

Enhancement of solar water distillation process by surfactant additives

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Abstract

The presence of surfactant additives in water is found to enhance the boiling heat transfer significantly. The effect of using a surfactant as sodium lauryl sulfate (SLS) in relatively small dosages of concentration with a small size unit of solar water distillation process is investigated. Sun simulator (electric heater and variac transformer) is used to quantify the same input power for each experiment for the system instead of the sun. The experimental results show that a small amount of surfactant additive makes the top brine temperature (TBT) considerably higher, hence the freshwater product. Temperature curves for various surfactant concentrations are obtained and compared. The percentage of the increase in the system productivity is 0.7%, 2.5%, 4.7% and 7% at additive concentration equal to 50, 100, 200 and 300 ppm respectively. It is found that increasing the surfactant concentration more than 300 ppm not affecting the system daily productivity (DP) and TBT. Using surfactant concentration more than 400 ppm will decrease the DP by 6%.

Keywords: Surfactant; Solar water heater simulator; Flash evaporation process

1. Introduction

Surfactants are specialized additives, and are being used in many areas such as mineral processing, paper making, paint making, etc., formulated to improve the emulsifying, spreading, sticking and absorbing properties of liquids [1]. Generally;

surfactants are used to change the surface properties of water. Many effects of surfactants are known — they reduce surface tension, skin friction in tubes and enhance boiling heat transfer. Most of them can be explained by the basic structure of the surfactant molecules [2]. Ionic surfactant consists of one hydrophilic and another hydrophobic end and when it is introduced into water may form micelles depending on the concentration

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spherical, disc or rod-shaped conglomerations of molecules are formed. They also form hydrogen bonds with water and with each other, thus changing the properties of water. Also surfactants are effective at extremely low concentrations — in the range of 100 ppm or so — and hence find application in almost all industrial processes in addition to their use in cleaning and detergent products. Boiling heat transfer is a very effective and efficient mode of heat transfer, and it is encountered in numerous engineering applications.

Also heat/mass transfer enhancement additives are routinely used in absorption chillers primarily to increase the rate of the transfer process occurring in the absorber. The enhancement additives also increase the condensation rates [3]. Though enhancement additives have been in use in commercial absorption chillers since the 1950's there has been no complete understanding of the enhancement mechanism. Boiling with surfactant additives is generally an exceedingly complex process, and it is influenced by a larger number of variables than the phase-change process of pure water [4]. A few numbers of studies have been made in the past to relate the nucleate boiling heat transfer coefficient to the surface tension of a boiling liquid. Many researchers examined the behavior of the surfactant additives on pool boiling heat transfer. Tzan and Yang [5] examined such effect on pool boiling. The experiments were carried out for relatively wide ranges of surfactant concentration and heat flux. It is claimed that the obtained results verify that a small amount of surfactant additive makes the nucleate boiling heat transfer coefficient of water considerably high. It was also found that there was an optimum additive concentration for high heat flux. Hetsroni et al. [4] examined the same effect with different values of surfactant concentration. The experimental results showed that the addition of small amount of environmentally acceptable alkyl glycosides makes the boiling behavior quite different from

that of pure water. Todor Stoyanov [2] studied the effect of surfactant on heat transfer and bubble formation in sub-cooled pool boiling. Toshiaki Inoue et al. [6] measured surface tension of ethanol/water mixtures over the whole ethanol fraction range and the effect of the surface-active agent on surface tension is also measured in the mixtures, in order to gain basic data related to enhancement of the heat transfer coefficient in water and the mixtures. The experiment was carried out in the whole range of the ethanol fraction and in a surfactant concentration of 0–5000 ppm. It is found that depression of the surface tension by the surfactant remarkably enhances the heat transfer coefficients in the nucleate pool boiling. Kulankara and Herold [3] measured the surface tension of aqueous lithium bromide with and without various surfactant additives, using a drop weight method. Measurements were also made on water, with and without an additive. The results provide new information that clarifies several confusing aspects of the literature data. The major result is the realization that the surface tension of aqueous lithium bromide is strongly affected by the presence of surfactant vapor around the liquid interface. One important field of the application of boiling and evaporation is in desalination of seawater, which is becoming essential in some arid regions [4]. It was shown by Sephton [7] in 1974 that addition of small amounts of surfactants to seawater can substantially enhance the boiling process, and reduce the price of the desalinated water to an acceptable level. At that time, the research was discontinued because the environmental impact of surfactants was not known. Since the concentrations are usually low, addition of the surfactant to water causes no significant change in the saturation temperature and the majority of other physical properties, except for the surface tension and, in some cases, the viscosity. Sayed Siavash et al. [8] examined the fouling restricts membrane performance. In that work reverse osmosis membranes were fouled with water. Chemical cleaning of

the RO membranes using acid, alkaline, surfactant and detergent solutions was discussed. Cleaning efficiency depends on the type of the cleaning agent and its concentration. It was shown that the efficiency increases with increasing the concentration of the cleaning agent. Desalination by means of renewable energy sources is a suitable solution for providing fresh water to a number of regions so far apart as the Mediterranean basin, Africa and world-wide remote areas [9]. This solution becomes more competitive, especially for remote and rural areas where small quantities of water for human consumption are needed. For some time, a single-effect basin-type solar still has been the cheapest way to produce drinkable water using solar resources. Due mainly to the rejection of the latent heat condensation, small daily production less than 4–5 kg/m², with specific energy consumption around 7000 kJ/kg was obtained [9]. Badran and Al-Tahaineh [10] presented a flat plate solar collector coupled with solar still unit. The experimental investigation was made to study the effect of coupling a flat plate solar collector on the productivity of solar stills. It was found that coupling of a solar collector with a still has increased the productivity by 36%. The still area was about 1 m² filled with brackish water supplied to it from a collector. The flat plate collector area was found to be about 1.08 m². The system total productivity was found to give 3.51 kg/day and found to be 36% more than that when the still was operated alone (2.24 kg/day). Also Soliman [11] examined a humidification dehumidification desalination system powered by solar concentrator collector (area = 2.5 m²) with total unit productivity equal to 8 kg/day. Nafey et al. [12] presented a small size flash evaporation unit that operates by the solar energy for producing a small amount of potable water. The system is mainly consists of a flat plate solar collector (FPC) and a flash evaporation unit. The system is operated and investigated under real environmental conditions during winter and summer seasons. The total productivity of

the system in winter ranged between 1.04 and 1.46 kg/day/m², while the summer productivity ranged between 4.18 and 7 kg/day/m². From the literature [9–12]; it should be noted that solar desalination technologies have a limited productivity compared with other technologies. So, surfactant additives may be used to enhance the distillation process productivity by increasing the bubbles formations (releasing more vapors). The main objective of the current article is to examine the performance of the solar distillation system proposed by Nafey et al. [12] with different surfactant dosages. This study is performed at five concentration values of environmentally acceptable anionic (SLS) surfactant [4] in order to find out their effects on the top brine temperature (TBT) and the daily productivity (DP) of the considered system. For that aim, natural solar energy over the collector (original system) is replaced by a solar simulator system (new system) to examine the effect of surfactant concentration under a constant power input to the system.

2. System description and experimental work procedure

Fig. 1 shows a schematic diagram of the system components. Simply the original system

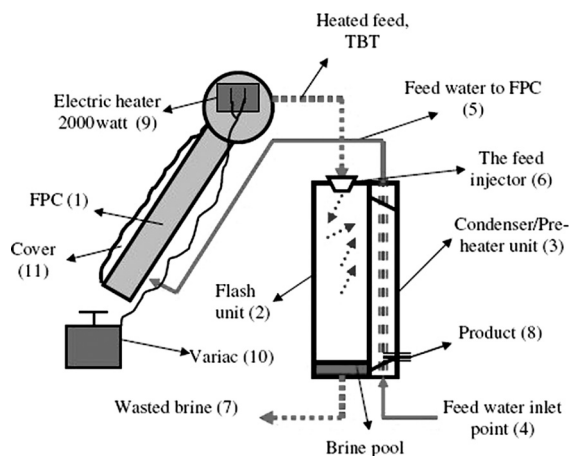


Fig. 1. A schematic draw of the system components.

containing: solar water heater (FPC) (1) and flash evaporation unit (2) designed vertically and attached to the condenser/preheater unit (3). Feed water enters the condenser inlet point (4) at a known temperature then passing through the condenser tubes till its discharge from the outlet point (5) with a higher temperature value which caused by the heat transferred from the vapor that condensate across the outside surface of the condenser tubes. Then feed water enters the solar collector (with its higher temperature) to raise it to the top brine temperature (TBT) before entering the flash chamber. Then hot feed water enters the flash chamber by passing through a feed injector (6). The wasted brine then exits after releasing its vapor (7). Vapor condensates on the condenser tubes (8) to produce fresh water. For the operation of the solar simulator; an A.C. electric heater (9) is used as a heat source to replace the solar flux in actual solar collectors. A variac transformer (10) is used to control the heating power input in the range of 0–2000 W, through controlling the voltage on the heater. A voltmeter and ammeter are used to measure the power input. The heater maximum load is about 2000 W, and its net surface area is about 140 cm². By switching the volt variation arm of the variac transformer to the desired watt (simulating the solar flux); the electric heater output load will become under control. The collector is full covered (11) and insulated just to quantify only the effect of electrical heater without the sun flux effect. So the collector is replaced to work as a storage system (tank) heated by electricity instead of the sun. Fig. 2 shows a photograph of the variac transformer connected with the voltmeter and the ammeter.

The surfactant is introduced at different dosages of concentrations into the inlet feed water tube (4). The experiments are run along 8 h for one concentration. Tzan and Yang [5] demonstrates that the effect of additives, on boiling heat transfer, decreases when the concentration of the solution was higher than 700 ppm. Therefore,

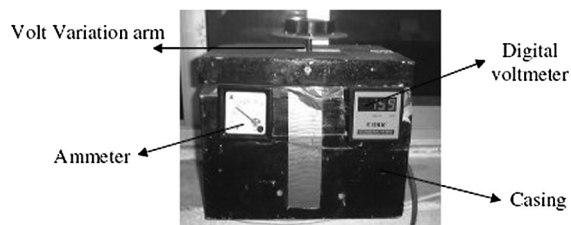


Fig. 2. A photograph of the variac transformer with its components (voltmeter and ammeter).

surfactant dosages equal to 50, 100, 200, 300, 400 and 500 ppm are used for this system. Actually, the results of the present work show that there is no significant increasing in the system productivity with additives concentrations more than 300 ppm. The original system (natural solar energy) is found to give a higher productivity when it is operated under the summer conditions than winter conditions. Therefore, the summer solar flux values are simulated and adjusted by the variac transformer to give the same equivalent power input to the electric heater. Eight different values of heating power input are adjusted for 8 h along the day. The eight values for 8 h of operation are illustrated in Table 1 in Watt, and are equivalent to eight values of solar flux W/m² respectively.

3. Measurements of the experimental data

3.1. Temperature

Different temperatures of the system (see Fig. 1) are measured by a digital volt meter through signals provided by number of thermocouples. The device relative error is less than $\pm 1\%$. The ambient temperature is measured by a common glass-tube-mercury temperature meter.

3.2. Condensate and wasted brine flow rates

By collecting the condensate and outlet wasted brine in two calibrated tanks at a certain time,

Table 1

The results obtained for the system at different values of surfactant additives

Operating conditions	Time (h)	9	10	11	12	13	14	15	16
$C = 0$ (ppm)	I_s (W/m ²)	560	652	704	773	710	654	575	492
	E_{power} (W)	1176	1370	1478	1623	1490	1373	1207	1033
	TBT (°C)	54	57	63	70	68	63	53	50
	DP (kg/h)	1.5	1.61	2	2.3	2.28	2	1.31	1.21
$C = 50$ (ppm)	The average values of TBT and DP at concentration = 50 ppm are 60.25°C and 1.79 kg/h respectively								
	TBT (°C)	54	57	63.5	70.5	68.5	64	53.5	51
	DP (kg/h)	1.5	1.61	2.01	2.31	2.29	2.06	1.32	1.22
$C = 100$ (ppm)	The average values of TBT and DP at concentration = 100 ppm are 60.65°C and 1.82 kg/h respectively								
	TBT (°C)	54.5	57.75	64	71	68.7	64.5	53.5	51.25
	DP (kg/h)	1.52	1.64	2.06	2.39	2.298	2.07	1.328	1.27
$C = 200$ (ppm)	The average values of TBT and DP at concentration = 200 ppm are 61.09°C and 1.86 kg/h respectively								
	TBT (°C)	54.5	58	65	71.5	69	64.75	54	52
	DP (kg/h)	1.57	1.7	2.07	2.4	2.3	2.08	1.5	1.28
$C = 300, 400$ (ppm)	The average values of TBT and DP at concentration = 300, 400 ppm are 61.65°C and 1.91 kg/h respectively								
	TBT (°C)	55	58.5	66	72	69.25	65	55	52.5
	DP (kg/h)	1.58	1.85	2.15	2.44	2.32	2.09	1.57	1.29
$C = 500$ (ppm)	The average values of TBT and DP at concentration = 500 ppm are 59.87°C and 1.79 kg/h respectively								
	TBT (°C)	54	57	63	69	67.5	64	53	51.5
	DP (kg/h)	1.51	1.618	2.013	2.32	2.3	2.06	1.325	1.23

the flow rate of both the condensate and brine are measured.

3.3. Electric power input

In the original system, solar radiation is measured by a solar radiation pyranometer laid on the collector surface with slope angle equal to 45°. But for the solar simulator, the input power to the electric heater is measured by both digital voltmeter and ammeter. The voltmeter range is from 0 to 500 V with an error percentage equal to ± 1 digit and frequency equal to 50–60 Hz.

The ammeter range is about 0–15 A with an error percentage equal to ± 0.1 A. The estimation of the electric power input is presented as follows:

$$E_{\text{power}} = I_s \times A_c \quad (1)$$

where A_c is the collector effective heat transfer area of the absorber plate and equal to 2.1 m², and I_s is the solar radiation from the sun.

Also

$$E_{\text{power}} = V \times I \times \text{PF}_H \quad (2)$$

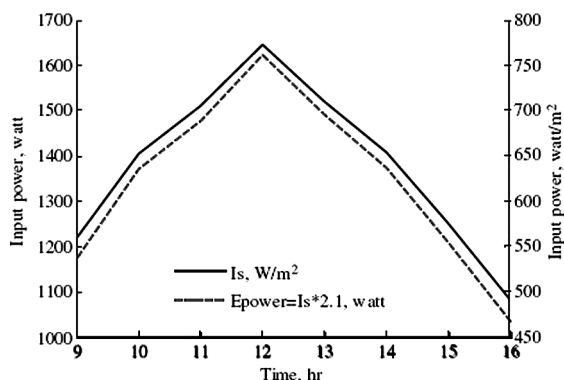


Fig. 3. Variation of the equivalent electric heater power input based on the solar flux input.

where PF_H is the electric heater power factor, nearly equal to one ($PF_H \approx 1$), I is the electric current and V is the voltage input power. From Eqs. (1) and (2) the equivalent power input to the electric heater is given as

$$E_{power} = V \times I \times 1 = I_s \times 2.1 \quad (3)$$

By knowing the power input from the sun (previously recorded day by the original system) the variac transformer can be adjusted by multiplying the volt reading by current reading from the voltmeter and ammeter respectively. Eq. (3) is presented in Fig. 3.

4. Results and comments

For the original system (without surfactant); the system is operated and investigated along one year (2005), and the system summer productivity was higher than winter [12]. The maximum allowable system productivity was ranged between 1.04 and 1.46 kg/day/m² in winter and about 4.18 and 7 kg/day/m² in summer. So the system productivity under summer operating conditions (solar radiation) is higher than winter productivity by 80%. Therefore; summer operating conditions and environmental data (solar radiation) are simulated and adjusted for the

variac transformer to quantify higher system DP. The experiments are performed based on these following assumptions:

- (1) The fluid feed flow rate is constant and equal to 0.0183 kg/s.
- (2) Thermal losses to the ambient are neglected.
- (3) The energy stored in the collector is neglected.
- (4) The collector glass cover is full covered and insulated to quantify only the effect of the electric heater on the process.
- (5) The system goes under steady state condition.
- (6) The experiments were carried out under atmospheric pressure.

Table 1 shows that at $C = 0$ ppm the maximum obtained TBT is 70°C with total daily productivity equal to 14.21 kg/day. However, at $C = 50$ ppm, the results show that there is a little bit increasing in the DP and TBT. The TBT is measured 70.5°C and the increasing percentage of the DP is 0.7%. The total DP is found to be not exceeding about 14.32 kg/day. At $C = 100$ ppm, the DP is increased by 2.5% while the TBT is reached to 71°C. The total system productivity is increased to 14.57 kg/day. At $C = 200$ ppm, the system produces an amount of distillate water reaches to 14.9 kg/day with increasing percentage equal to 4.6%. At 300 ppm; the DP is increased by 7% with accumulative productivity equal to 15.3 kg/day. At surfactant concentration ranged from 300 to 400 ppm, the system productivity has not been changed. From Table 1 it may be noted that by increasing the surfactant additives concentration the TBT, and DP would increase.

Fig. 3 shows the variations in electric power input (E_{power}) based on the variations in solar flux input under summer conditions. The equivalent electric power input (watt) is found to be equal to $I_s \times A_c$, where A_c is the collector effective heat transfer area and equal to 2.1 m². Fig. 4 shows the hourly variations of DP under different surfactant concentration at the same operating conditions. The figure shows that by increasing the surfactant

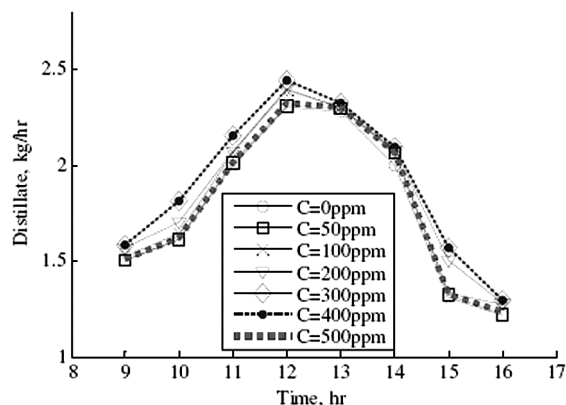


Fig. 4. The variation in the distillate product according to the variation in surfactant concentration.

concentration the DP increases. The DP increased till 300 ppm of additives concentrations. The increase of DP may be explained by the decrease in the surface tension relative to water surface. Increasing the additive concentration up to 400 ppm gives nearly the same results as 300 ppm. However, increasing the additive concentration up to 500 ppm leads to decreasing the DP and TBT. This is happened due to the formation of some foam. Adding surfactant up to 500 ppm decreases the DP by 6% (from 15.3 to 14.38 kg/day). Fig. 5a

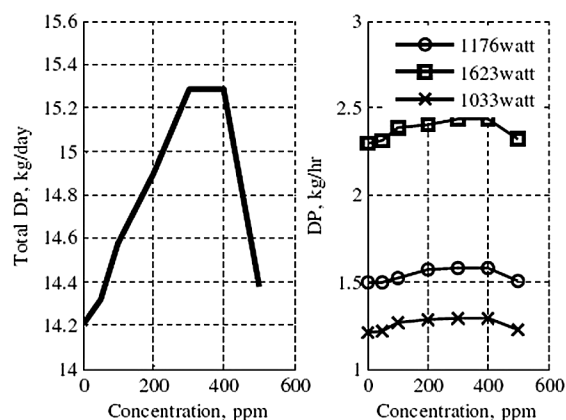


Fig. 5. The relation between distillate productivity and the concentration: (a) the total DP vs. concentration; (b) the DP/h vs. concentration at different values of input power.

shows the variation of DP with the variation of surfactant concentrations. The figure shows that the DP has no significant change at additives from 300 to 400 ppm and the system DP nearly constant at this case. However the DP is decreased at surfactant additives equal to 400–500 ppm as regarded before. Fig. 5b shows the changing of DP against the changing in additives at different values of input power. The figure represents the effect of increasing the input power and surfactant concentration on the DP. By increasing the input heat flux; the DP is increased. This may because by increasing the heat fluxes, the dynamic and kinematic viscosity decrease gradually allowing more vapor to produce more distillate. But by increasing the surfactant concentrations the viscosity will increase. Also, viscosity is decreasing with the increasing the TBT. Fig. 6 shows the hourly variations of TBT at different surfactant concentrations. The figure shows that by increasing the surfactant concentration the TBT is increased. Fig. 7 represents the effect of the equivalent power on the DP with the variation in surfactant concentration. The figure shows that the DP increases with increasing the equivalent power. At constant equivalent power the DP increases with increasing the surfactant concentrations until $C = 400$ ppm, then the DP decreases.

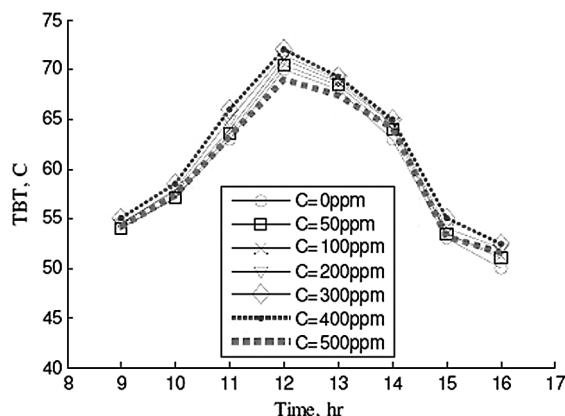


Fig. 6. The variation of the TBT according to the variation in surfactant concentration.

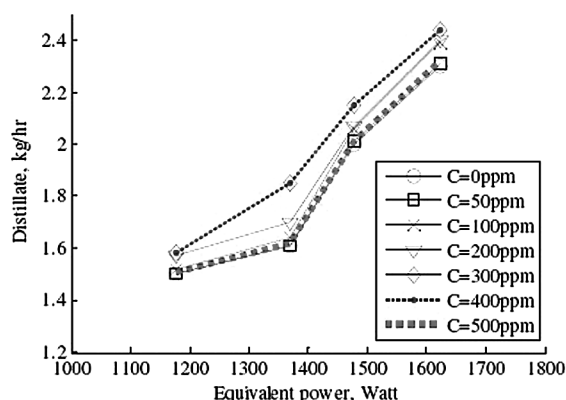


Fig. 7. The effect of increasing the equivalent power on the DP at different concentrations.

This is due to; by increasing the surfactant concentrations the viscosity will increase and also the surface tension and that will retard interfacial evaporation of the solution. Thus, the effect of surfactants in the solution on interfacial evaporation has two effects: as the concentration of surfactant is lower than the optimal value (300 ppm) and the interfacial superheat is not extremely high, the application of surfactant additives promotes the interfacial evaporation; otherwise, retards the interfacial evaporation. Fig. 8 shows the same behavior of the effect of equivalent power input on the TBT. Thus, it is evident

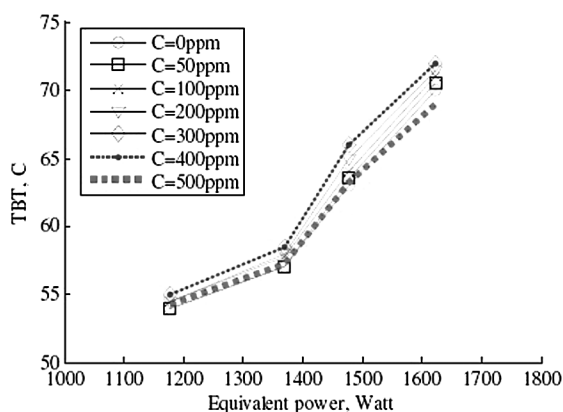


Fig. 8. The effect of increasing the equivalent power on the TBT at different concentrations.

that the influence of the surfactant on the TBT curve behavior has an optimum, depending on the concentration. So, for adding surfactant materials, it is not allowed to be exceeded over the range of 300–400 ppm.

The coefficient of performance of the system (COP) which can also be defined as the energy recovery or the performance ratio, it is the measure of energy efficiency of the thermal consumption of the system. The COP can be determined from the following relation:

$$\text{COP} = \frac{\text{DP} \times H_v}{E_{\text{power}}} \quad (4)$$

where H_v is the latent heat of condensation and DP is the distillate product of the system and E_{power} is the electric power input to the electric heater (data from Table 1). Fig. 9 shows the hourly variations of the system COP at different dosages of the surfactant material. The figure shows that the COP increases gradually with the concentration increase. However, it decreases with additives concentration 500 ppm.

A sample of the obtained distillate water is analyzed to examine if there are some organic or toxic particles in the distillate or not. Table 2 illustrates the water ingredients before and after adding the surfactant material. For these two

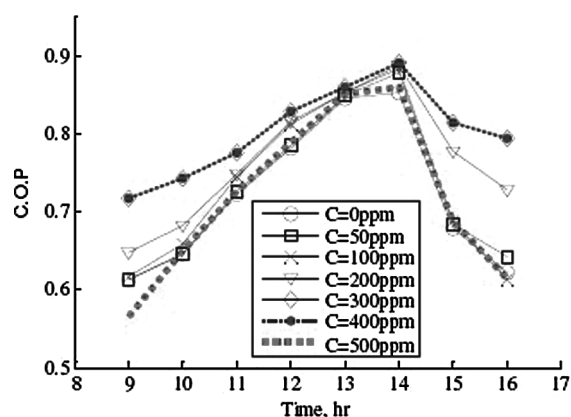


Fig. 9. The hourly variation of the COP vs. time.

Table 2

The water samples ingredients before and after adding surfactant material

Item	Sample of tap water	Sample of distillate water without surfactant	Sample of distillate water with surfactant	Units
T.D.S	350	115	113	mg/L
pH	8.1	8.48	8.48	
Phosphate	0.2	0.05	0.05	mg/L
Nitrite	0.3	0.26	0.26	mg/L
Ammonia	2	3.68	3.68	mg/L
Calcium	60	26	25	mg/L
Magnesium	19	3.8	3.3	mg/L
Sodium	35	11	10	mg/L
Potassium	3	2.2	2	mg/L
Bicarbonates	115	60	60	mg/L
Sulphates	31	10	10	mg/L
Silica	10	7	6	mg/L
Conductivity	–	239	239	m/s
Fluorides	–	0.1	0.1	mg/L
Nitrate	–	0.98	0.98	mg/L
Organic	–	–	–	–

cases; the total dissolved salts (TDS) of water is not exceeding about 113–115 mg/L. Also the analysis show that the organic or toxic particles are not appear in the distillate even after using surfactant concentration equal to 400–500 ppm. May that because the high efficiency of the condensation operation.

5. Conclusion

A solar distillation system compound from a flat plate solar collector and flash a evaporation unit was explained. This original system was operated under out door conditions (solar energy). The original system productivity was limited (10–16.5 kg/day in summer and about 2.5–3.5 kg/day during the winter). To examine the effect of the system concentration at a constant input power an electrical heater with variant transformer is used as a sun simulator. An environmentally acceptable anionic surfactant is used to study its effect on the system DP and TBT. The results verify again that a small amount of

surfactant material makes the TBT and DP considerably higher. 50, 100, 200 and 300 ppm of surfactant concentrations are studied. The DP is increased as 0.7%, 2.5%, 4.7% and 7% at additive concentration equal to 50, 100, 200 and 300 ppm respectively. The effect of power input on the system productivity at different values of surfactant concentration is also studied. The system COP is affected by the increasing of surfactant additives hence the TBT. Increasing the surfactant concentration more than 300 ppm is not affecting the system DP and TBT. Using surfactant concentration more than 400 ppm decreases the DP by 6%. Thus, the effect of SLS surfactants in aqueous solution on evaporation operation is dual: as the concentration of SLS surfactant additives is lower than a certain value (400 ppm) and the heat flux is not extremely high, the application of SLS surfactant promotes the interfacial evaporation; otherwise, retards the interfacial evaporation. A sample of distillate water is analyzed and showed that there is no appearing of organic or toxic particles in the

distillate water. The mechanism of interfacial evaporation in heating and condensation process with the application of surfactants has still not been clarified. Results verify that there is an important possibility to enhance the water distillation process by surfactant additives.

Nomenclature

A_c	collector heat transfer area (m^2)
C	surfactant concentration (ppm)
COP	coefficient of performance
DP	distillate product, daily productivity (kg/h)
E_{power}	electric (equivalent) power input (W)
FPC	flat plate collector
H_v	the condensation latent heat (kJ/kg)
I	electric current (A)
I_s	solar radiation (W/m^2)
PF_H	electric heater power factor
TBT	top brine temperature ($^{\circ}C$)
V	voltage (V)

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