}) \tag{16}$$

$$h_{c(g-a)} = 5.7 + 3.8\,V_a \quad (17)$$

Energy balance for the PCM:

$$m_{PCM}\,Cp_{PCM}\,\frac{dt_{PCM}}{d\tau} = Q_{b-PCM} - Q_{Lost} \quad (18)$$

The heat losses by convection through the basin base and sides to the ground and surrounding, Q_{lost}, given as (Rahul and Tiwari, 2009)

$$Q_{lost} = U_{bp}\,A_{bp}\,(t_{PCM} - t_a) \quad (19)$$

Where U_{bp} (40 W/m^2 K) is the heat loss coefficient from basin plate and to ambient

Solar still productivity

$$m_{prod} = \frac{Q_{evap}}{h_{fg}} \quad (20)$$

At the first iteration, the temperatures of basin plate, saline water, and glass cover are taken as ambient temperature and the increase in basin temperature (dt_b), saline water temperature (dt_w), and glass temperature (dt_g) are computed by solving the energy equations (1, 5, 13 and 18). The equations are evaluated numerically using the first order backward difference formula (Gerald and Wheatley, 1984). The size of the time step is one second. The value of the heat loss coefficient from basin to ambient for the solar still were taken as that of (Kabeel et al., 2012). In the next time step, the parameters are redefined as follows:

$$t_{sw} = ts_w + dt_{sw} \quad (21)$$

$$t_g = t_g + dt_g \quad (22)$$

$$t_{bp} = t_{bp} + dt_{bp} \quad (23)$$

$$t_{PCM} = t_{PCM} + dt_{PCM} \quad (24)$$

To be very close to real ambient conditions, the theortical values of the solar insolation and ambient temperature are not used. The actual insolation (I) and ambient temperature (t_a) are measured at different days from 9 am to 8 pm during the period of June to August 2016 at the Faculty of Engineering, Tanta city, Egypt, and the average values of insolation and ambient temperature are used. The physical and operating parameters that used in the theoretical calculations are shown in Table 2.

Table 2. Physical and operating parameters used in the theoretical calculation.

Item	*Mass (kg)*	*Area (m^2)*	*Specific heat (J/kg K)*	*Absorptivity*	*Emissivity*
Saline water	*5.9*	*1.00*	*4190*	*0.05*	*0.96*
Glass cover	*9.0*	*1.15*	*840*	*0.05*	*0.85*
Basin plate	*14.5*	*1.00*	*460*	*0.95*	----

Latent heat (h_{fg}) =2,335,000 J/kg.

3 RESULTS AND DISCUSSIONS

A detailed study of the effect of different PCM for the conventional solar still has been investigated. To show the effect of these parameters on the distillate productivity and radiation heat transfer inside the still individually, a FORTRAN computer program is designed.

Fig. 1 shows the variation of the hourly solar still distillate productivity to day time for conventional solar still and conventional solar still when used there different PCM's. It could be seen from this figure that over the entire range of insolation day time, the distillate productivity of the solar still with PCM is greater than that for still without PCM. The distillate productivity of the solar still with PCM is increased by about 120 to 198%. This is because when using PCM the system working time is increased to 2 to 3 h, as shown in Fig. 1. Moreover, PCM increases the thermal resistance for losing heat. Figure 2. Shows the daily productivity for solar still at different PCM material. Finally, It could be noted that capric-palmitic is consider the best PCM at which maximum solar still productivity has been obtained. This is because it has very low melting temperature and latent heat.

Fig. 3 shows the variation of the pay pack period for solar still when using different PCM. It could be noted that the lowest the pay pack period may be obtained for solar still that used capric-palmitic. This is because slar still with capric-palmitic has the highest productivity.

Fig. 4 shows the comparison between present work results to Kabeel and Abdelgaid (2016) work at the same working conditions. It could noticed from this figure that the present results are very close to Kabeel and Abdelgaid (2016) experimental results. Therefore, the present model is verivaied

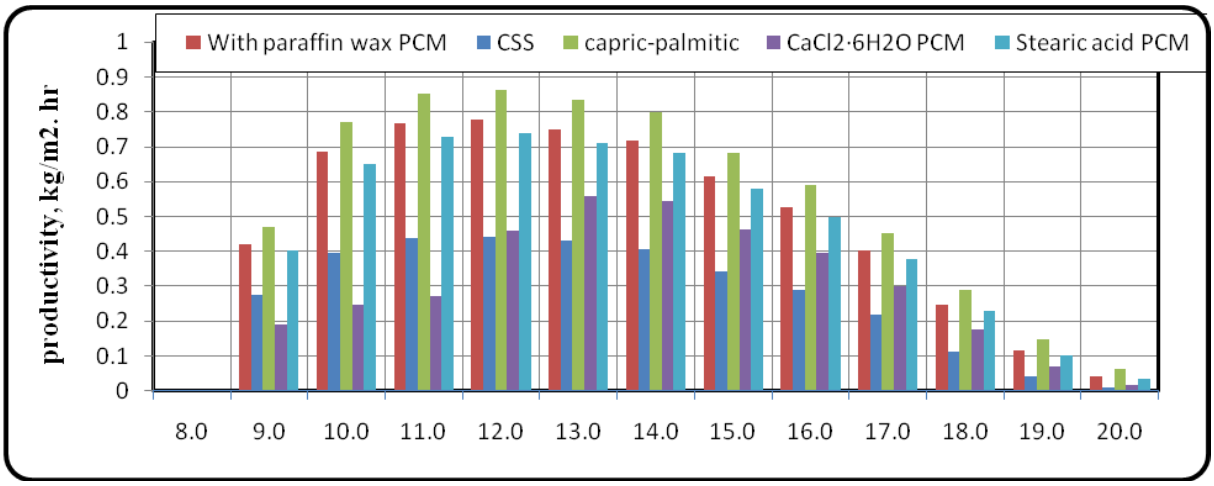

Figure 1. Productivity for solar stills when using different PCM and without using PCM(CSS)

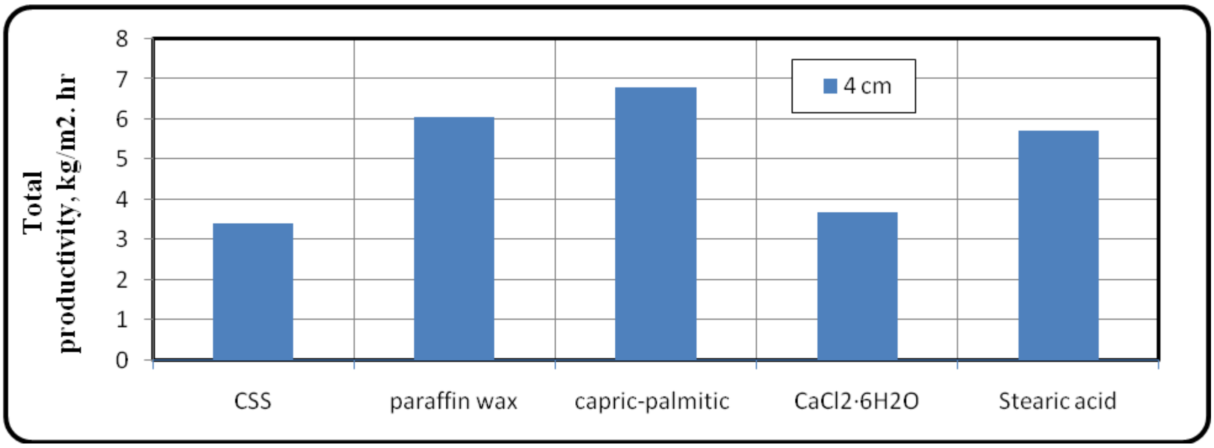

Figure 2. Daily productivity for solar stills when using different PCM and without using PCM(CSS)

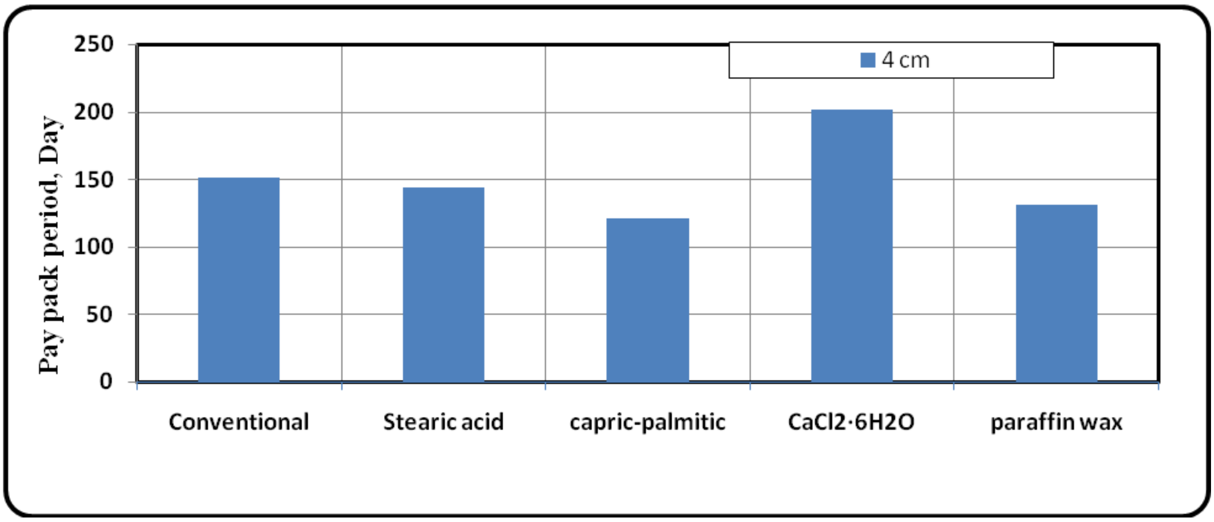

Figure 3. Pay pack period for different PCM and without using PCM(CSS)

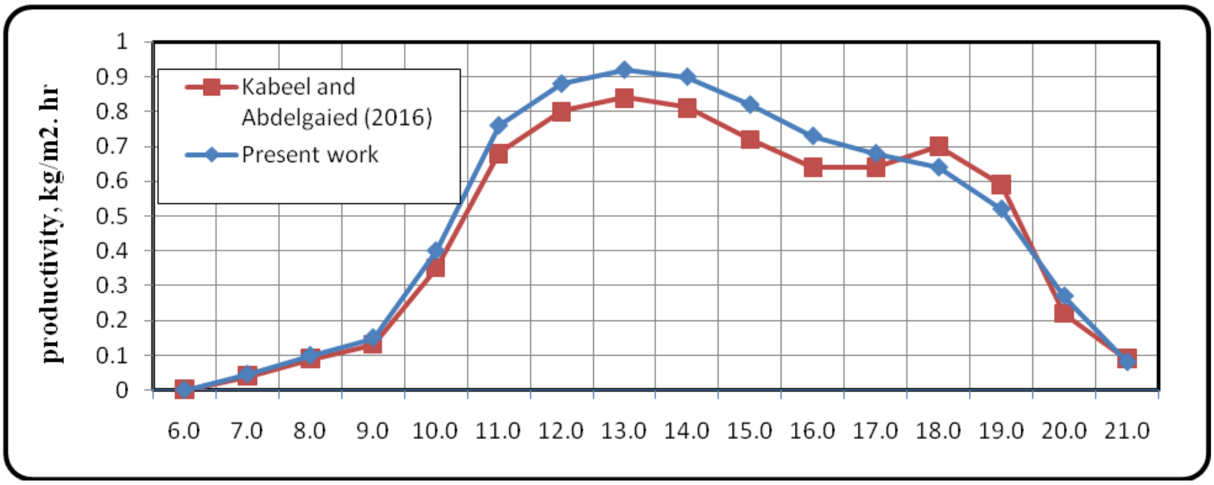

Figure 4. comparison between present work and Kabeel and abdelgaid (2016) work at the same working conditions

4 CONCLUSIONS

The performance evaluation of a conventional still was theoretically investigated. The effect of considering PCM into consideration on the productivity of solar still was studied numerically. From the analysis, the following conclusions can be drawn.

1. The distillate productivity of the solar still with PCM is increased by about 120 to 198%.
2. Using PCM increases the system working time by 2 to 3 h
3. PCM may increase the total heat lost from the still
4. PCM properties is very important factor to enhance still productivity
5. In the present study, capric-palmitic is consider the best PCM at which maximum solar still productivity has been obtained and minimum pay pack period is offerdable
6. A good agreement between the present theoretical work and previous experimental results has been obtained

ABBREVIATIONS

A	Area, m^2
Cp	Heat capacity, J/kg °C
F	Radiation shape factor
$h_{b\text{-}sw}$	Convection heat transfer coefficient between the basin and saline water, W/m^2 °C.
$h_{c(g\text{-}a)}$	Convection heat transfer coefficient with the ambient, W/m^2 °C
$h_{c(sw\text{-}g)}$	Convection heat transfer coefficient between the water in basin and glass, W/m^2 °C
h_{fg}	Latent heat of vaporization, J/kg
I	Solar insolation normal to glass cover, W/m^2
L	Length of glass cover, m
m	Mass, kg
m_{prod}	Rate of mass evaporation, kg/s
P_g	Water vapour pressure at glass temperature, Pa
P_{sw}	Water vapour pressure at water temperature, Pa
$Q_{b\text{-}sw}$	Heat transfer from basin to water in basin, W
$Q_{c(g\text{-}a)}$	Heat transfer from glass to ambient, W
$Q_{c(sw\text{-}g)}$	Heat transfer from water in basin to glass, W
Q_{evap}	Heat transfer due to evaporation, W
Q_{lost}	Heat transfer from basin to ambient, W
Q_{mw}	Energy needed to heat makeup water to water basin temperature, W
$Q_{r(g\text{-}a)}$	Radiation heat transfer from glass to ambient, W
$Q_{w\text{-}g}$	Radiation heat transfer between water in basin to glass, W
t	Temperature, °C
V_a	Wind velocity, m/s
W	Width of the solar still, m
U	heat loss coefficient from basin and sides to ambient,W/m^2 K

Greek letters

α	Absorption coefficient
ε	Emissivity coefficient
μ	Dynamic viscosity, kg/m s
τ	Time, s
ρ	Density, kg/m^3
X'	Characteristic length, m
σ	Stefan-Boltzmann constant, W/m^2 K^4

Subscripts

a	Ambient
bp	Basin plate
g	Glass
sky	Sky
sw	Saline water in basin
PCM	phase change materail

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