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Multi-Effect Passive Desalination System, An Experimental Approach

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Abstract: Solar stills are very simple to construct and to operate but their efficiency and productivity are fairly low. To increase the yield from stills different methods were adopted. In this paper, an experimental investigation on single and double effect desalination systems are reported and effects of some parameters such as water depth, input radiation intensity and salinity on the productivity of the system is discussed. Increase in water depth in the basins, decrease in the radiation intensity and increase in the salinity reduces the system production rate. Using a passive double effect desalination system increases the yield of the system considerably.

Key words: Desalination · Multi-effect · Concentration · Solar still · Passive · Radiation

INTRODUCTION

More than two-third of the earth's surface is covered with water. Most of the available water is either present as seawater or icebergs in the Polar Regions. More than 97% of the earth's water is salty; rest around 2.6% is fresh water. Less than 1% fresh water is within human reach [1]. The shortage of drinkable water in many areas of the world is an old problem. In addition, these areas also have a limited supply of conventional energy, although some have a great potential in solar energy. Nowadays, various methods of desalination have been developed including reverse osmosis (RO), multi-stage flash (MSF), multi-effect distillation (MEF) and electro dialysis. These desalination units require fossil/electric energy sources. A small-scale, cost-effective conventional solution such as reverse osmosis (RO) or electro dialysis (ED) is not presently available to meet this need. This necessitates designing desalination processes that use renewable energy such as solar energy in the least capital-intensive manner.

Desalination from oceans is the attractive solution for this fresh water shortage problem. Solar distillation is a process where solar energy is used to distill fresh water from saline/ brackish water. There are several methods of using solar energy to distill water from a salt solution. One of the simplest is used in the conventional solar stills for desalination of brackish water. In this method, the sun's rays passes though the glass roof (condensing surface) and are absorbed by blackened bottom of the basin. As the water is heated, its vapor pressure is increased. The produced vapor goes up due to difference temperature between water and condensation surface. The resultant vapor is condensed on the condensation surface and runs down into the reservoir.

Desalination is generally classified into passive and active distillation systems. The work on passive solar distillation has been reviewed by Malik *et al.* [2]. Later on further review was carried out by Tiwari [3], which also includes the work on active solar distillation.

Since the early 1960s, numerous solar stills single/ double or multiple passive / active have been built and investigated by engineers and scientists. Their yields were in the range of 2-4 lit/m^2-day according to the type of still and the location/season in which it was operated [4]. Solar stills are very simple to construct and to operate but their efficiency and productivity are fairly low. To increase the yield from stills different methods were adopted by various researchers such as:

Reducing bottom loss coefficient, reducing water depth in basin/multi-wick solar still, using reflector, using internal and external condensers, using back wall with cotton cloth, use of dye ,use of charcoal, use of energy storage element , use of sponge cubes, multi-wick solar still, condensing cover cooling, inclined solar still and increasing evaporative area [1].

In conventional solar still, the latent heat of vaporization is transferred to ambient. By reusing latent

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heat of vaporization the yield will be increased. This can be achieved either by flowing water over the condensing cover or by placing another basin of water over the condensing cover of the first basin, as done in the case of the double-basin solar still. However, in a double-basin solar still, the incoming solar flux available at the blackened surface is reduced in comparison to a single-basin solar still.

In conventional solar still, the same surface (transparent cover) is used for input as well as output of energy. On the other hand by passing the sun's rays though the glass roof, its temperature increased. This subject has a negative effect on evaporation coefficient. This problem has overcome by using another surface for energy input, so the transparent cover acts only as a condensation surface. Due to separation of condensing cover (cold surface) and receiving of solar energy surface, the temperature difference between condensing cover and water surface is increased for higher yield.

Three models have been suggested to separate the input and output surfaces as shown in

Both of inverted absorber and multi effect solar still, reuse the latent heat of vaporization, so the daily output in these methods are higher than external condenser method.

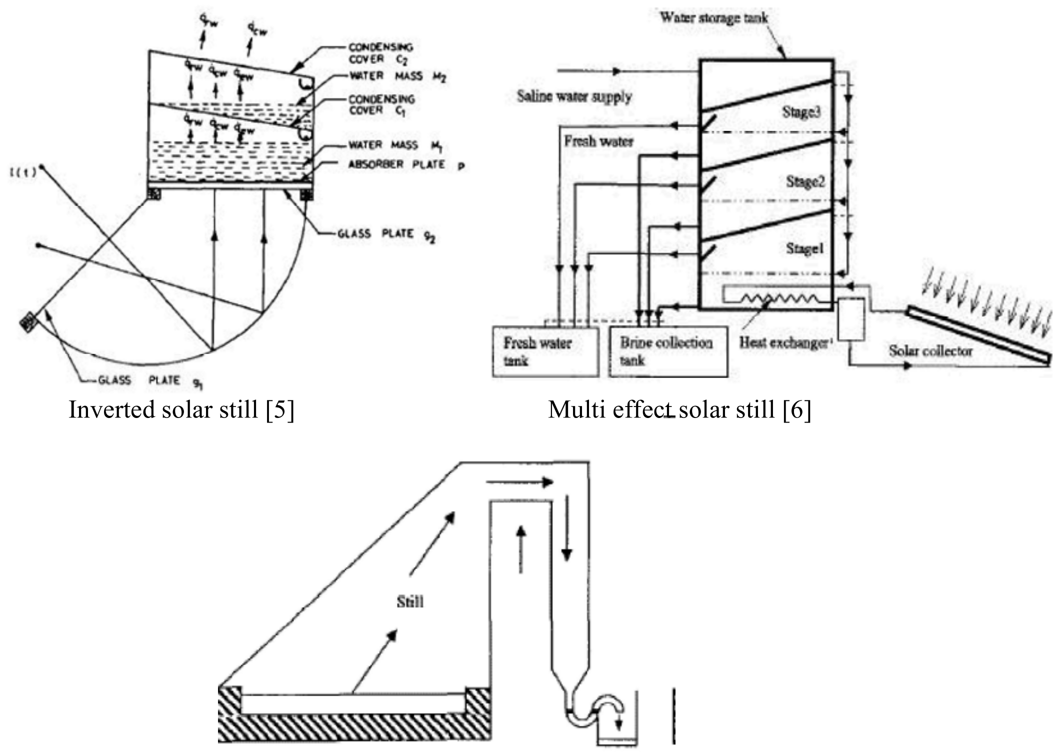
The work on multi effect solar still has been done by various researchers. Fernandez and Chargoy [8] built a solar still based on the principal of a stacked tray array for tandem distillation and heat recovery. A simple mathematical model was evolved and calibrated with field data to make it fit adequately experimental results gathered along 14 months of continues. In the experimental set-up used by them, the water in the lowest basin was preheated by the use of a flat plate liquid collector. They studied the performance of the solar still up to seven stages and observed that the yield increases with the number of stages. No optimization of the number of stages was reported.

Adhikari [9] prepared a computer simulation model for studying the steady state performance of a multi-stage staked tray solar still. Effect of heat input and variation of daily distillate yield as a function of the number of stages for a typical set of parameters has been studied. The proposed model has been validated by the results of simulated experiments on a three-stage stacked tray solar still. The results showed that the daily distillate yield increases with a corresponding increase in the number of stages of the distillation system.

Schwarzer [10] studied the numerical simulation and the experimental laboratory water tests for a thermal desalination unit with a heat recovery system. The system components were a solar collector and a desalination tower, although the system could be operated with other energy sources. Because of the heat recovery process, the proposed unit can reach a higher thermal performance than the conventional still-type solar distiller. The numerical results calculated using ambient data show that the production rate can reach 25 L/m^2.d which is by a factor of five times greater than the rate of a basin-type solar desalination unit. The proposed solar still had two basic system components; a flat plate collector and a desalination tower. A copper piping system connects these two components. As solar radiation hits the collector, the working fluid (an oil) is heated up and moves, by natural convection, to the highest point of the system where a heat exchanger is located.

Yousif and Ismail [6] worked on a new multistage evacuated solar desalination system. The new concept uses a vacuum to enhance the evaporation and to reduce the amount of the non condensable gases inside the solar still. The multi-stage evacuated solar still consists of three stages, which were perfectly insulated from the outside environment. The three stages were mounted on top of each other and perfect sealing is maintained between the stages to prevent any vapor loss through the contact surfaces between the stages. Heat is supplied to the system from the solar collector through the lower stage by means of a heat exchanger. A solar operated vacuum pump is used to evacuate the three stages from the non condensable gases. A model for the system was developed and used to optimize the system design. The new model was subjected to a Finite Element Analysis (FEA) structural analysis using MSC/NASTRAN™ FEA software. A Computational Fluid Dynamics (CFD) simulation of the evaporation and condensation process inside one stage of the new solar still was conducted using FLUENT™ software. The system prototype was fabricated and tested at the actual outdoor ambient conditions for a period of 3 months. Comparing the productivity of the solar still at the atmospheric pressure working conditions and the productivity at different vacuum pressure conditions showed that the productivity at the latter increased by about 20% when the pressure reduced to 0.7 bar and increased by about 45% when the pressure reduced to 0.5 bar

Tiwari [11] presented a report on the annual as well as seasonal performance analysis for six different water depths in a single slope passive solar still. The lower depth has found giving the highest annual yield. Increasing the water depth decreases the yield of the still up to depths of about 0.1 m but at greater depths than this the yield becomes almost constant.



Inverted solar still [5]

Multi effect solar still [6]

Conventional solar still with external condenser [7]

Fig. 1:

The effect of various parameters like solar fraction and hourly values of solar azimuth and altitude angles, air velocities, basin absorptivity have been studied and compared for the different water depths in still.

In this paper, both of technique; increasing difference (separating of input and output energy) and heat recovery (reuse of latent heat of vaporization) is used to increase the efficiency. In addition an experimental investigation on a double effect desalination system is reported and effect of some parameters such as water depth, power input and salinity on the productivity of the system is discussed.

Experimental Setup and Procedure: In solar stills, the glass cover serves both as condenser surface and solar radiation transmitter. One way to achieve a high performance desalination system is to accomplish these tasks in different places. In the present work, this has been achieved by designing a new system. The system comprises from two parts as is shown schematically in Fig. 2. The heating section which resembles a solar collector is comprised of an electric heater that heats up the heat transfer fluid at a desired rate. The heat input is then naturally convected to the desalination part which is a multi-effect evaporation-condensation unit. Heat is transferred from the hot fluid to saline water and makes it evaporate. Water vapor is then condensed on the lower surface of the next effect where heat of condensation of water acts as heat input to the next effect. Processes in the successive effects are similar to the first effect. The system is perfectly insulated except on the condenser surface of the upper effect which is exposed to surrounding air. The condensed water in each effect is collected and discharged as fresh water separately. The condenser surfaces are sloped at 3°. The still has a basin area of $80 \times 40 cm^2$ and is made of galvanized iron.

The system is constructed in such a way that it can be used as a single or multi-effect desalination plant. The heater power may be adjusted at any desired level. To be realistic in the experiments, the heat input to the heater followed the trend of sunshine intensity on a typical sunny day for which the radiation data was taken from [12] and is shown in Fig. 3. The average hourly radiation for this day is 186 W/m^2.

The system is equipped with several thermocouples for measuring temperature of heating fluid, water and different surfaces. Also few inlet/outlet taps are provided for adding or removing water in order to adjust or maintain a desired water level in each effect. Production of each effect is collected and measured separately.

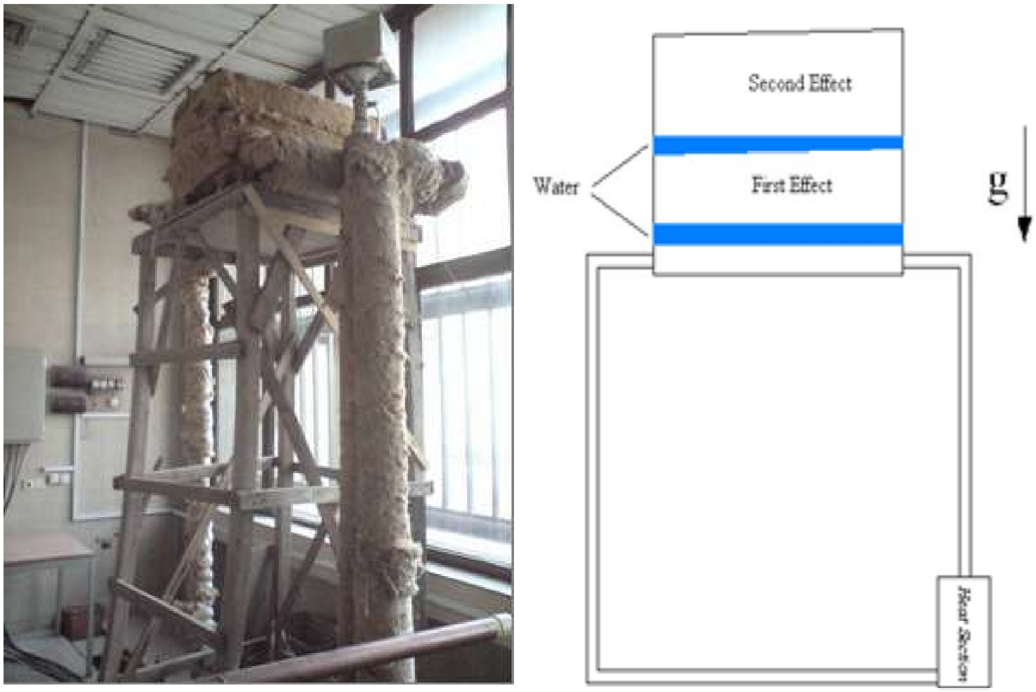


Fig. 2: Schematic of the system

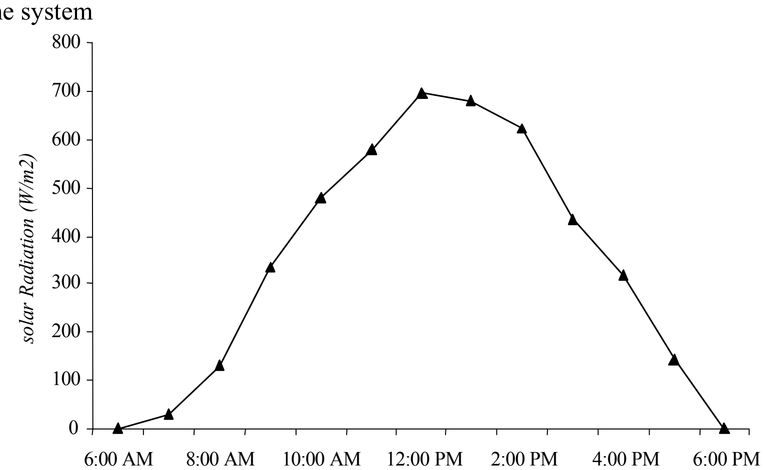


Fig. 3: typical hourly solar intensity [5]

Solar Still Efficiency Is Usually Defined As:

$$\eta = \frac{m \times h_{fg}}{I} \quad (1)$$

Where m and I are mass of water produced and total input energy to the system.

RESULTS AND DISCUSSION

The Single Effect System: The single effect solar still is formed by assembling the heating unit and one evaporator-condenser unit. Fig. 4 shows variation in the temperature of water in the basin and temperature of the condenser surface. Fig. 5 shows distilled water production rate as a function of time. Though heat input to the system has been seized since around 6 PM, production continues to around 12 PM. For these experiments, water depth in the basin was adjusted at 1 cm and ambient temperature was 15°C.

Tripathi et.al. used a conventional solar still and produced 2.5 lit/m^2-day fresh water under the same solar radiation condition [12]. The total yield for the present system was 4.86 liter, i.e. 94% increase with respect to a conventional solar still. The efficiency of the present single effect system was calculated at 67%.

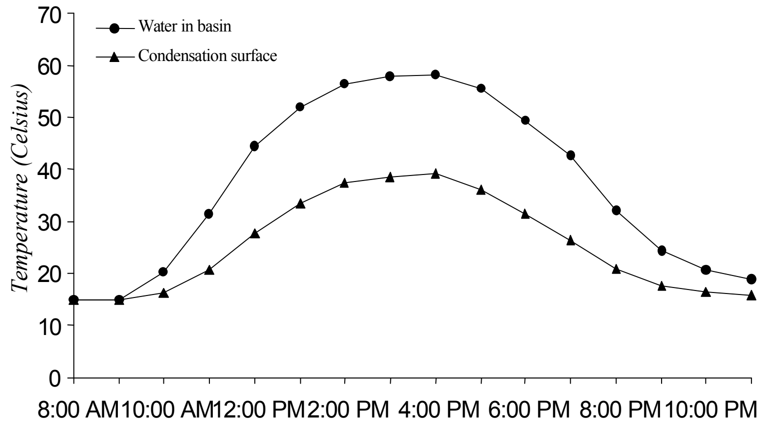


Fig. 4: Hourly variation of Temperature

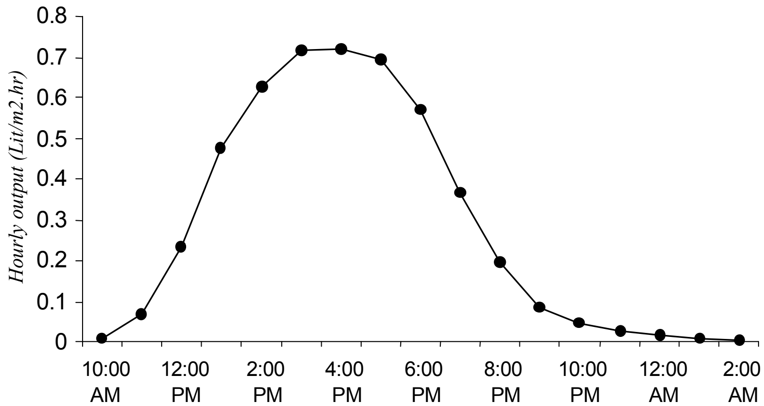


Fig. 5: Hourly water production rates

Table 1: Effect of constant input intensity on daily output

Power input(W/m2)	Basin water Temperature °C	Condenser Surface Temperature °C	Daily output(kg/m2.day)	Efficiency(%)
200	38.2	21.6	4.25	59
500	54.6	30.1	14.3	76.68
800	65.4	42.5	24.56	81.2

Table 2: Effect of water depth on production rate for a typical daily radiation

Water depth(cm)	Basin water Temperature °C	Condensation Surface Temperature °C	Daily output(kg/m2.day)	Efficiency(%)
1	38.2	21.6	4.25	59
2	38.2	21.6	3.96	55
3	38.2	21.6	3.63	50.4

The Influence of Input Energy: To investigate the effect of solar radiation intensity on the production rate, another set of experiments was arranged in which heat inputs to the system were set at three predetermined constant levels, i.e. 200, 500 and 800 W/m^2. Water depth was kept at the previous level of 1 cm.

Table 1 summarises the results. As is expected, the production rate is a strong function of input thermal energy. Increasing the power input from 200 to 500 W/m^2 (that is 150% increase) results in % 236 increases in the production rate (from 4.25 kg/m^2-day to 14.3 kg/m^2-day). However the rate of increase in production rate decreases at higher power input rates.

The Influence of Water Depth: As the water depth increases, so does the mass of water in the basin which means that more energy is needed to heat it up. In other words, the average daily water temperature would be lower for a typical daily solar radiation, hence lower evaporation and production rate. Table 2 shows the experimental results for this case.

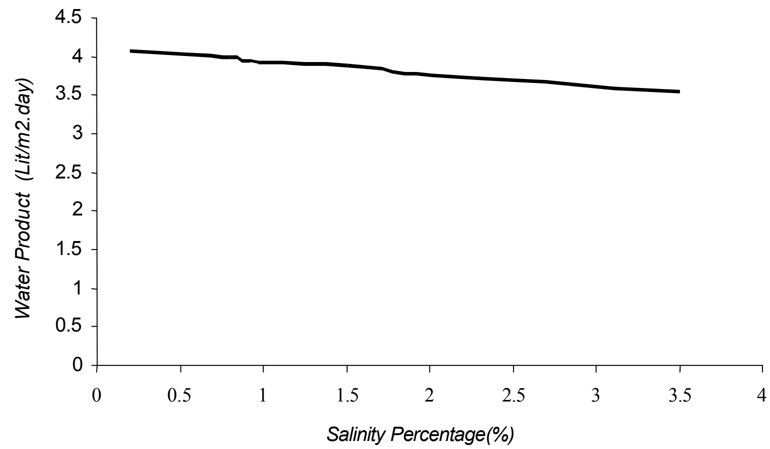


Fig. 6: Effect of salinity on daily output

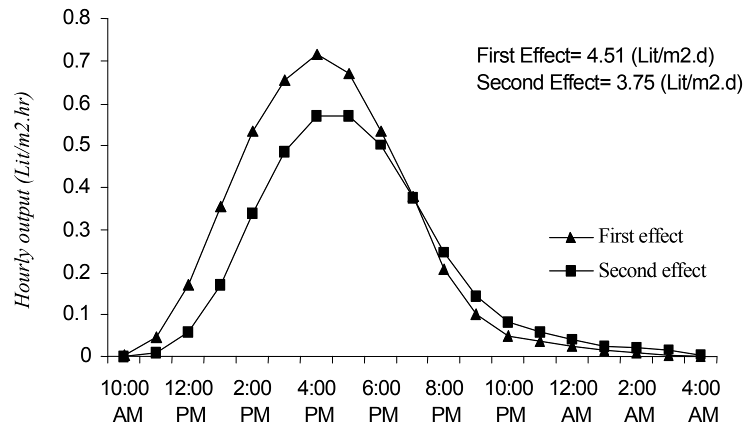


Fig. 7: Variation of hourly output in first and second effect

The Influence of Salt Concentration: To investigate the influence of salt concentration on the rate of production, a series of experiments was performed in which salt concentration in the supply water was varied by adding some salt to the water in the basin. Fig. 6 illustrates the variation of daily production as a function of salinity. As is seen, the daily production decreases as the salt concentration increases. Increase in the water salinity from 0% to 3.5% results in 20% decrease in the daily production. In these experiments the environment temperature and water depth in the basin were 15°C and 1 cm respectively. The power input was kept constant at 200 W/m^2 during the experiments.

According to Raoult's law, the vapour pressure, p, for a saline mixture is [13]:

$$P = x_{w,l}P_w^* + x_{s,l}P_s^* \quad (2)$$

Where P_w^* and P_c^* are vapor pressures of pure water and pure salt respectively and $x_{s,l}$ denotes the mole fraction of dissolved salt in the water. Therefore as the salt concentration increases the vapor pressure decreases. On the other hand, it is known that the boiling temperature of water will increase as some salt or other non-volatile material is dissolved in it. The enthalpy of evaporation ΔH_o is related to vapor pressure by Clausius-Clapeyron equation as [13]:

$$\Delta H_{vap} = -R\Delta Z_V \frac{d\ln p^{sat}}{d\left(\frac{1}{T}\right)} \quad (3)$$

Therefore as salinity increases, enthalpy of vaporization increases which results in lower evaporation and lower production rate.

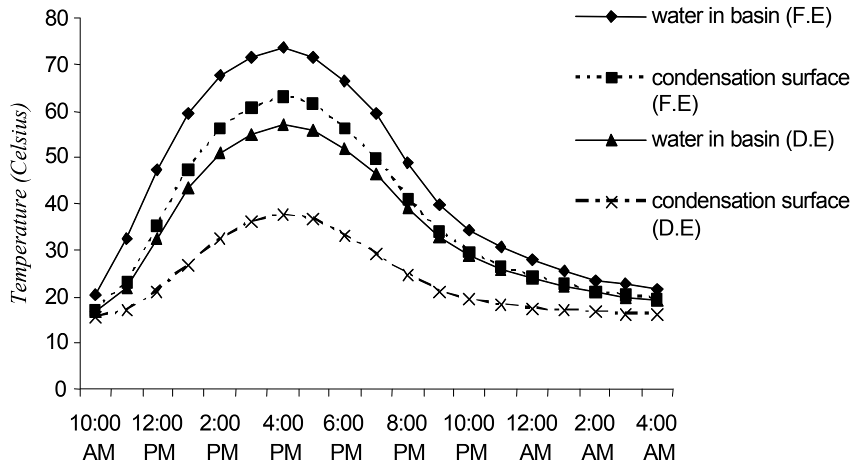


Fig. 8: Variation of temperature in first effect (F.E.) and second effect (S.E.)

Table 3: Variation of temperature and daily output versus power input

Power input (W/m2)	Basin water Temperature (first effect) °C	Condenser Surface Temperature (first effect) °C	Basin water Temperature (second effect) °C	Condenser Surface Temperature (second effect) °C	Daily output (first effect) $\frac{kg}{m^2.day}$	Daily output (second effect) $\frac{kg}{m^2.day}$	Daily output (total) $\frac{kg}{m^2.day}$
200	46.9	37.5	33.3	21.5	3.9	2.95	6.85
500	67	56.3	49.5	28	12.9	10.5	23.4
800	80	70	59.2	40.3	23	16.9	39.9

Table 4: Variation of temperature and daily output versus increasing water depth

Power input (W/m2)	Basin water Temperature (first effect) °C	Condenser Surface Temperature (first effect) °C	Basin water Temperature (second effect) °C	Condenser Surface Temperature (second effect) °C	Daily output (first effect) $\frac{kg}{m^2.day}$	Daily output (second effect) $\frac{kg}{m^2.day}$	Daily output (total) $\frac{kg}{m^2.day}$
1	46.9	37.5	33.3	21.5	3.9	2.95	6.85
2	46.9	37.5	33.3	21.5	3.4	2.55	5.95
3	46.9	37.5	33.3	21.5	2.95	2.2	5.15

Double Effect System: The single effect system is converted to a double effect one by installing a condenser to it. To study the effect of the second effect on the production rate, the power input to the system was adjusted to a typical hourly radiation variation shown in Fig. 3, as was done for the single effect system. The water depth was 1 cm in each effect and the ambient temperature was around 15°C. The system production rose from 4.86 to 8.26 liter (i.e. increased by 70%). Production rates of each effect are shown in Fig. 7 as a function of time. At the beginning, the hourly output of the first effect was more than the second one; however it reversed as time passed. This behavior can be justified regarding the fact that the first effect warms up faster than the second effect at the beginning and cools faster at the end of the day. Temperatures of water in the basins and condenser surfaces are plotted in Fig. 8.

The Influence of Input Power: To study the effect of power input on the production rate, a set of experiments was performed and the results are summarized in table 3. The water depth was 1 cm in each effect.

As is seen, increase in power input from 200 to 500 W/m^2 results in increase in daily total production rate from 6.85 to 23.4 kg/m^2.day. However the rate of increase in production rate declines at higher power input. The other point to notice is that the production rate in the second effect is always less than that of the first effect.

The Influence of Water Depth: Increasing the depth of water in the first effect while keeping it constant in the second effect will decrease the production intensely. In the present work the depth of water in the first effect was changed from 1 to 3 cm while water depth in second effect was kept constant at 1 cm. Table 4 shows the variation of production with respect to the water depth at a power rate of 200 W/m^2.

As mentioned in the previous section, increase in depth of water will increase the sensible energy of water at a specific temperature. Therefore the temperature of the water will increase to a less extend in a known period of time or known amount of thermal energy. In other words the water temperature increases at a lower rate which ends up with lower production. The increase in depth of water in the first effect of a double effect still will reduce the water production.

It is worth noting that the rate of decrease in output for double effect still is higher than the single on. In the case of double effect still in addition to the decrease in water temperature of the first effect, the difference between the temperature of water and condenser surface decreases too. As mentioned before the amount of water evaporation depends on the water temperature and the difference between the temperatures of water and condenser surface. The decrease in production rate remains constant at %13 while m_1/m_2 increases.

Table 4

CONCLUSION

By increasing water depth in the first basin by a factor of 2, the productivity reduces (7) %, (13) %, for single and double effect, respectively. Increase in the salinity from 0.5% to 3.5%, leads to (20) % reduction in the yield. Using double effect desalination system would increase the yield by (70) % for the same water depth and solar radiation.

Nomenclature:

m water mass, kg
h_{fg} Vaporization Enthalpy, kJ/kg
I Total Input Energy, kJ
x_s Mole Fraction of Dissolved Salt in the Water
x_w Mole Fraction of Water
T Temperature, K
P Pressure, kpa

Subscripts:

w Water
s Salt
sat Saturation

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