Experimental Investigation and Thermodynamic Performance Analysis of a Solar Distillation System with PCM Storage: Energy and Exergy Analysis

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ABSTRACT

This article presents the experimental performance investigation of solar still integrated with two types of phase change materials namely Lauric acid and Myristic acid independently, used as storage medium of solar energy. The experiments were performed during the months of April-May 2011, under Indian climatic conditions. The effect of input parameters such as mass of water in basin and mass of phase change material integrated with solar still basin on productivity of the solar still has been studied. Also on the basis of the experimental data the values of exergy and energy were calculated. It has been found that (i) productivity of solar still integrated with Lauric acid is 22% more than the solar still integrated with Myristic acid. (ii) the energy efficiencies for solar still integrated with Lauric acid and Myristic acid are found to be 39.6% and 34.4% where as exergy efficiencies values are 0.29% and 0.74% respectively (iii) the cost of using Lauric acid is lesser than using Myristic acid for same amount of productivity.

Key Words: Water distillation; Solar energy; Exergy; Efficiency; Melting, Lauric acid, Myristic acid

Acronyms

SSWLA	solar still with lauric acid
SSWMA	solar still with myristic acid
LA	Lauric Acid
MA	Myristic Acid
UNEP	United Nations Environment Programme

WHO World Health Organization
WMO World Meteorological Organization

Nomenclature

A Area, m^2
C_p Specific heat, J/kg°K
dt Time interval, s
Gr Grashof number
h Heat transfer coefficient, W/m^2°K
hcw convective heat transfer coefficient from water surface to the glass cover, W/m^2°K
hew evaporative heat transfer coefficient from water surface to the glass cover, W/m^2°K
hrw radiative heat transfer coefficient from water surface to the glass cover, W/m^2°K
h_1 Total heat transfer coefficient from water to glass cover, W/m^2°K°
h_2 Convective heat transfer coefficient from glass to ambient, W/m^2°K
h_3 Convective heat transfer coefficient from basin liner to water, W/m^2°K
i current, ampere
$I(t)$ Solar flux on an inclined collector, W/m^2
m Mass, kg
mew Productivity, ml/m^2hr
P Partial pressure, N/m^2
Pr Prandtl number
q Heat transfer, W/m^2
Ra Rayleigh number
T Temperature, °C
U_{ga} Overall heat transfer coefficient from inner glass to ambient, W/m^2
U_b Overall bottom loss coefficient, W/m^2
U_t Top loss coefficient, W/m^2
U_L Overall heat transfer coefficient, W/m^2
K Thermal conductivity, W/mK
L,x Thickness, m
l Liquid
s Solid
v Wind speed, m/s

Greek symbols

α Absorptivity
α Fraction of solar energy absorbed
ε Emissivity
δ incremental rise, °K
σ Stefan-Boltzmann constant, $W/m^2 °K^4$
τ Transmittance coefficient
η_i Instantaneous efficiency (%)
ΔT Effective temperature difference (°K)
γ Latent heat of vaporization J/kg

Subscripts

a Ambient
b Basin
c Convective
cond Conduction
e Evaporative
eff Effective
f Film temperature
g glass
in inner
ins insulation
mt melting
o outer
pcm phase change material
r radiation
w water

INTRODUCTION

In the 21st century, clean water supply to larger parts of the human population has become a great task. The most recent record of supplying potable water shows that 1.1 billion people worldwide still lack access to clean water[1,16-19]. The availability of clean water is one of the major challenges faced by human society, and the lack of water will be one of the key factors limiting development[2-3,14-15]. Half the urban population in Africa, Asia, Latin America and the Caribbean countries suffer from several diseases associated with inadequate clean water[2].

Moreover, it is a great challenge to keep water clean from the pollution caused by the industrial emissions and insecticides used in agriculture.

Naim and El-Kawi[4] devised a solar still which worked with energy storage material at its base. They experimented changing various factors with the aim of augmented still productivity. Al-Hamadani and Shukla[5] found that the higher mass of phase change material (PCM) with lower mass of water in solar still basin significantly increased the daily productivity and efficiency; the distillate productivity of the solar still with PCM at night and on day increased by 127% and 30-35% respectively than without using PCM. Fath and Elsherbiny[6] conducted an experiment to investigate the effect of a passive condenser in the single slope basin type solar still.A passive solar still with separate condenser has been modeled and its performance was calculated[7]. Results show that the distillate productivity of the developed still was 62% higher than that of the conventional one. Velmurugan[8] modified basin solar still using fins, sponges and wicks for enhancing its productivity. Experimental results showed that the average daily production was higher when fins were used in the still. For extensive solar energy utilization, most solar energy systems require thermal energy storage because it is intermittent by its nature. Latent heat thermal energy storage (LHTES) promises the highest performance and reliability. But selection of suitable PCM for use in storage medium with solar still is not possible without rigorous experimental study. No study has been found in this regard.

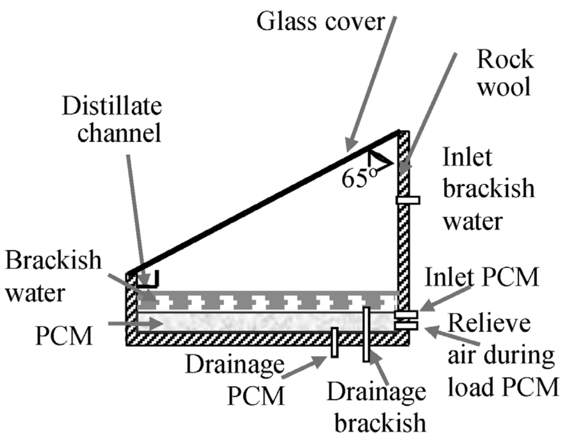
Therefore, in the present study, performance of a single slope solar still with Lauric acid (99% purity) and Myristc acid (99.2%) as PCM has been investigated for different masses during summer climatic conditions of Varanasi, India, (25^o 19` N,83$^o$ 00` E) to collect output data for the new design of solar still. The experiments were performed at roof top of Renewable Energy Laboratory, Mechanical Engineering Department, Institute of Technology, Banaras Hindu University, Varanasi, India. On the basis of collected data exergy analysis has been done to calculate the energy and exergy efficiencies for solar still system integrated with phase change materials.

EXPERIMENTAL SETUP

A photograph and a schematic diagram of the single slope solar still with phase change material (PCM) as a storage medium, is given in

Figure 1. The basin, fabricated from a black painted mild steel sheet of thickness 2 mm, has an area of 1 m^2 each.

(A)



(B)

Figure 1. A photograph of solar still with PCM (A) A schematic diagram of the single slope-single basin solar still with the PCM (B).

A vertical gap (0.05 m) beneath the horizontal portion of the basin liner is provided to upload and/or unload the PCM through a pipe which takes care of the volumetric expansion of the melting PCM as well. The operational and melting temperature of PCM, in fact, governs the applicability of different types of phase change materials. The bottom and sides of the basin are insulated by 5 cm thick layer of rock wool contained in an aluminium tray. The top cover of the still is made up of 4 mm thick window glass which inclines at an angle of 25° with horizontal, and has an average transmisivity (□) of value 0.88. A U-shaped channel is used to collect the condensate from the lower edge of glass cover and carry it to storage. A temperature scanner (Altop Industries ltd, Sn.1005164, model ADT 5003) with resolution 0.1°C and HTC DT-8811Infrared thermometer range: -20°C – 450°C Spectral response: 6-14 μm CE ASCO products had been used to record the temperature with k-type thermocouples in solar stills. The solar radiation was measured by using the daystar meter Watts/m^2 ASCO products, the wind speed was observed by HTC Instruments AVM-07 Anemometer vane probe CE.

ENERGY AND EXERGY IN A SOLAR STILL WITH PCM

The energy and exergy of solar still with PCM are defined next.

The energy efficiency of the solar still is:

$$mew_d = \sum_{24\ hr} mew_h \quad (1)$$

$$\eta_{en\_h} = \frac{mew_h\ \gamma}{A_b\ \sum I(t)*3600} * 100\ \% \quad (2)$$

$$\eta_{en\_d} = \frac{mew_d\ \gamma}{A_b\ I(t)*3600} * 100\ \% \quad (3)$$

The exergy balance of solar still with PCM is

$$\sum Ex_{lost} = \sum E\ x_{in} - \sum Ex_{out} + \sum W \quad (4)$$

The exergy input represents the exergy available from the sun

$$\sum Ex_{in} = A_b * I(t) * \left(1 - \frac{4}{3} * \left(\frac{T_a+273.15}{Ts+273.15}\right) + \frac{1}{3} * \left(\frac{T_a+273.15}{Ts+273.15}\right)^4\right) \quad (5)$$

The last term is the exergy of mechanical work. This term is negligible because no mechanical work occurs in a solar still. So,

$$\sum W = 0 \tag{6}$$

The exergy output or exergy useful is due to evaporation heat transfer.

$$\sum Ex_{out} = \sum Ex_{useful} = \sum Ex_{ev} \tag{7}$$

The exergy lost in solar still water is given by

$$\sum Ex_{lost} = mw * Cw * (Tw - Ta) * (1 - \left(\frac{T_a + 273.15}{Tw + 273.15}\right)) \tag{8}$$

Consequently, the second law efficiency is as follows:

$$\eta_{EX} = Ex_{output} / Ex_{in} = 1 - Ex_{lost} / Ex_{in} \tag{9}$$

RESULTS AND DISCUSSION

The experimentation started at 7:00 AM everyday during 30 April to 10 May2011 on the experimental setup of solar still integrated with Lauric acid (SSWLA) and during 12 May to 22 May on solar still integrated with Myristic acid (SSWMA). See Table A-1 in the Appendix. The temperatures of the outer and the inner surface of glass cover; basin liner, water basin and PCM were recorded at the time interval of one hour till 6:00 P.M. The values of solar radiation, and distillate productivity were also recorded simultaneously. The influence of the variation of the mass of PCM and water basin on daily productivity as well as day time productivity and night productivity was investigated. It was observed by analyzing the experimental data that the heat loss was significantly decreased and overall efficiency increased by adding PCM in solar still which enables storing the loss of heat from the bottom.The variation of the typical observed ambient temperature and calculated solar radiation have been shown in Figures 2 and 3. The experimental observation were taken from 7 am (shown as 0:00 hrs) to 6 pm (shown as 10:00 hrs.) The different water masses, i.e., 30, 40, and 50 kg and PCM masses, i.e., 10, 20, and 30 kg have been used. The solar radiation was varied from zero to 815 W/m^2 in summer day.

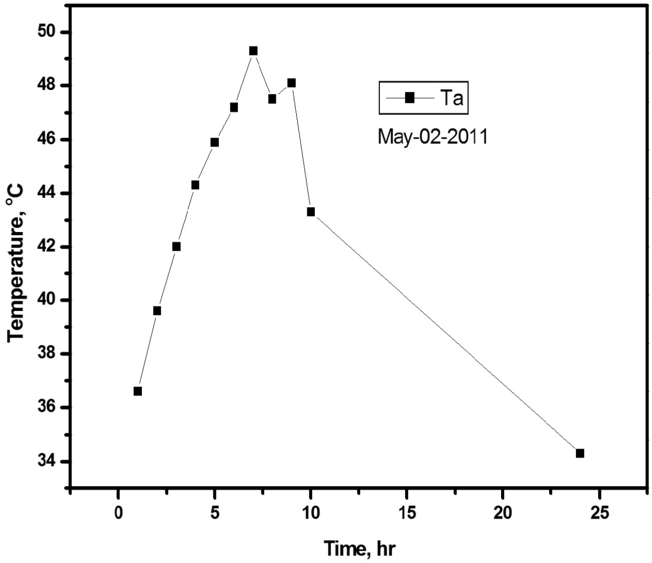


Figure 2. Variation of ambient temperature to solar still for 24 hour on May-02-2011.

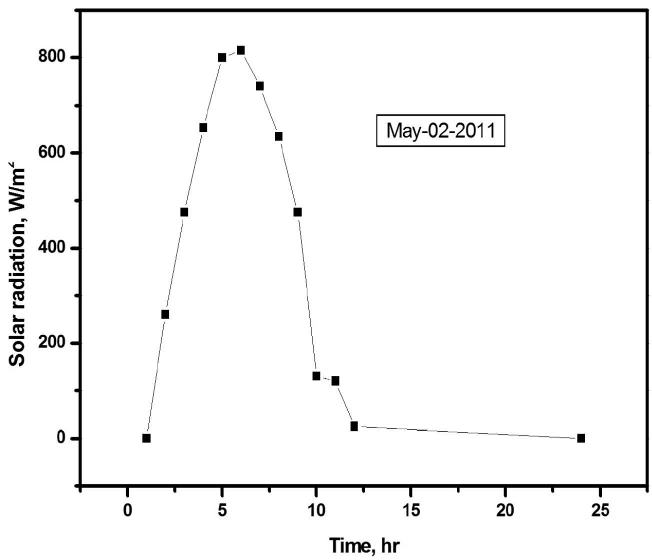


Figure 3. Variation of solar radiation to solar still with variation for 24 hour on May-02-2011.

DAY TIME PRODUCTIVITY FOR SSWLA AND SSWMA

The experimental results are plotted, to show the variation of daytime productivity for the SSWLA and SSWMA with 10 kg of mass of PCM with different masses of water (30-50 kg). Results are shown in Figures 4, 5 and 6 which reveal that the daytime productivity of SSWLA is more than the SSWMA, due to fact that Lauric Acid works better and both the PCM act as storage material as well as insulation for the base.

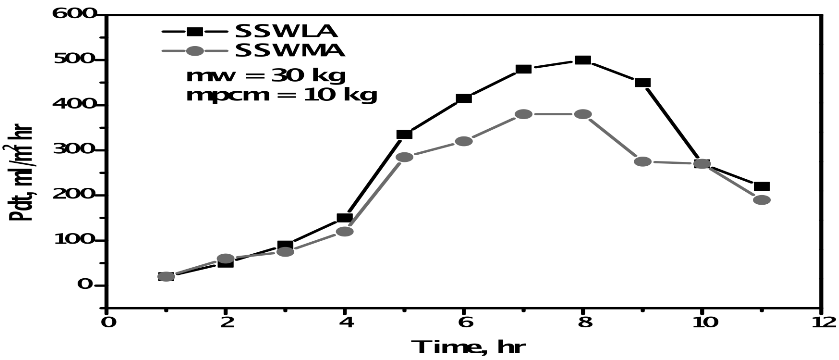


Figure 4. Variation of day time productivity for SSWLA and SSWMA for mw=30 kg and mpcm=10 kg

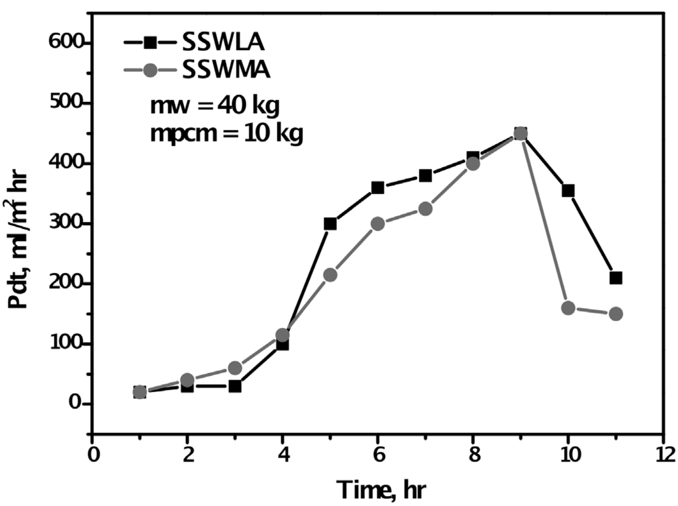


Figure 5. Variation of day time productivity for SSWLA and SSWMA for mw=40 kg and mpcm=10 kg

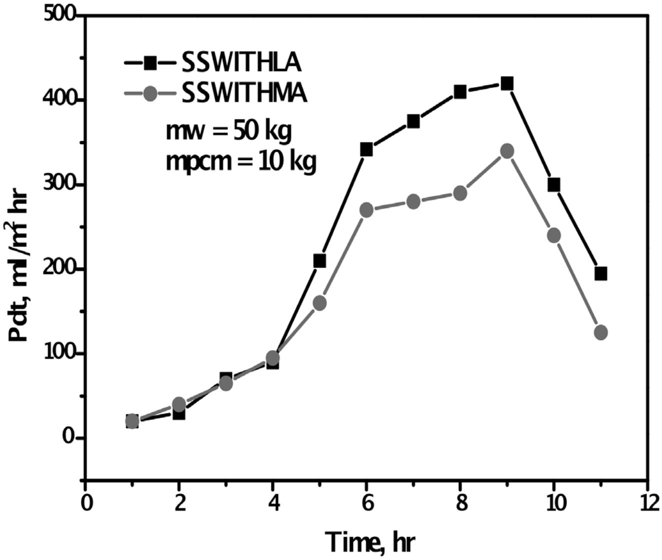


Figure 6. Variation of day time productivity for SSWLA and SSWMA for mw=50 kg and mpcm=10 kg

Night Time Productivity for SSWLA and SSWMA

The latent heat stored in PCM during the daytime charging is utilised by discharging in night to assist the evaporation process by heating the water basin. The two system were tested during night to know the performance of these systems. The recorded data of the productivity during night with different pcm's mass for two systems is shown in Figure 7. The Productivity for SSWMA in night for 10 kg of PCM is little higher than SSWLA But with change of mass of water from 10 kg to 20 kg and 30 kg, the SSWLA produce more distilate output inspite of the fact that input solar energy for SSWMA is larger than SSWLA, as shown in Table 2. The reason for higher productivity with lower input energy is attributed to fast melting of Lauric acid as compared to the myristic acid due to its low melting point.

The Melting of Lauric Acid and Myristic Acid

The melting of PCM is important factor to examine the heat energy storage. This energy can heat the water at night during discharge process. Figures (8-13) represent the variation of temperatures in SSWLA and SSWMA for different mass of water.

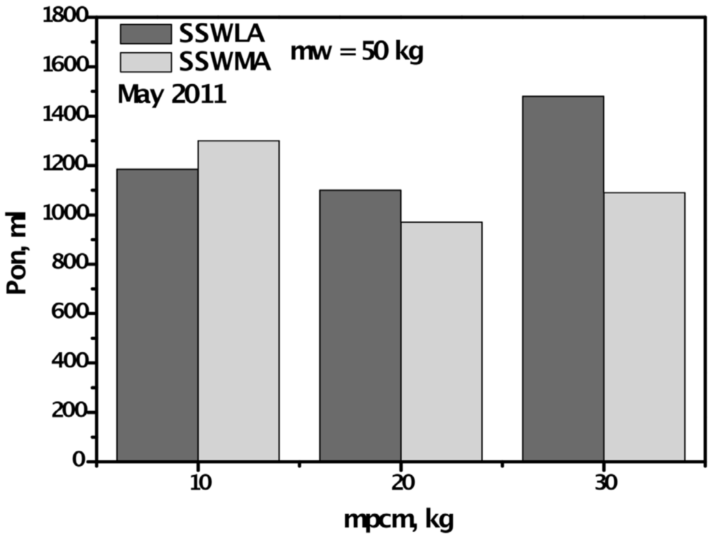


Figure 7. Productivity during night with different pcm masses for SSWLA and SSWMA

Table 2. Night productivity of SSWLA and SSWMA with the total solar energy incident on them.

	SSWLA		SSWMA	
Mass (In kg)	I(t) (W/m^2)	Pon (ml/m^2 hr)	I(t) (W/m^2)	Pon (ml/m^2 hr)
mw=50 kg mpcm = 20 kg	4572	1100	5429	970
mw=50 kg mpcm = 30 kg	5128	1480	5341	1090

Energy and Exergy Efficiency of Solar Still Systems

Equations (1), (2), (3) and (9) were used to calculate the energy efficiency and exergy efficiency of the solar still system performance. The values are depicted in Figures 14 and 15. It is clear from the figures that the energy effeciency for SSWLA is better than SSWMA. This is because solar still integrated with Lauric Acid utilises more stored heat for a larger duration and lower heat lost due to its melting characteristics.

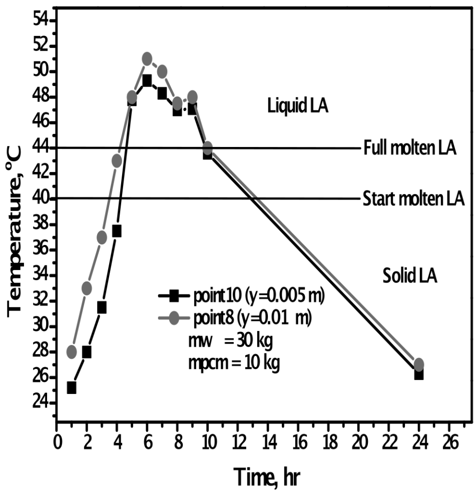


Figure 8. Evolution of temperature at with time for LA.

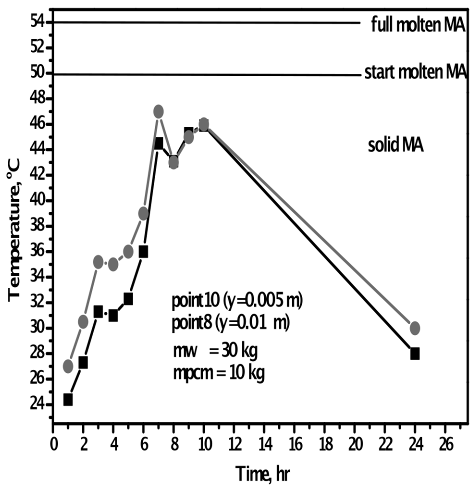


Figure 9. Evolution of temperature at with time for MA.

CONCLUSION

From the above studies, it is seen that when the temperature difference between night time ambient temperature and melting point of PCM is higher than 3°C, it attains lower rates for complete solidification of PCM within available night time hours. But if it is lower than 3°C then

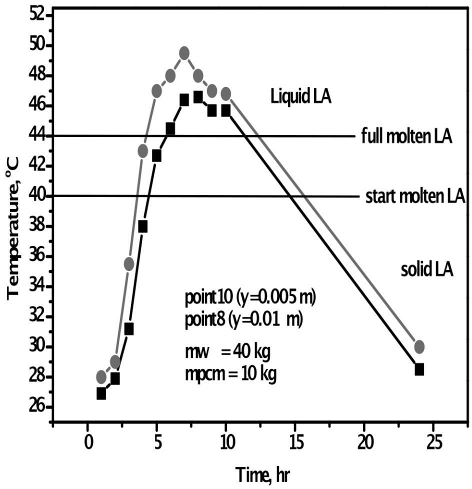


Figure 10. Evolution of temperature with time for LA.

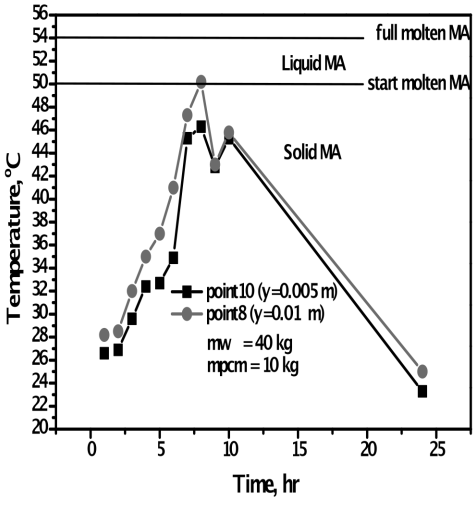


Figure 11. Evolution of temperature with time for MA.

either it will not solidify completely in both the cases. It is also inferred that (i) productivity of solar still integrated with Lauric acid is 22% more than the solar still integrated with Myristic acid. (ii) the energy efficiencies for solar still integrated with Lauric acid and Myristic acid are found to be 39.6% and 34.4% where as exergy efficiencies values are 0.29% and 0.74% respectively (iii) the cost of using Lauric acid is lesser than using

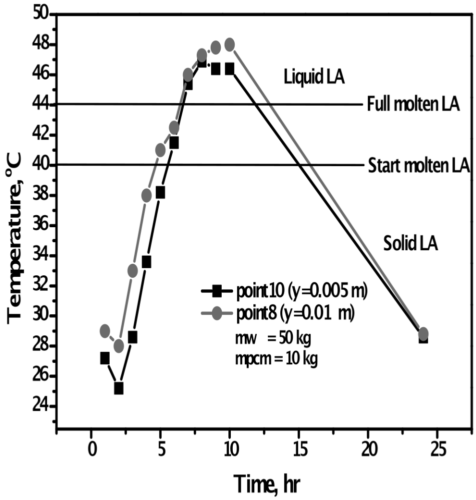


Figure 12. Evolution of temperature with time for MA.

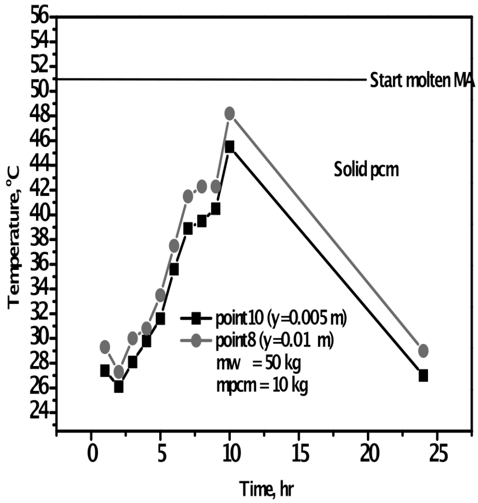


Figure 13. Evolution of temperature with time for MA.

Myristic acid for same amount of productivity due to market costs of these two materials.

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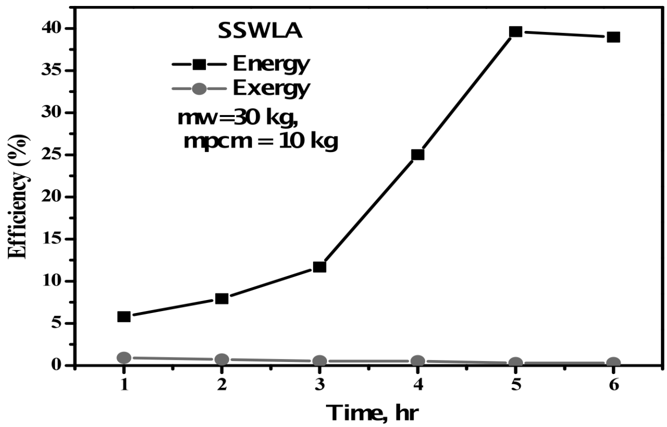

Figure 14. Evolution of temperature at Points 8 and 10 (shown in Figure5) with time for MA.

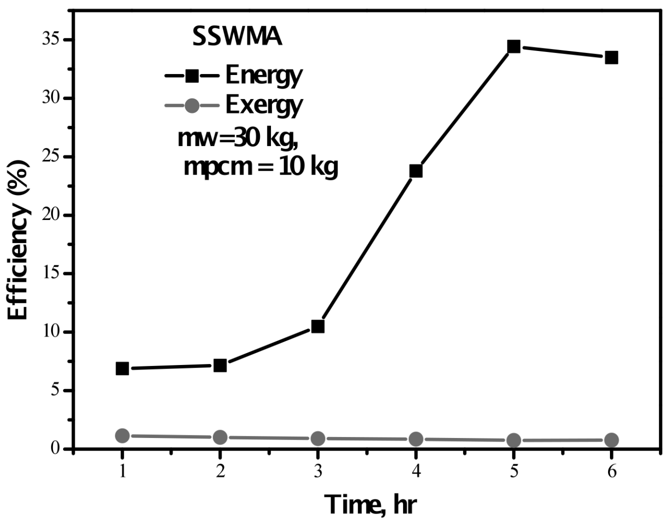

Figure 15. Energy and Exergy efficiency for SSWMA for MW=30 kg and mpcm=10 kg

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APPENDIX

Table A-1. Meteorological data of SSWLA and SSWMA

	SSWLA						SSWMA				
	Date	**I(t) W/m²**	**pdt ml/m² hr**	**pon ml/m² hr**	**pd ml/m² hr**		**Date**	**I(t)n W/m²**	**pdt ml/m² hr**	**pon ml/m² hr**	**pd ml/m² hr**
mw = 50 kg mpcm = 10 kg	10-05-2011	5411	2652	1185	3837		12 -05 2011	5372	1925	1300	3225
mw = 40 kg mpcm = 10 kg	09-05-2011	5368	2625	950	3575		14 -05-2011	5044	2235	820	3055
mw = 30 kg mpcm = 10 kg	08-05-2011	5413	2980	750	3730		15-05 -2011	5275	2375	860	3235
mw = 30 kg mpcm = 20 kg	06-05-2011	5344	2440	800	3240		17-05-2011	4616	2185	910	3095
mw = 40 kg mpcm = 20 kg	05-05-2011	4876	1723	900	2623		18-05-2011	4616	1515	1050	2565
mw = 50 kg mpcm = 20 kg	04-05-2011	4572	1713	1100	2813		19-05-2011	5429	1885	970	2855
mw = 50 kg mpcm = 30 kg	02-05-2011	5128	2200	1480	3680		21-05-2011	5341	1930	1090	3020
mw = 40 kg mpcm = 30 kg	01-50-2011	4736	1600	1110	2710		22-05-2011	5258	1810	1190	3000
mw = 30 kg mpcm = 30 kg	30-4-2011	4788	1775	875	2650		23-05-2011	5865	2340	880	3220

Engineering. He has been graduated from Babylon University College of Engineering, Iraq in 1994 and post graduated from Technology University College of Engineering in 2003.

Currently he is pursuing Ph.D. in the field of Solar Thermal Engineering System form IIT (BHU) Varanasi, India. His areas of interest are Modelling of Solar Distillation System, Life Cycle Cost Analysis etc.

S.K. Shukla is working as Coordinator, Centre for Energy Resources and Development, Indian Institute of Technology (BHU), Varanasi, India. He has been post graduated and completed his Ph.D. from IIT Delhi. His areas of interest are Thermal Engineering, Heat and Mass Transfer Analysis in Solar Thermal Systems and Design of Renewable Energy Systems, Modelling etc.