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Using Aluminium Powder with PCM (Paraffin Wax) to Enhance Single Slope Solar Water Distiller Productivity in Baghdad – Iraq Winter Weathers

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Abstract-Heat transfer enhancement during the phase change is necessary for the design of latent heat thermal energy storage system. This paper presents a practical study of heat transfer enhancement of paraffin wax existing in single slope solar distiller base and sides. Aluminum powder was added to paraffin wax to enhance its thermal conductivity. Three distillers fabricated; one without any modification, the second took the advantage of placing PCM inside it. The third one used PCM with aluminum powder to enhance its thermal conductivity. The practical tests conducted in Baghdad – Iraqi weathers at January and February, 2013. The results show that aluminum powder ameliorated phase change materials exhibit enhanced thermal conductivity in comparison to the base material. Adding aluminum powder to PCM, increased distiller productivity as well as increased distillation time.

Keywords—Aluminum powder; Phase change material; Thermal energy storage; solar distiller productivity; and Single slope still.

1. Introduction

Renewable energy sources are attractive, and due to increasing demand for energy there are focusing on using these energies. One of the main parameters in developing the utilization of these energies is storing it in a suitable form. As an example, one of the difficulties of using solar energy is how to storage it during nights or whenever it doesn't access [1].

Phase change materials (PCMs) have drawn a considerable attention [2]. They possess a considerable heat of fusion and can be used as latent heat storage and release units. They can be used for thermal management of computers, electrical engines, solar power plants, and for thermal protection of electronic devices [2]. Paraffin wax is considered the most prospective PCM between several materials, because of some of its desirable characteristics. Paraffin wax has high latent heat of fusion, limited super-cooling, low vapour pressure in the melt. Also, it is chemically stable and can be 100% recyclable. However, it has low thermal conductivity that results in lower heat transfer rates during phase changing (melting/freezing) processes. The thermal conductivity usually can be improved by adding highly conducting materials to the paraffin wax. As an example, metallic fins heat exchanging surfaces or metal pieces distributed in the wax in a way that makes them not connected to each other [3]. Therefore, increasing the thermal conductivity of the solidified material will enhance its usage in the storage application [4]. However, although the conductivity needs to be improved, it has to be achieved while maintaining the phase change enthalpy. To achieve this goal, several methods have been developed including improving encapsulation techniques [5], mixing the PCMs with high conductive fillers such as carbon nanotubes [6] and silver nanowires [7], and dispersing PCMs in highly conductive cellular structures [8].

Desalination is one of the numerous applications of solar radiation energy especially in countries with abundant sunshine and arid regions [9]. The usage of free energy made solar distillation exhibits a considerable economic advantage over other types of water distillation processes [10]. Distillation with solar energy characterized by its simplicity and favourable for small compact water desalting at geographic locations where there is considerable solar radiation [11]-[12].

Single basin solar still is a simple device used solar energy to convert the available brackish or waste water into potable water. It can be fabricated from locally available materials. Also, its maintenance is cheap and requires an unskilled labour [13]. However, its low productivity makes it difficult to use it [14]. The production capacity of a simple type still is in the range of 2–5 l/m^2/day only that makes the system highly uneconomical [15]. Numbers of valuable works conducted to enhance the productivity of the still, and numbers of methods are available to improve the effectiveness of the still [16].

Many researchers investigated the methods of enhancing the thermal response of paraffin wax heat storage by incorporating aluminium thermal conductivity promoters of various designs into body of the wax [17]-[18].

Aluminium is one of the particles used by many researchers in their experimental investigations [19]. Recently Ho [20] investigated experimentally the active thermophysical properties of PCM prepared by his team, including latent heat of fusion, density, dynamic viscosity, and thermal conductivity. The experimental tests showed that there is a relative increase in the dynamic viscosity of the paraffin containing alumina particles. Mettawee carried out an experimental study to investigate the influence of aluminium particles on melting and solidification processes of paraffin used in a solar collector. The results revealed that the time required for charging and discharging operations could be reduced substantially by adding the aluminium particles. Hence, the mean daily efficiency of the solar collector with composite PCM was much higher than that of with pure paraffin [21].

As the conductivity enhancement of PCM is one of the most difficult challenges [22].

The aim of this study was to evaluate the enhancement in simple solar stiller productivity in Baghdad-Iraqi weathers with PCM usage and the effect of improving paraffin wax thermal conductivity by adding aluminium powder as an additive

2. Experimental Setup

Three single sloped effect horizontal basin types solar still were manufactured and used in this study. The solar still basins were made from galvanized iron plate, with a total base area of 1 m length, 0.4 m width and 36 cm height from end side. A small channel was welded to collect the slipping distilled water from the transparency cover. This channel extended longitude on its side, and with 5 degrees inclined from distiller sides. The stiller edges were 11 cm height; the stiller top was with 30 degree inclined from the horizontal. The upper edges were banded horizontally by 1cm width at the edge, to fix the glass (transparency) cover on it. To ensure of steam complete blockade inside the stiller and to prevent its leakage to outside, a plastic stuffing was used, with 1 cm width and 3 mm thickness. This substance fixed with silicon material to assure total adherence of the plastic stuffing on the upper edge. The glass cover adhered to the stuffing material. The inner surface of the metal basin coloured with non-shiny selective black colour, to increase solar absorption.

Two solar stills fabricated like the above mentioned except for isolating a space from three sides of the inner part of the basin by the same galvanized plate used in the basin body. These isolating parts fixed at 1 cm from the right, lift and back sides of the basin. The space between these new walls and the original wall filled with paraffin wax (Table 1 gives some of the thermo-physical properties of the used paraffin wax). At the basement, 1 cm thick of paraffin wax was filled and covered with galvanized plate and welded. The upper type of the new channels covered and welded, so the paraffin wax covered totally. Iraqi paraffin wax used in this study costs about 1.5 US$/ kg in the local markets.

Three thermocouples fixed in the middle of the wax in the stiller sides. In addition to three thermocouples were attached in three different places in base wax. These thermocouples drew out of the basin. Fig.1 represents the distiller parts with PCM.

In one solar still, the sides and the ground base were filled with PCM and aluminium powder. Table 2 lists the used aluminium powder specifications. Aluminium powder mixed with paraffin wax by using ultra-sonic shaker for several times. In each time, half kilogram of PCM was mixed with 5 grams of aluminium powder to preserve 1% rate of mixing. The weights measured using an electronic balance. As we used 4.8 kg of PCM in the still, the used aluminium powder was 48 gram. Aluminium powder selected because it offers components with high thermal and electrical conductivity and due to its reasonable cost (1.3 US$/gram). Aluminium powder has excellent conductivity values, both thermal and electrical. Aluminium powder has better thermal conductivity than brass, bronze, and ferrous-based materials significantly. Other significant property advantages associated with aluminium powder include corrosion resistance characteristics. The excellent corrosion resistance of aluminium alloys has been well established through years of experience in marine, aerospace and chemical industry applications.

The three distillers manufactured from local inexpensive materials. So their costs were 85, 92.2 and 154.6 US$ for simple still, still with paraffin wax, and still with PCM and aluminum powder respectively.

The slipping distillated water from the transparency cover collected in inclined collecting channel. Four thermocouples fixed two on each face of the cover, and the average of their readings took as glass temperature. The portable water left the distiller by means of an orifice fixed on one side of the distiller, connected by a polyethylene pipe 1.27cm (1/2 in) dia. The pipe extended into the collecting channel to ensure steam persisted inside the still without any leakage from the exit opening to the outside. A wooden box was manufactured to put the metal basin inside it. The box was built from wood boards 2 cm thicknesses each. A thermal insulator (glass wool) was used to insulate the basin. Another operational parameter was used to preserve the collected energy that is to cover the glass after sunset (in order to minimize the heat losses to the environment).

Several thermocouples type K were used to measure varied temperatures. These thermo-couples were calibrated by comparing their readings with a calibrated mercury thermometer. One thermocouple was fixed on the distiller base to measure its temperature. The temperature of the water came from the tank to the distiller measured by means of a mercury thermometer set in the connecting pipe. The surrounding temperature measured by a thermometer placed in the shadow.

Table 1. Thermo-physical properties for the used paraffin wax in the present study

Material properties	
Melting temperature (°C)	45 °C
Latent heat of fusion (kJ/kg)	190
Solid liquid density (kg/m^3)	930/830
Thermal conductivity (W/m °C)	0.21
Solid/liquid specific heat (kJ/kg °C)	2.1

Table 2. The used aluminium powder specifications

Nominal chemistry	Al 99.0 min
Powder name	Al-104
Flow density	53 sec, 1.4 g/cm^3
Size	-90µm/+45µm
OEM Specs/Trade Names	B50TF57 CLA
Application Data	• Corrosion protection coating • Good for repair of Al based parts • Very dense coating • Good for thermal and electrical conductivity

The following equations used in calculating convection and evaporation energies [23]-[25]:

Radiation energy (q_r) computation can be carried out from the equation:

$$q_r = \varepsilon_w \sigma \left(T_B^4 - T_s^4\right) \qquad W/m^2 \tag{1}$$

Convection energy (q_c) can be carried out from the equation:

$$q_c = 0.884\left[(T_B - T_{Cm}) + \frac{(P_B - P_{Cm}) \times T_B}{268 \times 10^3 - P_B}\right]^{\frac{1}{3}} (T_B - T_{Cm}) \frac{W}{m^2} \tag{2}$$

Evaporation energy (q_e) can be carried out by the equation:

$$q_e = 4.52 \times 10^{-3} \left[q_c \ \frac{P_B - P_{Cm}}{T_B - T_{Cm}}\right] \quad (W/m^2) \tag{3}$$

The transferred energy from the transparency cover to ambient air by convection and radiation can be carried out by the equation:

$$q_{ca} = h_{ca}\left(T_g - T_a\right) + \varepsilon_g \sigma \left(T_g^4 - T_a^4\right) \quad W/m^2 \tag{4}$$

Hourly efficiency (η_h)can be carried out by the equation:

$$\eta_h = \frac{P \times h_{fg}}{I \times A} \tag{5}$$

Test Procedure

Three cases of simple solar distiller tested in Baghdad city-Iraq wintertime, 2013. These cases are:

1. Case 1: simple solar distiller without any additions, and it considered as the baseline for comparison.
2. Case 2: simple solar distiller with PCM (paraffin wax) distributed as mentioned above.
3. Case 3: simple solar distiller with PCM and aluminum powder distributed as noted above.

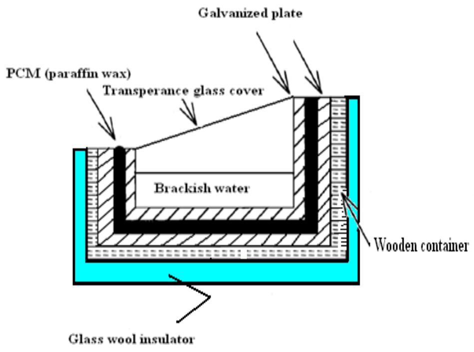

Fig. 1. Schematic diagram represent the details of distiller parts

3. Results and Discussions

In the present study, the productivity of simple solar distiller was considered and evaluated at Baghdad's city wintertime. The affecting environmental parameters include the (sinusoidal) solar intensity; ambient temperature and wind speed anticipated. Distiller productivity increases from zero (l/m^2 h) to reach its peak at 1-2 PM then it reduces to reaches zero at sunset, as figures 2 & 3 indicate. Simple solar distiller provided more distilled water for the period from 7 to 12 AM, after this time the other tested cases produced much more water than it. The increments of distilled water produced in January were 6.11, 21.91% of cases 2 & 3 respectively compared with the first case. For February, the results illustrated that the increments were 10.38, 25.51 % of cases 2 & 3 respectively compared with case 1.

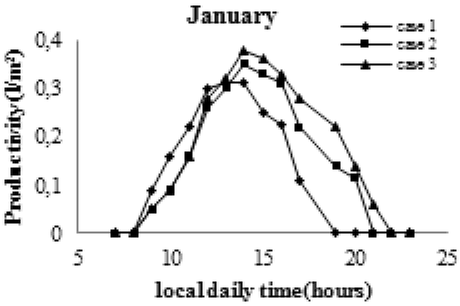

Fig. 2. Distiller productivity with time at January

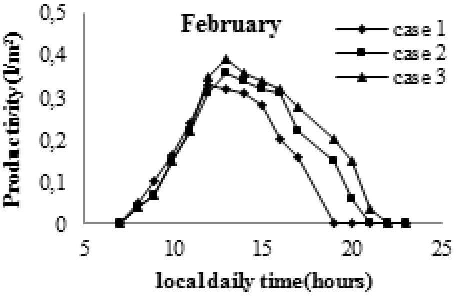

Fig. 3. Distiller productivity with time at February

Figures 4 to 7 show that Q_e and Q_C increased. The increments in basin and water temperatures increased the evaporation and convection energies. Due to the greater energy stored in aluminium powder distiller the larger evaporation and convection energies losses it demonstrated as figures show.

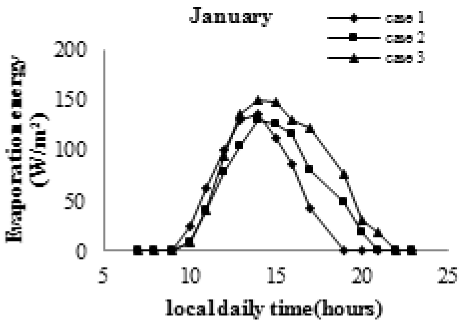

Fig. 4. Distiller evaporation energy versus time at January

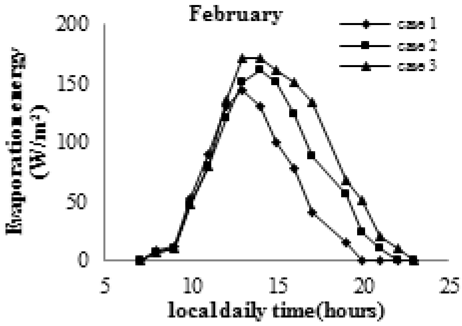

Fig. 5. Distiller evaporation energy versus time at February

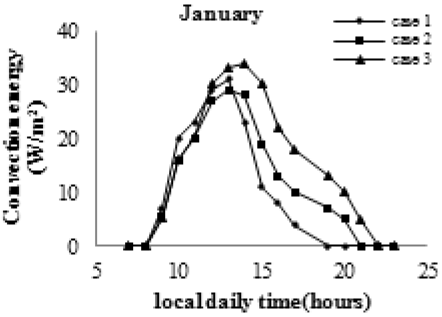

Fig. 6. Distiller convection energy versus time at January

Adding paraffin wax to simple distiller increases its production time for about two hours after sunset in January and about three hours in February. Adding aluminium powder to paraffin wax increased its production time for about three hours after sunset in January and February. The average total water productivity for the three cases was 1.91, 2.347 and 2.7875 l/day for cases 1, 2 and 3 respectively during the studied period. If we take the 1 litre water price in the local market does not exceed 0.25 US$. Then the productivity of the stills will be 174.2, 214.16 and 245.35 US$/year for cases 1, 2 and 3 respectively. From this simple economic analysis, one can estimate that the payback period or the three distillers does not exceed 9 months. The transferred energy from basin to transparency covers (which stayed almost cooler) increased.

The energy lost from the glass to ambient air (Q_{ca}) will start to increase as the productivity increased resulting in more compensating on transparency cover. Vapour condensation on the cover will lead to increase its temperature causing more energy emitted from it to air, as figure 8 indicates. January data took as an example for the lost energy. The lost energy from simple solar distiller at morning was greater than that of the other distillers due to wax absorption of most of the energy to warm PCM.

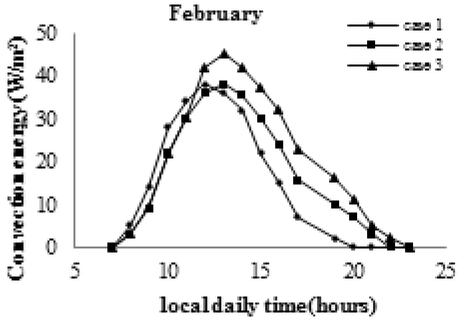

Fig. 7. Distiller convection energy versus time at February

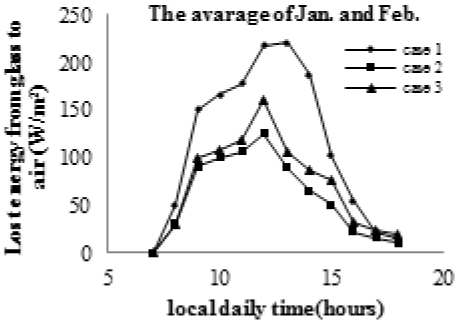

Fig. 8. Lost energy from glass to ambient air versus time at January

Fig 9 represents the relationship between solar intensity and convection, evaporation and lost energies for case 3 in January. Case 3 selected due to its high response for the temperature and solar intensity variations. Convection energy is limited in the system all day hours; in the opposite of the lost energy that starts high from 7 AM to 3 PM then it declines highly. Evaporation energy begins to rise until it reaches its maximum from 1 to 3 PM.

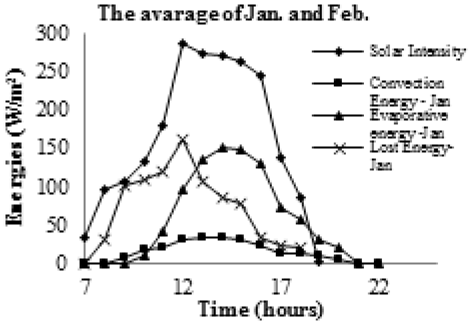

Fig. 9. The relation between solar intensity and convection, evaporation, and lost energies with time.

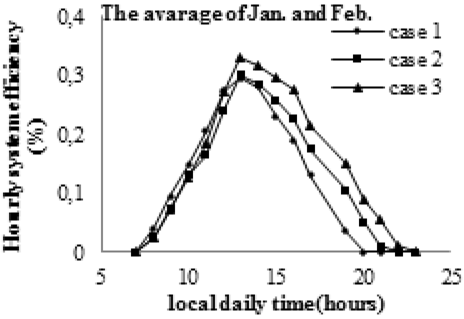

Fig. 10. The average hourly system efficiency versus time for the tested period

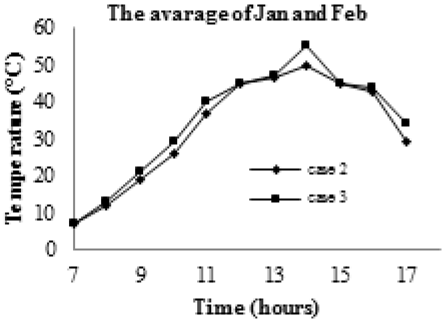

Fig. 11. The average paraffin wax temperatures versus time during the charging period for the studied period

Fig. 10 represents the relation between day time and the average hourly system efficiency for the tested period. Systems efficiency correlated with solar intensity. It reached its peak value at 1 PM. After this hour PCM distillers demonstrated higher efficiencies especially with aluminium powder. For this distiller, the average maximum efficiency achieved was 34.6% for the tested period.

Fig. 11 manifests the paraffin wax temperatures for the still working period starting from 7 AM. The temperatures for the two cases converge most the time, but they become identical at the phase change period.

Adding the Al powder increased the wax maximum temperature about 5°C. As a clarification for paraffin wax phase change periodic behavior fig. 12 shows the relation between time and temperature divided into intervals of 10 minutes starting from 11 AM to 2 PM. Paraffin wax temperatures increased with time until it reached its melting point (45°C for the used paraffin). At this stage, the temperature will suspend until all wax melt and becomes liquid. After that the wax temperature will continue rising. This phenomenon happened up to 2 PM where the solar intensity high and can provide energy. The melting time reduced by using aluminium powder about 10 minutes compared to pure PCM. Also, melting time for this distiller preceded that for case 2 with about 10 minutes. This result ensures the effects of thermal conductivity on the distillers' behavior and productivity.

Fig. 13 reveals the behavior of discharging paraffin wax for the hours from 2 PM to 5 PM. Paraffins temperatures reduced with time until it reached its solidification point (45°C for the used paraffin). At this stage, the temperature will suspend until all wax solidified and became solid. After that the wax temperatures will continue to reduce. Solidification time reduced by using aluminium powder about 10 minutes compared to pure PCM. Also, this time for this distiller retarded compared with that for case 2 about 10 minutes. These retarded minutes were due to higher supercharging temperatures gained by aluminium powder and PCM.

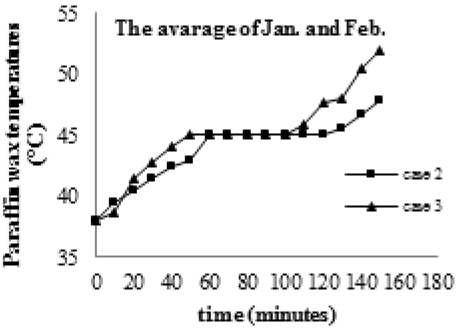

Fig. 12. Paraffin wax temperatures versus time during the charging period at February

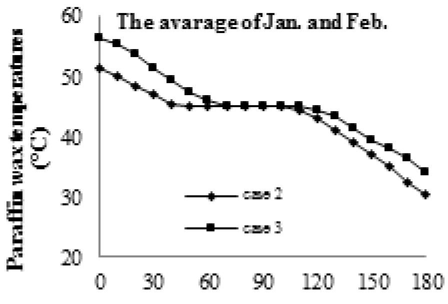

Fig. 13. Paraffin wax temperatures versus time during discharging period at January

A practical study conducted to examine the enhancement single slope solar distiller productivity by adding paraffin wax to the still base and sides. Aluminium powder was mixed with paraffin wax to enhance its thermal conductivity. Three distillers fabricated; one without any modification, the second took the advantage of placing PCM inside it. The third one used PCM with aluminium powder to enhance its thermal conductivity. The practical tests conducted in Baghdad - Iraqi weathers at January and February, 2013.

The study revealed that adding paraffin wax improved the solar distiller productivity with 6.11% in January and 10.38% in February compared to simple solar distiller. While, adding aluminium powder to paraffin wax enhanced its productivity by 21.91% in January and 25.51% in February compared to simple solar distiller productivity. Distillation systems efficiency correlated to solar intensity, and it enhanced with adding PCM. Adding additive to PCM increased thermal conductivity; that enhanced the evaporation and convection energies remarkably. Charging and discharging time for aluminium powder-PCM is reduced, compared with other cases, due to better thermal conductivity.

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NOMENCLATURE

T_B	Basin water temperature K	q_r	Transferred thermal energy by radiation between solar still basin and glass cover.
P_B	Partial pressure at basin water temperature Pa	η_h	The daily hour efficiency.
q_c	Transferred thermal energy by convection between solar still basin and glass cover.	I	Actual solar intensity, the exact values were obtained from solar energy tables prepared by Iraqi Meteorology Enterprise.
q_e	Transferred evaporating energy between solar still basin and glass cover.	h_{fg}	water enthalpy
A	Basin base area.	P	Productivity
T_{Cm}	Average transparency cover temperature K	h_{ca}	Heat transfer coefficient
P_C	Partial pressure at average transparency cover temperature Pa		