THERMO-ECONOMIC PERFORMANCE OF INCLINED SOLAR WATER DISTILLATION SYSTEMS

by

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This study investigates the thermo-economic performance of different configurations at inclined solar water desalination for parameters such as daily production, efficiency, system cost, and distilled water production cost. The four different configurations considered for this study are;
1. Inclined solar water distillation with bare absorber plate (IISWD) with daily production of 5.46 kg/m² per day and daily efficiency of 48.3%.
2. Inclined solar water distillation with wick on absorber plate (IISWDW) with daily production of 6.41kg/m² per day and daily efficiency 50.3%.
3. Inclined solar water distillation with wire mesh on absorber plate (IISWDWM) with daily production of 3.03 kg/m² per day and daily efficiency 32.6%.
4. Inclined solar water distillation with bare absorber plate ISWD Control System, and with daily production of 3.25 kg/m² per day and daily efficiency of 40.1%.
The systems potable water cost price ranges from 0.03 $/L for IISWDW to 0.06$/L for IISWDWM system. All the systems are economically and technically feasible as a solar distillation system for potable water in Northern Cyprus. The price of potable water from water vendors/hawkers ranges from 0.11-0.16 $/L. It is more economically viable to have the rooftop inclined solar water desalination system than procuring potable water from vendors.

Key words: *solar desalination, potable, water, incline solar water desalination, solar radiation, production cost*

Introduction

In most parts of the world, the demand for water outweighs its supply, a situation calling for innovative technologies for new water sources. Cyprus is located on the Mediterranean basin, with very limited potable water sources. The country is surrounded by the Mediterranean Sea, and the seawater source is not readily consumable. The northern part of Cyprus is under economic embargo, a situation that exponentially worsens the fresh water availability on the part of the island. The price of potable water from water vendors/hawkers in 19 litres plastic kegs ranges from 0.11-0.16 $/L. Desalination of seawater is a proven technology and a practical way of producing fresh water where freshwater sources are either not available or limited. Desalination of brackish or seawater presents an alternative way of getting a new water source. One

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main drawback to this solution however is high-energy consumption and high cost of the plants. The huge energy requirement of desalination systems is the driver of renewable energy integration into desalination. The availability of renewable energies in most water scarce areas has allowed the consideration of renewable energy in desalination. The current events in desalination technology are to couple desalination systems with renewable energy technologies. The use of renewable energy in desalination will guarantee fresh water production in a sustainable and environmentally friendly manner. At present the use of wind and solar energy in desalination is gaining more attention. The use of renewable energy in desalination is common with the popular solar still system. A solar still is a simple device that can be used to convert seawater and/or brackish water into potable water. In order to improve the productivity of the solar desalination system a number of authors have tested the system under difference climates with different design configurations [1-13]. Today, other solar desalination systems have emerged with better efficiency and daily production capacity. One of such is the inclined solar water distillation (ISWD) system. Unlike a conventional solar still, the feed in water in the ISWD system flows down on the absorber plate that is inclined at an angle. Since it was first designed in 2006 by Aybar *et al*. [14] and Aybar [15], a couple of designs have emerged [16] varying some specific parameters in the first design to enhance the performance of the system.

Experimental set-up and instrumentation

The schematic diagrams of the four configurations of ISWD systems are as seen in figs. 1-4. The systems were tested under the climatic weather condition in city of Famagusta, at northern Cyprus. The experiments were performed between 8:00 to 16:00 hours daily. The ISWD system consists of an absorber plate and a glass cover that creates a cavity, the cavity is made of stainless steel. The cavity dimension is 1 m^2 area with height of 0.2 m. Galvanized steel of 0.2 cm is used as the absorber plate which was painted matte black to increase the surface absorptivity (absorptivity of 0.96 and emissivity of 0.08, as given by the supplier), the cavity was constructed from stainless sheet due to better resistance to corrosion and the inner surface of the cavity was painted matte black. The outer surface was insulated at the sides and at the bottom insulated with specialized foam of 15 mm thickness. The need for the insulation is to prevent heat losses from the stainless sheet material. The system is covered with a 3 mm glass, transmissivity of 0.88 (measured using the pyranometer). The system was inclined at angle 36° (the angle 36° is the ±1 of latitude of the test area) to optimally utilize the 1 m^2 surface (solar radiation inci-

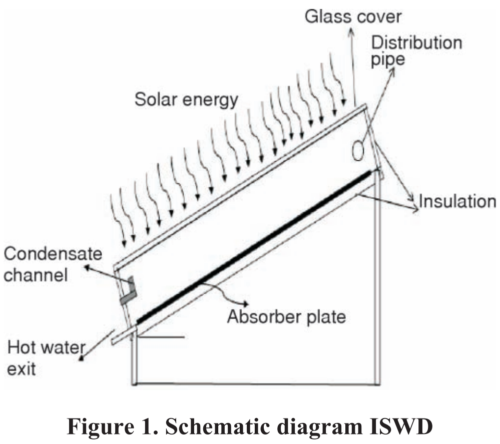

Figure 1. Schematic diagram ISWD

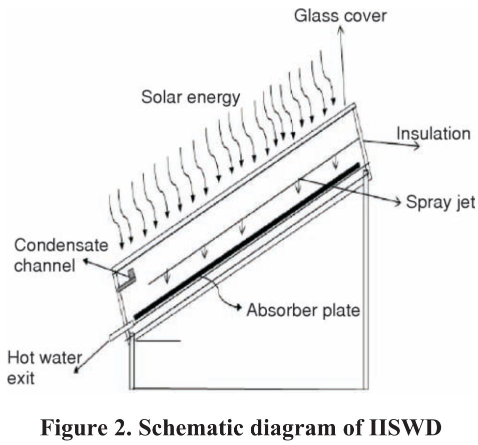

Figure 2. Schematic diagram of IISWD

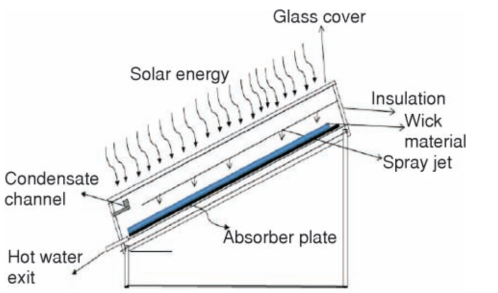

Figure 3. Schematic diagram of IISWDW

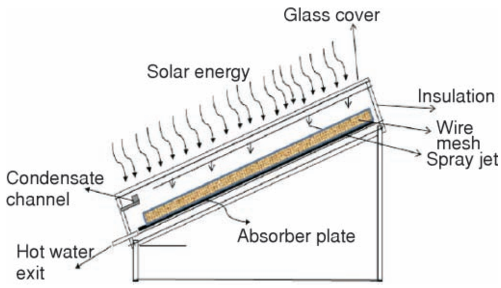

Figure 4. Schematic diagram of IISWDWM

dence) of the plate and to allow water flow through the whole length and width of the surface [14]. The feed water for the ISWD is through a longitudinal pipe with multiple holes.

The IISWD, IISWDWM, and IISWDW systems feed water through the jet (nozzles) on the absorber plate intermittently, also the thickness of the absorber plate (galvanised steel) in these systems was 0.4 cm. The jets spray allows evenly distribution of the feed water throughout the surface of the absorber plate unlike the longitudinal pipe in which the feed water follows the holes path. Figure 5(a) and (b) give a pictorial view of the IISWD and ISWD. In figure 5(a), the spray jets (for evenly distribution of inlet water on the absorber plate) were used to feed in the inlet water while in fig. 5(b) the longitudinal pipe with multiple holes (the inlet water was not evenly distributed was used to feed in the inlet water. The ISWD was used as a control system. It was tested concurrently with the new improved systems.

Figure 5. Pictorial view of the experimental set-up; (a) IISWD, (b) ISWD

The K-type thermocouple was used for taking temperature from the systems. The K-type thermocouples were fixed at different location within the system for the temperature data. The temperature data were retrieved by a ten-channel digital thermometer (MDSSi8 series digital, Omega) with ±0.5 °C accuracy. A calibration test was carried out on thermocouple, the result agrees with the stated accuracy from the manufacturer (±0.25). The solar radiation were measure with Eppley radiometer pyranometer coupled with solar radiation meter model HHM1A digital, Omega 0.25% basic DC accuracy and a resolution of +0.5 from 0 to 2800 W/m^2.

The instantaneous efficiency (η_i) of ISWD is defined as the ratio of the energy used for water production to the total solar radiation rate given by:

$$\eta_i = \frac{Q_{ev}}{HA_b} \tag{1}$$

$$Q_{ev} = M_{ev}L \tag{2}$$

where Q_{ev} [W] is the evaporative heat transfer, M_{ev} [(kgm^{-2}h^{-1}] – the distilled water production rate, A_b [m^2] – the still base area, L – the latent heat of vaporization, and H [Wm^{-2}] – the total solar radiation falling upon the absorber plate surface. Daily efficiency (η_d) is obtained by summing up the hourly condensate production multiplied by the latent heat of vaporization, and divided by the daily average solar radiation over the solar cavity area and calculated from the following equation:

$$\eta_d = \frac{\int_0^t m_{ev} L \mathrm{d}t}{3600 A \int_0^t H \mathrm{d}t} \tag{3}$$

where t is the time and A is the area [m^2].

Discussion of experimental result

On a clear day solar radiation measurement should follow the curve as shown in fig. 6.1-6.3. At an incline angle of 36° the maximum solar radiation is collected over the 1 m^2 surface of the systems. The solar radiation pattern in each case of the experiments agrees with the theory. The experiment reveals that solar radiation is high in Cyprus especially during the summer season. Although there is no experimental correlation between solar radiation and ambient temperature, it was observed that the ambient temperature increase with increase in the solar radiation. The maximum solar radiation recorded during the experiment is almost 1000 W/m^2 while the maximum temperature recorded was around 38 °C (see fig. 6.4-6.6). The solar radiation and ambient temperature factors are necessary for a high yield of distilled water. As

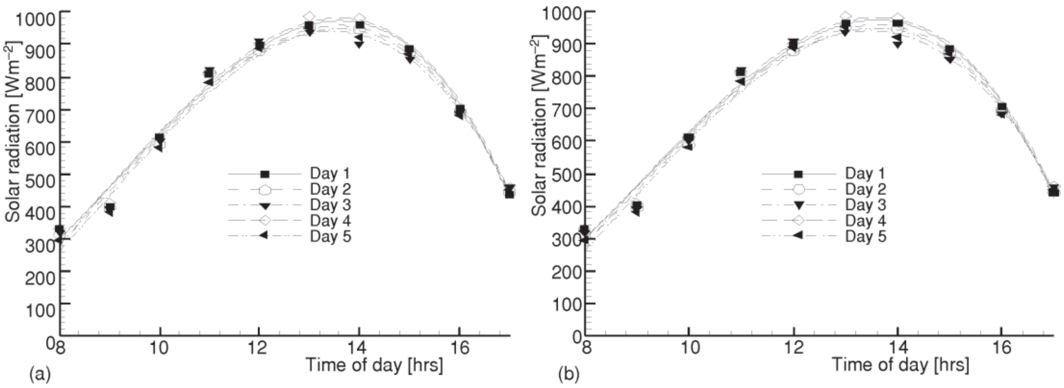

Figure 6.1. Hourly variation of solar intensity *vs*. local time in summer season for (a) IISWDW with two spray jets and (b) ISWD control system

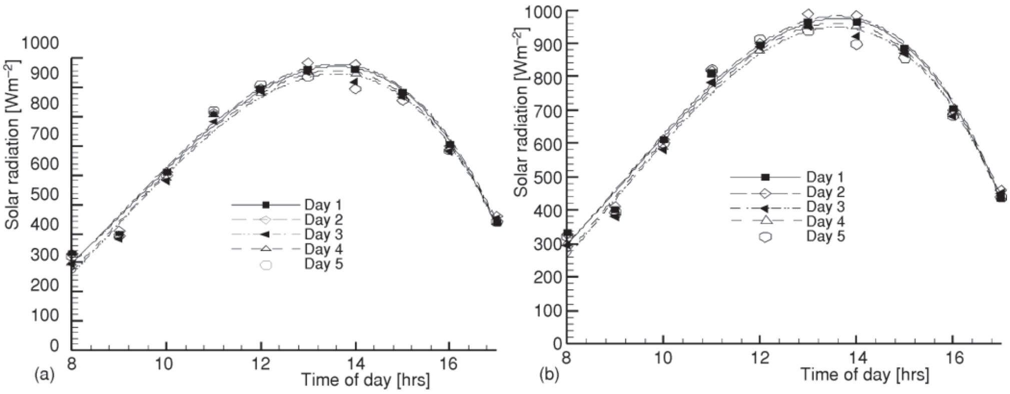

Figure 6.2. Hourly variation of solar intensity *vs.* local time in summer season for (a) IISWDWM and (b) ISWD control system

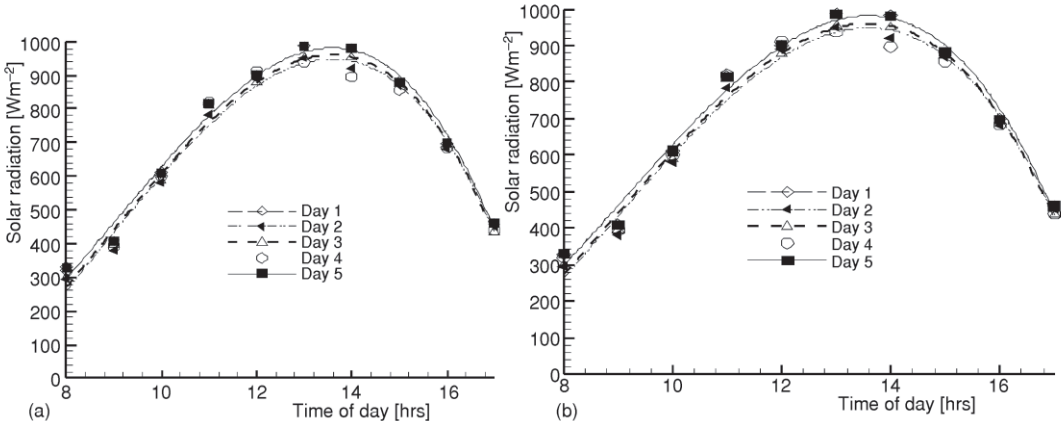

Figure 6.3. Hourly variation of solar intensity *vs.* local time in summer season for (a) IISWD and (b) ISWD

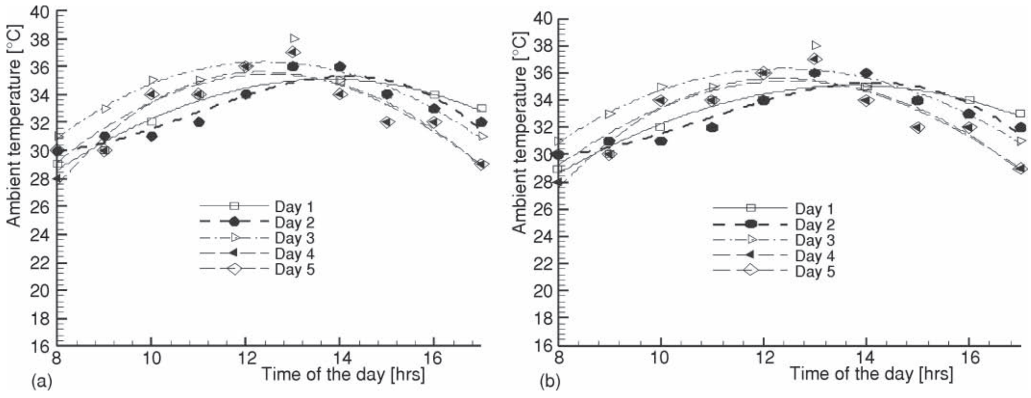

Figure 6.4. Ambient temperature *vs.* local time of the days for (a) IISWDW with two spray jets and (b) ISWD

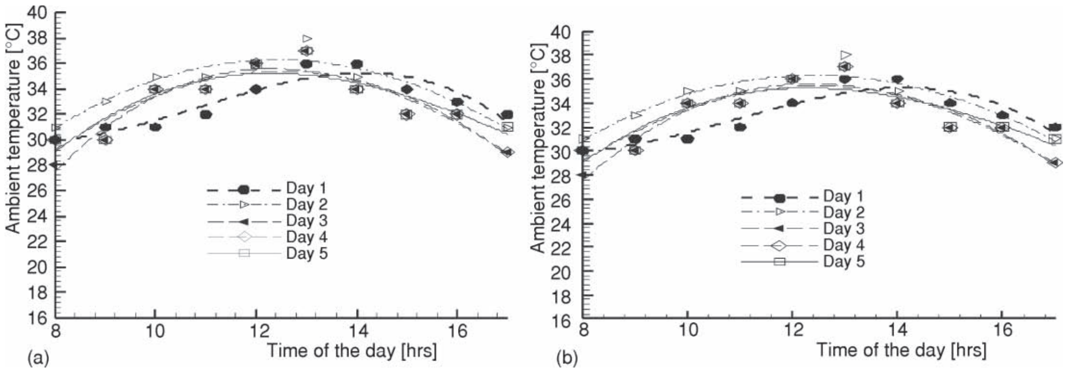

Figure 6.5. Ambient temperature *vs.* local time of the days for (a) IISWDWM and (b) ISWD

mention earlier, each IISWD set-ups are ran currently with the ISWD as a control system. For the solar radiation and ambient temperature as shown in fig. 6.1-6.6, one can see that the solar radiation and ambient temperature data were almost the same. Exposing the two systems to the same weather condition was to test the effect of designs.

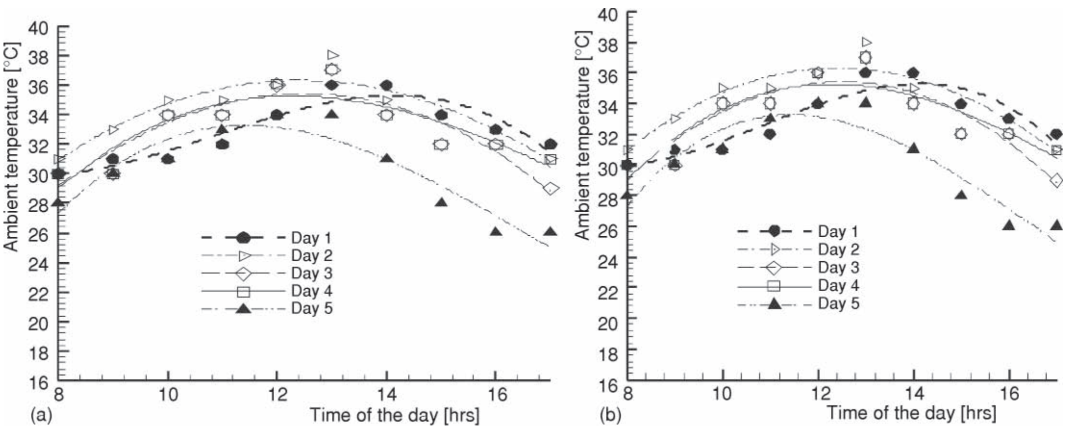

Figure 6.6. Ambient temperatures *vs.* local time of the days for (a) IISWD and (b) ISWD

In fig. 6.7(a) and (b), the temperature distribution of IISWDW and ISWD was shown. In fig. 6.7(a) the early hours of the experiment shows a close temperature result for the cavity air temperature and the cover glass temperature. This can explain the low productivity of the system in the early hours of the day. The close temperature measurement of the cavity air and the cover glass shows that the absorber plate (due to thickness) takes longer time to absorb the heat energy from the Sun and to release the same to the feed water. In addition, the low temperature of the early hours feed water is also a factor. The afternoon hours shows a wide temperature difference between the cavity air temperature and the cover glass, a situation that explains the distilled water production greatly. Comparing the temperature variation of the absorber plate, air in the cavity, and that of the glass cover in the two systems as seen in fig. 6.7(a) and (b), IISWDW have higher temperature variation of those influencing parameter as compared to ISWD.

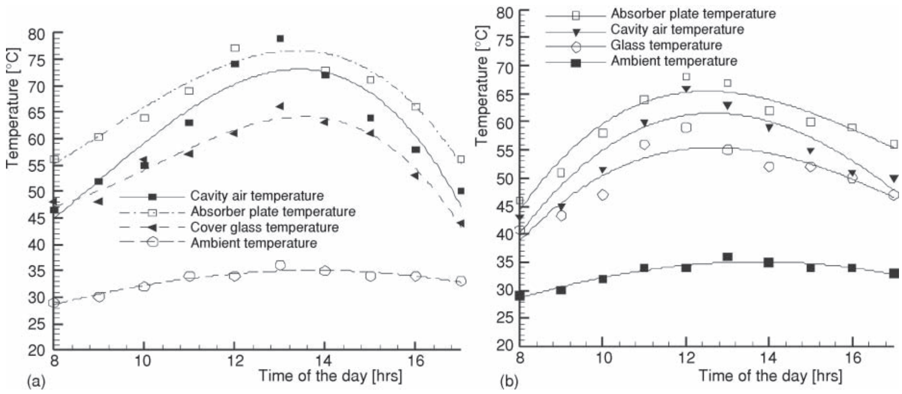

Figure 6.7. A typical variation in temperature of (a) IISWDW and (b) ISWD

Figure 6.8 show similar temperature with fig. 6.7. In fig. 6.9 one will observed that the temperature profiles were very wide apart. The wire mesh on the absorber plate absorbs solar radiation easily and easily gives the heat out without transferring it to the flowing water. The in-

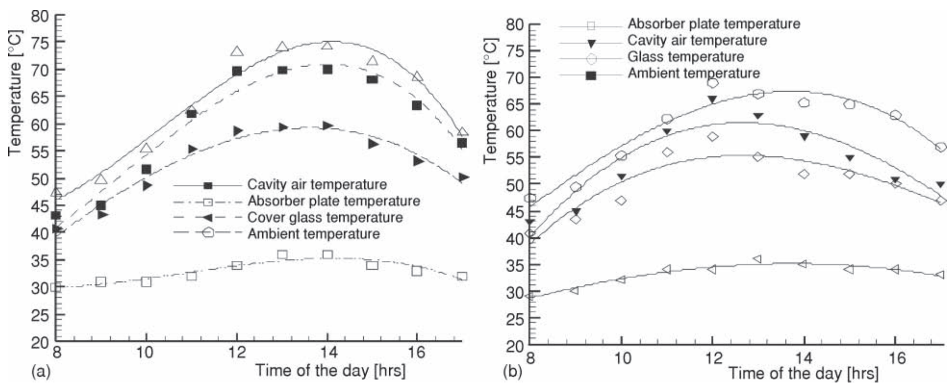

Figure 6.8. A typical variation in temperature of (a) IISWD and (b) ISWD

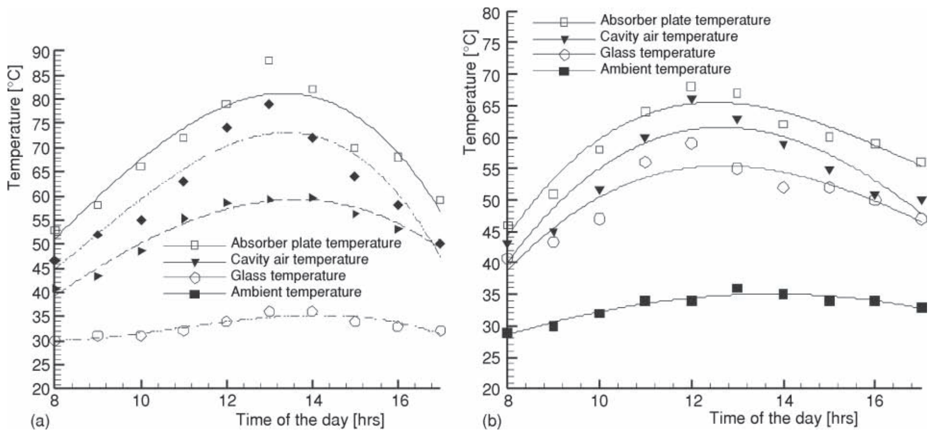

Figure 6.9. A typical variation in temperature of (a) IISWDWM and (b) ISWD

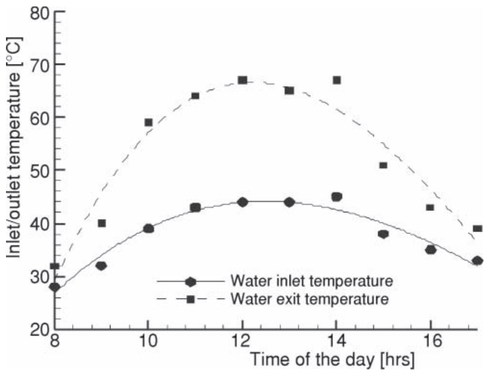

Figure 6.10. Inlet and outlet temperature for the IISWDW

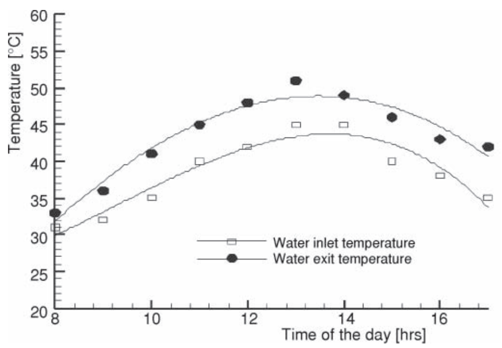

Figure 6.11. Water inlet temperature and water exit temperature for the IISWD

clusion of the wire mesh on the absorber plate in this experiment was to improve the distill water production but rather it decrease the production. The wire mesh increase the temperature of the absorber plate, the air cavity and the cover glass but the reason for low condensation was not known. One thing noticed with the wire mesh inclusion was that the water does not have much contact with the wire mesh. The mesh trapped heat but the heat was not released to the flowing water for evaporation. The exit water in IISWD, IISWDW, and IISWDWM is returned in to the feed water tank to increase the temperature of the inlet water. As seen in fig. 6.10 the exit water in IISWDW got to almost 70 °C at noon. The hot exit water was collected at interval and return to the feed water. The hot water re-injected into the feed water contributed to the high daily production of IISWDW system, figs. 6.11 and 6.12.

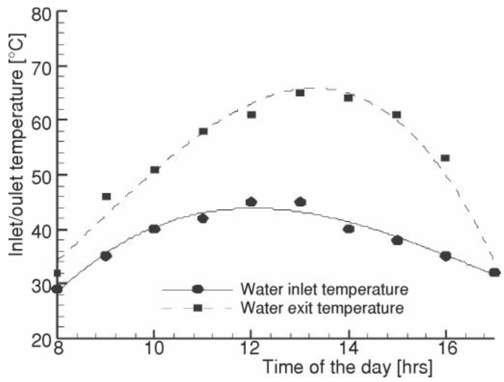

Figure 6.12. Water inlet temperature and water exit temperature for the IISWDWM

The daily productions of the systems with variation in spray jets were shown in figs. 6.13-6.16. In fig. 6.13, the IISWDW with two spray jets, four spray, and six sprays jets produced the 6.41 kg/m^2 per day, 4.55kg/m^2 per day, and 3.33 kg/m^2 per day, respectively. The IISWDW with two spray jets performed the best. In fig. 6.14 IISWDWM with two, four, and six productions are 3.03 kg/m^2 per day, 2.07 kg/m^2 per day, and 1.80 kg/m^2 per day, respectively. Figure 6.15 gives the daily production of IISWD with two, four, and six spray jets as 5.46 kg/m^{2}per day, 4.36 kg/m^2 per day, and 3.35 kg/m^2 per day, respectively. The control system

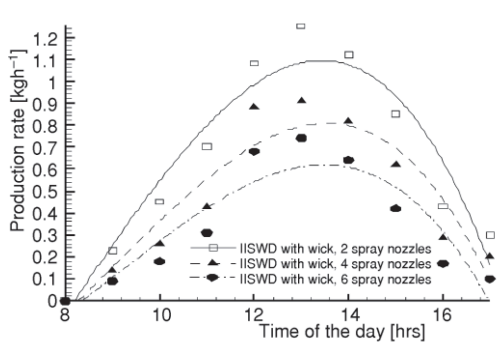

Figure 6.13. Effects of number of spray nozzles on production rate of IISWDW

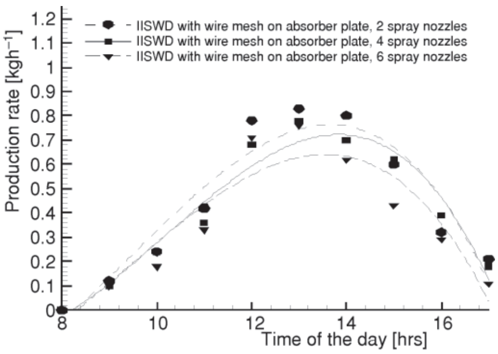

Figure 6.14. Effects of number of spray nozzles on production rate of IISWDWM

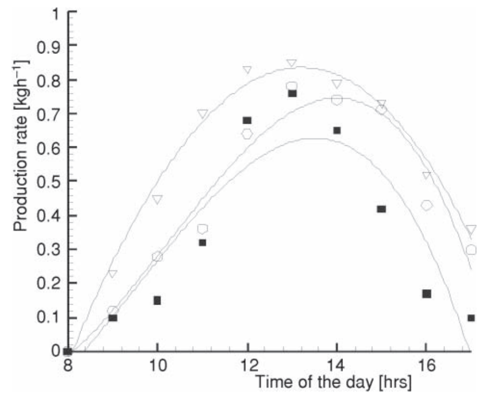

Figure 6.15. Effects of number of spray nozzles on production rate of IISWD

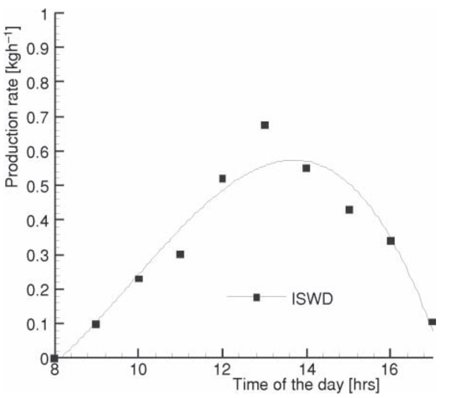

Figure 6.16. Daily production rate for ISWD

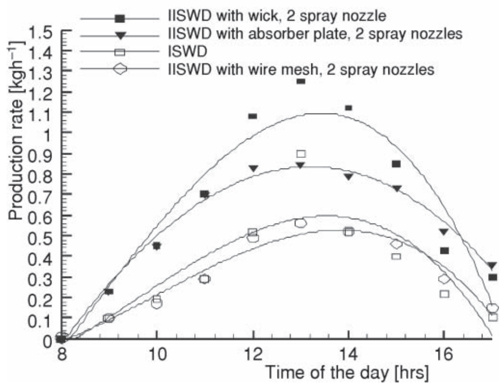

Figure 6.17. Daily production of all the systems

ISWD gives 3.25 kg/m^2 per day as the maximum daily production. Figure 6.17 compares all the systems together, and shows that the IISWDW performed better than the ISWD system. Table 1(a) gives summary of the daily production of the systems while tab. 1(b) summarizes the daily production, daily efficiency, and cost price per liter of the optimum systems.

Table 2 shows the average daily production of the systems in comparison with other solar desalination systems. The ISWD systems in comparison with other solar desalination systems as is shown in tabs. 1(a) and (b), are placed among the best solar desalination systems. The system is a simple device and cheap to construct as can be seen in tab. 3.

Table 1(a). Summary of daily production of the systems

System type	Daily production [kgm^{-2}per day]
IISWDW with 2 spray jets	6.41
IISWDW with 4 spray jets	4.55
IISWDW with 6 spray jets	3.33
IISWDWM with 2 spray jets	3.03
IISWDWM with 4 spray jets	2.07
IISWDWM with 6 spray jets	1.80
IISWD with 2 spray jets	5.46
IISWD with 4 spray jets	4.36
IISWD with 6 spray jets	3.35
ISWD	3.25

Table 1(b). Summary of daily production, daily efficiency, and cost price per liter of optimum systems

System type	Daily production [kgm^{-2} per day]	Daily efficiency [%]	Cost price per liter [$/L]
IISWDW with 2 spray jets	6.41	50.3	0.028
IISWDWM with 2 spray jets	3.03	32.6	0.062
IISWD with 2 spray jets	5.46	48.3	0.033
ISWD	3.25	40.1	0.036

Table 2. Experimental result of some selected solar desalination systems

System name	Location	Average solar intensity [Wm^{-2}]	Productivity [kgm^{-2} per day]	Ref.
1. Single slope solar still	Jordan	710	3.560	[4]
2. Single slope solar still, asphalt covered basin	Jordan	525	4.120	[5]
3. Single slope solar still with potassium permanganate in water	Jordan	840	5.750	[10]
4. Solar still coupled to an outside condenser	Turkey	480	6.520	[21]
5. Double basin solar still	Bahrain	630	3.910	[7]
6. Triple basin solar still	Jordan	740	4.896	[22]
7. Forced condensation in the solar still	Bahrain	512	2.370	[23]
8. Vertical solar still oriented toward east	Algeria	520	6.630	[24]
9. Asymmetrical green-house type solar still with added dye	Jordan	584	7.000	[25]
10. Close air solar HD system	Jordan	500	3.530	[26]
11. Solar HD system with water heating collector	China	700	6.200	[27]
12. Solar HD system with heat recovery	China	652	9.100	[28]
13. Inclined solar water desalination system	North Cyprus	680	3.250	
14. Improved inclined solar water desalination system	North Cyprus	680	5.460	
15. Improved inclined solar water desalination system	North Cyprus	680	6.410	
16. Improved inclined solar water desalination system	North Cyprus	680	3.030	

Table 3. Cost breakdowns of different configurations of ISWD system (US$)

Components	IISWD	IISWDW	IISWDWM	ISWD
Absorber plate	79.00	79.00	79.00	52.63
Cover Glass	26.32	26.32	26.32	26.32
Rubber materials	5.26	5.26	5.26	5.26
Matte paint	5.26	5.26	5.26	5.26
Insulation	5.26	5.26	5.26	5.26
Pump	52.63	52.63	52.63	–
Wick	–	2.63	–	2.63
Wire mesh	–	–	7.90	–
Labor	26.32	26.32	26.32	26.32
System cavity	36.84	36.84	36.84	36.84
Nozzle jets	18.95	18.95	18.94	–
Total	255.84	258.47	263.73	160.52

Economics analysis

The cost of distilled water produced from an ISWD system is influenced by capital and running cost of the system. Costs are influenced by unit size, site location, feed water properties, and product water required quality [17]. The better economic return on the investment depends on the production cost of the distilled water and its applicability. Economic analysis of water desalination unit is given by Kabeel *et al.* [17], Fath *et al.* [18], Kumar and Tiwari [19], and Govind and Tiwari [20]. The capital recovery factor (CRF), the fixed annual cost (FAC), the sinking fund factor (SFF), the annual salvage value (ASV), average annual productivity (M), and annual cost (AC) are the main calculation parameters used in the cost analysis of the desalination unit. The annual maintenance operational cost (AMC) of the solar still is required for regular filling of brackish water, collecting the distilled water, cleaning of the glass cover, removal of salt deposited (scaling), and maintenance of the DC pump. As the system life passes on, the maintenance on it also increases. Therefore, 10% of net present cost has been considered as maintenance cost. Finally, the cost of distilled water per liter (CPL) can be calculated by dividing the annual cost of the system AC by annual yield of solar still (M). Where S is the salvage value, taken as a fraction of present capital cost. The above mentioned calculation parameters can be expressed [18]:

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{4}$$

$$\text{FAC} = P(\text{CRF}) \tag{5}$$

$$\text{SFF} = \frac{i}{(1+i)^n - 1} \tag{6}$$

$$S = 0.2P \tag{7}$$

$$\text{ASV} = (\text{SFF})\text{S} \tag{8}$$

$$\text{AMC} = 5\%\text{FAC} \tag{9}$$

$$\text{AC} = \text{FAC} + \text{AMC} - \text{ASV} \tag{10}$$

$$\frac{\text{AC}}{\text{M}} = \text{CPL} \tag{11}$$

where P is the present capital cost of desalination system, i – the interest per year, which is assumed as 12%, n – the number of life years, which is assumed as ten years in this analysis. The cost price of raw materials is as seen in tab. 3. Also, the cost comparison of different configurations of ISWD is presented in tabs. 4 and 5 shows the life cycle analysis of the different configurations of the ISWD systems. The detailed life cycle analyses of the systems are presented in tab. 5. It is assumed that these systems are roof mounted and there will be no need for acquiring land. Large scale solar plants require huge land space, a factor that contributes to the cost of water. The life cycle indicators show that the entire design configurations are feasible, since none give a negative net present value. The net present value (NPV) approach of assessing projects is viable because it is the algebraic sum of the discounted values of the incremental expected positive and negative net cash flows over a system anticipated lifetime. The NPV helps to measure the changes in wealth created by the system.

Table 4. Cost comparisons of the different configurations of ISWD (cost price in US $)

ISWD types	P	CRF	FAC	S	SFF	ASV	AMC	AC	M	CPL
ISWD [Aybar design]	160	0.18	28.41	32	0.057	1.83	1.42	28.00	781.10	0.036
IISWD [2 spray jets]	255	0.18	45.18	51	0.057	2.91	2.26	44.53	1328.60	0.033
IISWDWM [2 spray jets]	264	0.18	46.67	53	0.057	3.00	2.33	46.00	737.30	0.062
IISWDW [2 spray jets]	258	0.18	45.74	52	0.057	2.95	2.29	45.10	1600.00	0.028
IISWDW [4 spray jets]	277	0.18	49.10	55	0.057	3.16	2.45	48.39	1107.20	0.044
IISWDW [6 spray jets]	296	0.18	52.44	59	0.057	3.38	2.62	51.69	810.30	0.064

Table 5. The life cycle indicators of different ISWD configurations

ISWD types	Net present value [$]	Internal rate of return	Savings to investment ratio	Simple payback [Years]
ISWD	312.63	2.8	50%	1.9
IISWD [2 spray jets]	545.68	2.9	54%	1.7
IISWDWM [2 spray jets]	163.89	1.6	25%	3.2
IISWDW [2 spray jets]	709.79	3.4	65%	1.5
IISWDW [4 spray jets]	385.58	2.2	40%	2.3
IISWDW [6 spray jets]	190.42	1.6	25%	3.3

A positive NPV means the project is viable and when comparing different systems the one with the highest NPV value is the best. In this work we have used NPV, internal rate of return, savings to investment ratio and simple payback (years) to evaluate the economic feasibility of the system. The simple payback approach evaluates economic viability of a system with the shortest payback period. This approach is biased because it did not put into consideration the discounted benefit of the systems. In spite of the biasness, the simple payback is still considered as suitable for assessing a system if the life span of the system is not older than ten years. The internal rate of return ranks mutual systems. The system with highest internal rate of return is judged the best or the most economically viable. According to tab. 5 the NPV, internal rate of return, savings to investment ratio, and simple payback period for ISWD with wick and two spray jets is the most economically viable. It is interesting to note that of all the economic approaches used the ISWD with wick and two spray jets was the best. The NPV approach is taken as the most reliable economic evaluation of the approach. According to the NPV evaluation the SWDWM is the system with the weakest economic benefit. In the economic consideration the system life (year) was taken as ten years and interest rate on the capital as 12%.

Conclusions

This work presents experimental and economic results of four different configurations of ISWD System. The following conclusion were drawn from the work:

- The IISWD with two spray jets has a maximum daily production of 5.46 kg/m^2, daily efficiency of 48.3%, $255.84 as the system cost, $0.033 as the cost price per litre.

- The IISWDW on absorber plate has a maximum daily production of 6.41kg/m^2, daily efficiency 50.3%, $258.47 as the system cost, $0.028 as the cost price per litre
- The IISWDWM on absorber plate has a maximum daily production of 3.03 kg/m^2, daily efficiency 32.6%, $263.73 as the system cost, $0.062 as the cost price per litre
- The ISWD with bare absorber plate has a maximum with daily production of 3.25 kg/m^2, daily efficiency of 40.1%, $160.52 as the system cost, $0.036 as the cost price per litre

The results obtained show that solar radiation, wick material, and the jets variation are the main factors that influence the system. The IISWDW system performed the best with 6.41 kg/m^2 per day with 50.3% efficiency while he IISWDWM performed the worst with 3.03 kg/m^2 per day and 32.6% efficiency. The use of porous media in IISWDWM system did not work as expected. The distilled water cost price analysis also shows that IISWDW with two spray jet is the most economically viable among all the systems while the IISWDW with six spray jets was the most expensive. Life cycle analysis of the systems also shows that IISWDW with two spray jets has the highest NPV value of 709.58 $/L for interest rate of 12% and ten years life span. In addition, the IISWDW with two spray jets has the least payback period of 1.5 years. The pump used in the IISWDS, IISWDW, and IISWDWM for powering the spray jets is a 33 W pump, and the pump works for four minutes in one hour. The electricity consumption in this system is negligible compared to the effect on the system performance.

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