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Full Length Research Paper

An experimental investigation of an improved incline solar water desalination system in Famagusta

O. Phillips Agboola* and F. Egelioglu

Mechanical Engineering Department, Eastern Mediterranean University, Famagusta, TRNC via Mersin 10, Turkey.

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This study investigated the performance of an improved incline solar water desalination (ISWD) system under the influence of two different weather conditions (winter and summer seasons) in Famagusta, Northern Cyprus. The experimental investigation studied the effects of solar radiation intensity, wick on the plate absorber and the bare plate absorber on the daily production and efficiency of the ISWD system. The results obtained from this investigation were compared with other researcher works (mathematical and experimental) in literature. The experimental results of the system (with wick) gave daily production (P_d) as 6.41 kg/m^2 day in summer (with an experimental duration of 8:00 am to 16:00 pm) while it was 3.327 kg/m^2 day (with an experimental duration of 8:30 am to 15:30 pm) in winter. One major comparison was with the theoretical results by Aybar (2006) which yield between 3.5 to 5.0 kg/m^2 day (7:00 am to 7:00 pm) for summer season. The summer experimental result was higher than the predicted theoretical result range by Aybar (2006). One possible reason for disagreement between the experimental investigation and the theoretical prediction in summer was that the theoretical work did not put into consideration the re-use of the exit water (that is, higher temperature) as feed water for the system as used in the experiment. The daily efficiency (η_d) was found to be 52.4% in summer season while the efficiency dropped in winter to 43.6%.

Key words: Solar desalination, incline solar water desalination, solar still, daily production, potable water.

INTRODUCTION

The shortage of water for domestic and agricultural use in Northern Cyprus (N. Cyprus) is quite evident; the problem is further compounded by the international economic embargo on the northern part of the island (Biyikoglu, 1995; Bicak, 1996). Water scarcity is arguably one issue that is currently dominating the agenda of the international community. The United Nations has suggested that without a significant reversal of economic and social trends in water scarce areas, the issue of water scarcity will become increasingly acute with time. Water is a renewable resource, but in many parts of the world, water resources have become so depleted or contaminated that they are unable to meet the ever-increasing demand of most communities (EIA, 2006). In Northern Cyprus in the 1960's the exportation of citrus fruits and potatoes was a significant source of revenue for the government but with the current water crisis this has ceased to be (Katircioglu, 2006). The water shortage has grossly affected farm land irrigation leading to a decline in the yearly quantity of agricultural produce as vast quantities of arable land suffer from low yield. Farmers have also lost arable land used for Citrus fruits cultivation due to the high salt content of the water resources available to them for irrigation (Baig, 2002). The escalating demand for water in the area has led to extraction of water from groundwater resources which resulted into salinization (up to 5000 part per million of total dissolved solid) and a high value of salt contamination due to sea-water intrusion along the coastal aquifers located in N. Cyprus. The municipality water supply to homes contains around 1,950 part per million (ppm) of dissolved salt content making it unsafe to drink. These challenges are more acutely felt under the

*Corresponding author. E-mail: phillips.agboola@cc.emu.edu.tr. Tel: +903926301160.

Table 1. Sector wise annual water withdrawals (m^3).

	Agricultural use				Domestic use					Total
	Irrigation	Losses	Subtotal	Live stock	Hotels	Universities	Residents	Losses	Subtotal	
LMR										
C. Lefkosa	82,022	70,215	152,237	75,387	18,834	226,555	4,513,408	1,450,255	6,284,438	6,436,675
Degirmenlik	575,349	513,982	1,089,331	165,500	0	0	1,732,564	569,419	2,467,483	3,556,814
Ercan	550,961	522,686	1,073,647	192,050	0	0	143,354	100,621	436,025	1,509,672
Guzelyurt	37,812,296	21,863,489	59,675,785	248,173	2,774	0	6,930,926	2,154,562	9,336,434	69,012,219
Lefke	3,170,069	2,490,606	5,660,675	30,746	5,256	40,184	682,185	227,511	985,882	6,646,557
Total	**42,190,697**	**25,460,978**	**67,651,675**	**711,856**	**26,864**	**266,738**	**14,002,437**	**4,502,368**	**19,510,262**	**87,161,937**
MMR										
Magosa A	1,824,077	1,673,518	3,497,595	118,877	125,414	359,211	2,705,380	992,664	4,301,546	7,799,141
Magosa B	348,666	344,259	692,924	70,089	0	0	256,869	98,087	425,045	1,117,969
Akdogan	1,335,133	1,103,063	2,438,196	177,768	0	0	659,920	251,306	1,088,994	3,527,190
Y. Erenkoy	1,228,282	1,078,670	2,306,952	187,094	4,672	0	834,390	307,847	1,334,002	3,640,954
Mehmetcik	686,154	673,919	1,360,073	92,392	0	0	453,330	163,717	709,439	2,069,512
Y. Iskele	485,257	463,085	948,342	123,857	39,420	0	844,793	302,421	1,310,491	2,258,833
Gonendere	212,983	212,984	425,967	72,330	0	0	487,275	167,882	727,487	1,153,454
Gecitkale	373,223	360,357	33,579	136,433	0	0	131,856	80,487	348,776	1,082,355
Total	**6,493,774**	**5,909,854**	**12,403,628**	**978,841**	**169,506**	**359,211**	**6,373,813**	**2,364,411**	**10,245,781**	**22,649,409**
GMR										
Girne East	669,566	642,904	1,312,470	62,118	315,506	47,897	1,966,620	717,642	3,109,783	4,422,253
Girne West	2,826,507	2,729,797	5,556,304	10,001	248,127	0	1,017,620	382,724	1,658,472	7,214,776
Bogaz	374,485	369,072	743,557	139,131	0	0	1,032,494	351,487	1,523,112	2,266,669
Camlibel	926,917	834,605	1,761,521	131,732	0	0	258,694	117,128	507,554	2,269,075
Total	4,797,475	4,576,377	9,373,852	342,981	563,633	47,897	4,275,428	1,568,982	6,798,920	16,172,772
North Cyprus	**53,481,946**	**35,947,209**	**89,429,155**	**2,033,678**	**760,003**	**673,846**	**24,651,678**	**8,435,761**	**36,554,963**	**125,984,118**

economic isolation imposed on the area by the international community (except Turkey).

The embargo prevents bilateral relationship and impedes economic development of this community thereby rendering the government incapacitated in responding adequately to the water crises. Other factors that contribute significantly to the water shortage in Northern Cyprus is the increase in population growth rates, increased rural - urban migration, the growing tourist industries, late adoption of modern irrigation techniques, poor water network systems, increase in number of industries and recent huge investments in real estate. Tables 1, 2 and 3 shows the sector wise annual water withdrawals, the aquifers capacities in N. Cyprus and quality of underground water sample from selected sources respectively. According to Table 1 about 126 million m^3 of water is needed to meet the need of the country while the various aquifers can contribute 74 million in save yield but they were

Table 2. The aquifers capacities in N. Cyprus (DSI 2003).

Aquifers	Recharge (10^6 m^3)	Safe yield (10^6 m^3)	Withdrawals (10^6 m^3)
Guzelyurt	37	37	57
Akdeniz	15	1.5	1.5
Lefke -G. Konagi- Y. dalga	15.5	6	6
Yesilirmak	7	1.5	1.5
Girne Mountains	11.5	11.5	11.5
Gazimagusa	2	2	8.5
Beyarmudu	0.5	0.5	0.5
Cayonu-Guvercinlik- Turkmenkoy	2	2	2
Lefkosa-Serdarli	0.5	0.5	0.5
Yesilkoy	1.6	1.6	3
Girne Coast	5	5	5
Yedikonuk- Buyukkonuk	0.3	0.3	0.3
Dipkarpaz	1.5	1.5	1.5
Korucam	1.2	1.2	1.2
Others	2	2	2
Total	89.1	74.1	103

Table 3. Quality of underground water sample from selected Sources (Baig, 2002).

Source of water	Total dissolved solids (ppm)	Conductivity (µS/cm at 25°C)
E.M.U campus (Famagusta)	3175	1820
Gunesoglu	5941	3530
Lastikgi	6679	4570
Guvercinlik 4th well	10657	6030
Buyukonuk	2668	1720
Iskele	5862	3201

ppm: part per million.

excessively drawn in excess of about 29 million m^3 causing the seawater intrusion (Table 2). The seawater intrusion had affected the land water quality badly as seen in Table 3 of sampled underground water. These problems necessitate this research to produce potable water from the bad quality underground water. It is possible to get potable water from salinated water (sea water or brackish water) using desalination techniques. Solar desalination is one of the many processes used in purifying water for domestic and agricultural use. Solar desalination uses solar radiation as a source of heat energy to separate pure water from brackish or sea water to produce potable water. Water desalination has become a major source of fresh water supply in many countries, especially in the Middle East, North Africa and Eastern Europe regions where fresh water supplies are very limited. Solar still is one type of solar desalination systems that is well studied in literature (Hiroshi el al., 2007; 2009; Abdallah et al., 2008; Nassar, 2007; Samee, 2007; Tiwari, 2003; El-Sebaii, 2009; Delyannis, 1987). Many researchers studied several configurations of solar stills to improve its performance and daily production that ranges from 1 to 5 kg/m^2 day (Tabrizi and Sharak, 2010; Mousa and Arabi, 2009; Zhani and Bacha, 2010; Gude et al., 2011). In this work, an improved incline solar water desalination system was tested under the climatic weather condition of Famagusta, Northern Cyprus in winter and summer seasons.

The ISWD system is different from solar still; the feed water in the improved ISWD system uses jets to spray water on the incline absorber plate allowing the water to run down the absorber plate uniformly till the whole area of the absorber plate is covered with water. The system produces fresh and hot water simultaneously but the hot water is re-fed into the system as feed water.

MATERIALS AND METHODS

The improved ISWD system was constructed and tested for daily performance and productivity in winter and summer seasons. The system was tested with bare plate absorber and when the absorber plate was covered with black wick. Figure 1a shows the schematic diagram of the improved ISWD system. The improved ISWD systems consist of an absorber plate and a glass cover that creates

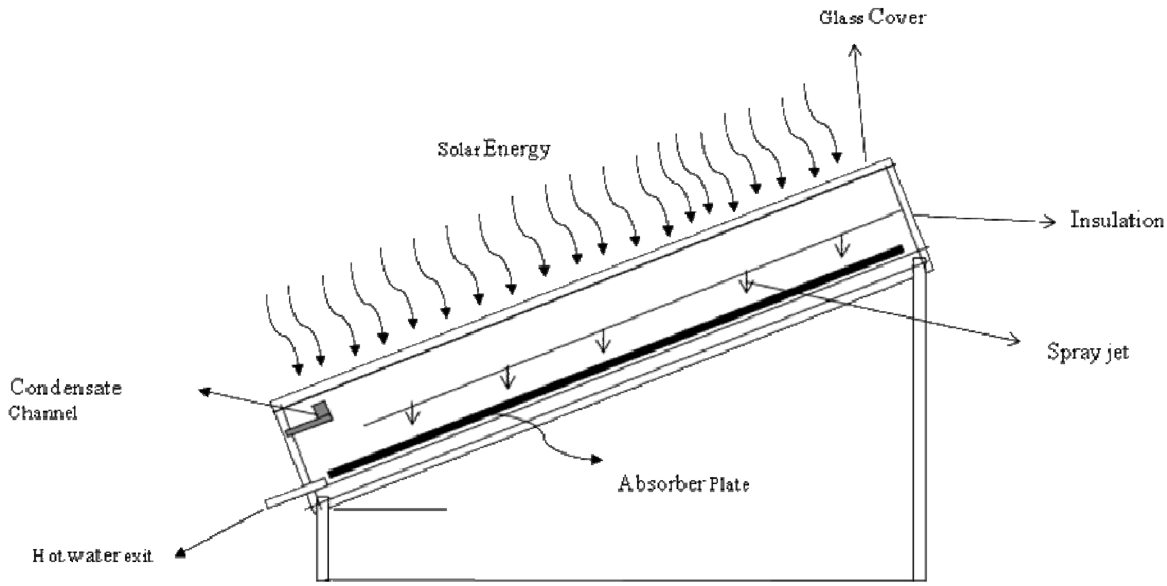

Figure 1a. Schematic diagram of the incline solar water distillation system.

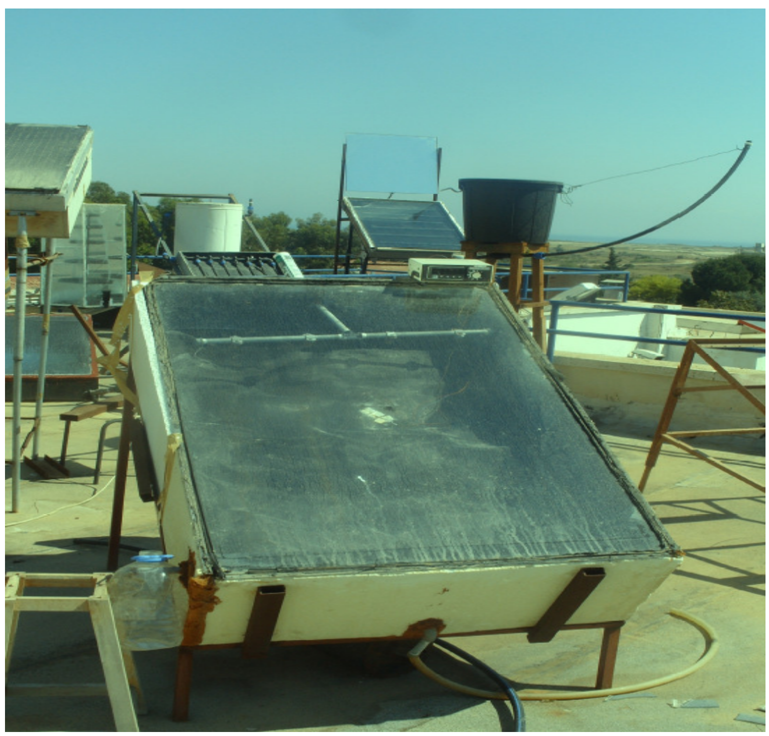

Figure 1b. A photograph of the incline solar water distillation system.

a cavity. The cavity dimension is 1 m^2 with height of 0.2 m. A galvanized steel of 0.4 cm is used as the absorber plate which was painted Matt black to increase the surface absortivity (absortivity of 0.96 and emissivity of 0.08), the cavity was constructed from stainless sheet due to better resistance to corrosion and the inner surface of the cavity was painted Matt black. The outer surface was insulated at the sides and at the bottom insulated with specialized foam. 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. The system was inclined at angle 36° to optimally utilize the 1 m^2 surface (solar radiation incidence) of the plate and to allow water flow through the whole length and width of the surface (Aybar et al., 2005; Tiwari, 2002). The system feed water was spray through the jet (nozzles) on the absorber plate intermittently (variation in number of jet applies), the use of jets to spray water evenly on the absorber plate was to improve the first

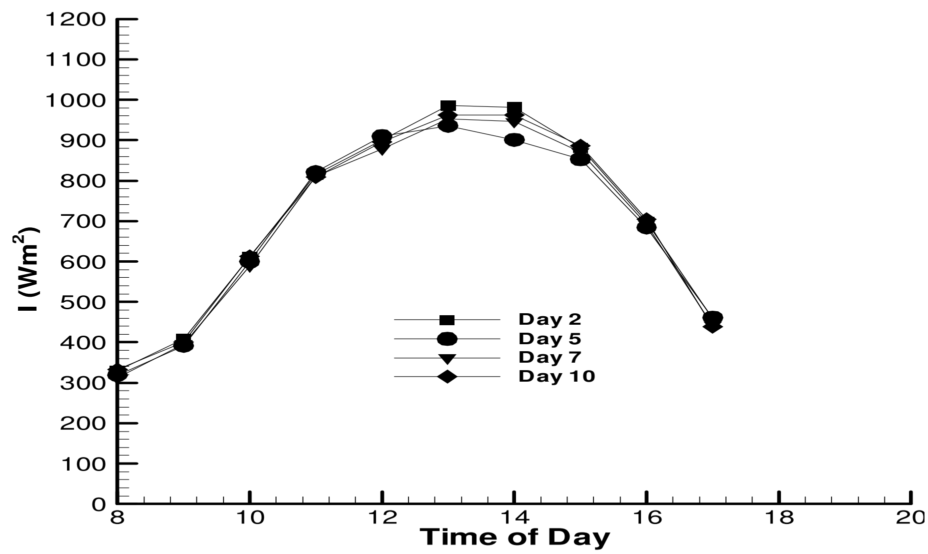

Figure 2. Hourly variation of radiation intensity for some selected days in summer season

version of the IWSD system by Aybar et al. (2005). The first version of ISWD used a longitudinal slot of 2 mm to feed in water to the system, the distribution of water through the longitudinal slot onto the absorber plate was not effective which affected the performance of the system. The improved ISWD system was exposed to solar energy at a roof top to heat up the absorber plate/wick as the case may be.

The heat from the sun causes some of the water to evaporate and condense due to the temperature difference at the glass top cover. The condensate is collected through a condensate channel extracted from the cavity by a small pipe that extrude from the condensate channel to a plastic water collector outside the system. The remaining water (hot) in the ISWD is collected through an exit and re-fed to the feed water tank to increase the temperature of the feed water thereby increasing the efficiency of the system. The materials selection for the construction of the systems was done in line with American Iron and Steel Institute (AISI) standard code and they are generally available in the market and cheap. T-type thermocouples were fixed both at the inner and outer parts of the systems to measure various necessary temperatures like absorber plate temperature, the air temperature, the inner glass temperature, ambient temperature, feed water inlet temperature and outlet temperature. The temperature readings were retrieved by a Ten-Channel Digital Thermometer (MDSSi8 Series digital, Omega) ±0.5° C accuracy. A calibration test was performed on the thermocouple before use and returned an accuracy reading of ±0.15°C. The solar radiation was measured using the Eppley Radiometer Pyranometer (PSP) - coupled to a solar radiation meter model HHMiA digital, Omega 0.25% basic dc accuracy and a resolution of ±0.5 ranging from a value of 0 to 2800 Wm^{-2}. The jets spray 0.75ml/min of water into the system cavity four times in 1 h (at 15 min interval). The hourly measurement of the amount of distillated water, temperatures at different parts of the systems were taken using thermocouples attached with the ten channel digital thermometer. Uncertainty associated with the experimental measurements is as recorded against the measurement instruments.

Incline solar water desalination efficiency

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

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

$$Q_{ev} M_{ev} L \times 3600 = 1 \tag{2}$$

Where Q_{ev} is the evaporative heat transfer (W), M_{ev} is distilled water production rate (kg/m^2 h), A_b is the still base area (m^2), L is the latent heat of vaporization (J/kg) and H is the total solar radiation falling upon the ISWS surface (W/m^2). ISWD 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 (this is the same as the length and breadth of the system) and calculated from the following equation:

$$\eta_d = \frac{\int_0^t m_{ev} L\,dt}{3600 A_b \int_n^t H\,dt} \tag{3}$$

Where t is the time.

RESULTS

The performance of any ISWD system depends on several parameters such as the temperature of the absorber plate, the inlet water temperature, the cavity air temperature, the glass temperature and the distribution of the feed water on the absorber plate (Aybar et al., 2005). The temperatures of the system constituents increase with the time of day when the solar radiation (Figure 2) increases until their maximum values at 13:00 pm, afterwards, the various temperatures decrease (the absorber, cavity air, glass etc) with time with decrease in solar radiation and ambient temperature. The maximum

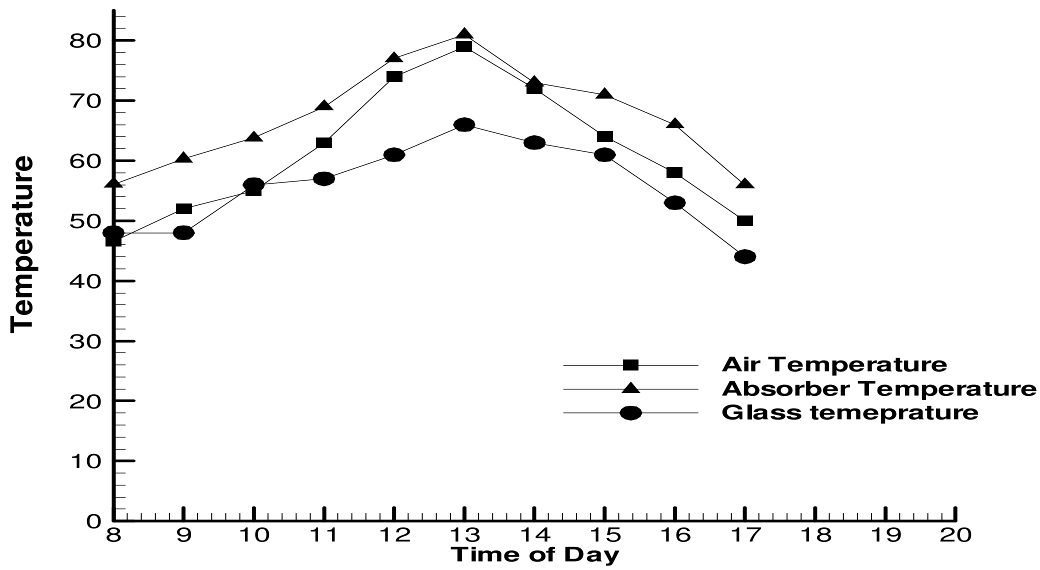

Figure 3a. Temperature distribution of the system on a typical day in summer.

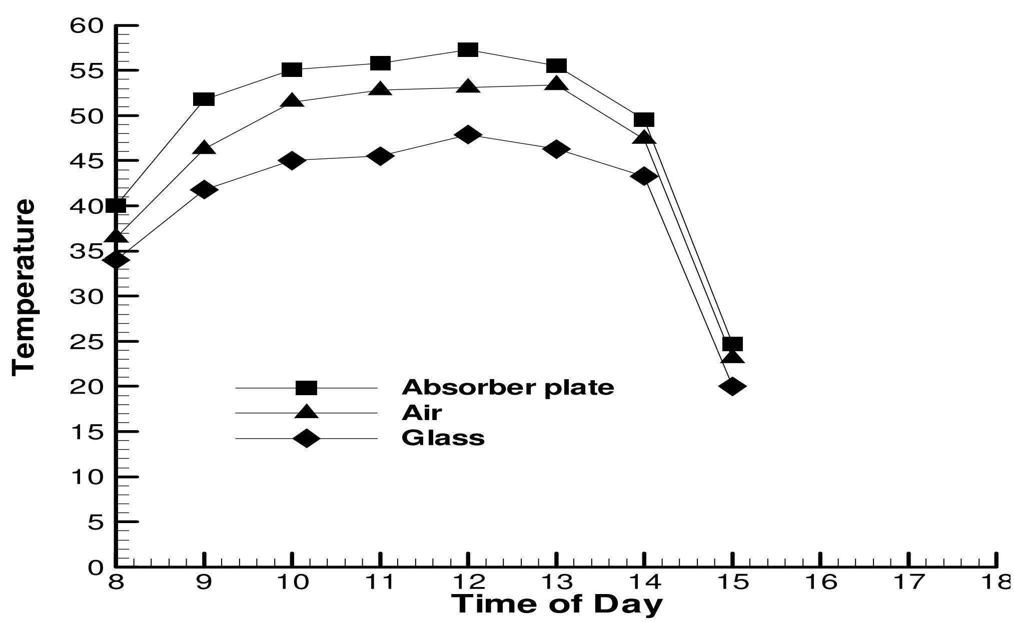

Figure 3b. Temperature distribution of the system on a typical day in winter.

temperatures achieved by the absorber plate, cavity air temperature, glass cover temperature and ambient temperature were 82, 78, 62 and 38°C respectively for summer and 56, 50, 45 and 21°C respectively for winter. Figure 2 shows the hourly solar radiation of four selected days in summer, it will be observed that the hourly solar radiations are consistent over the period of the experiment. The absorber plate temperature, cavity air temperature, glass surface temperature for a typical day in summer and winter are shown in Figures 3a and b. Figures 3a and b presented the daily maximum and minimum obtainable temperatures for the plate absorber, the cavity air temperature and the glass temperature, a wide temperature difference between the cavity air temperature and glass temperature will increase the condensation. In order to increase the temperature difference between the cavity air and the glass; the glass cover is been cooled with water at 15 mins interval. The ambient air temperature during a typical day in summer and winter are shown in Figures 4a and b. The ambient temperature is the temperature of the surroundings, it will be observed from Figures 4a and b that the difference in

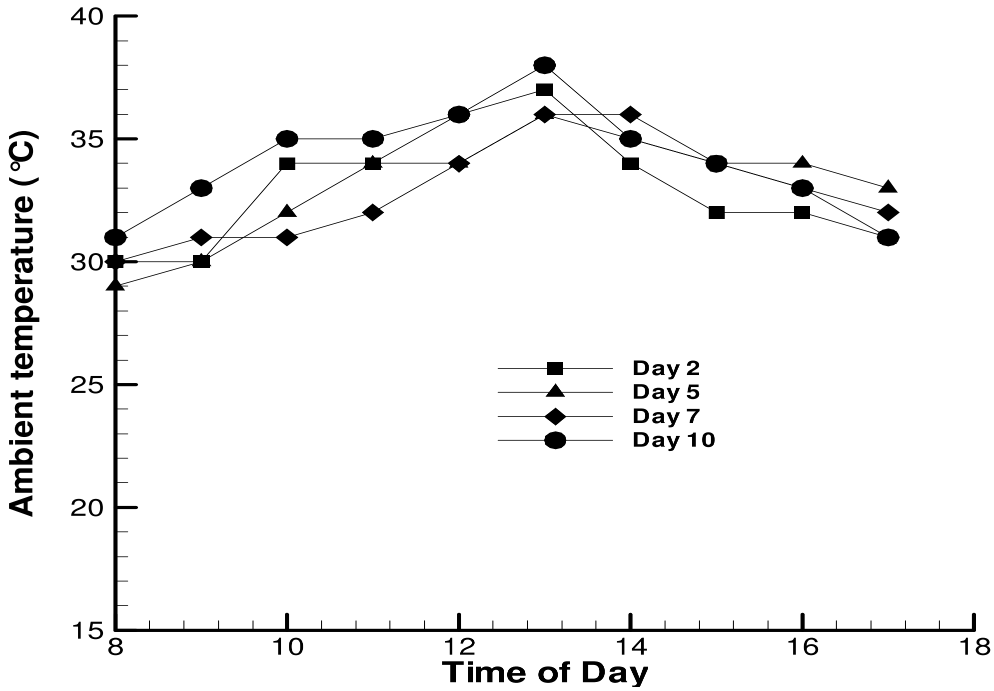

Figure 4a. Hourly variations of ambient temperature for some selected days in summer season.

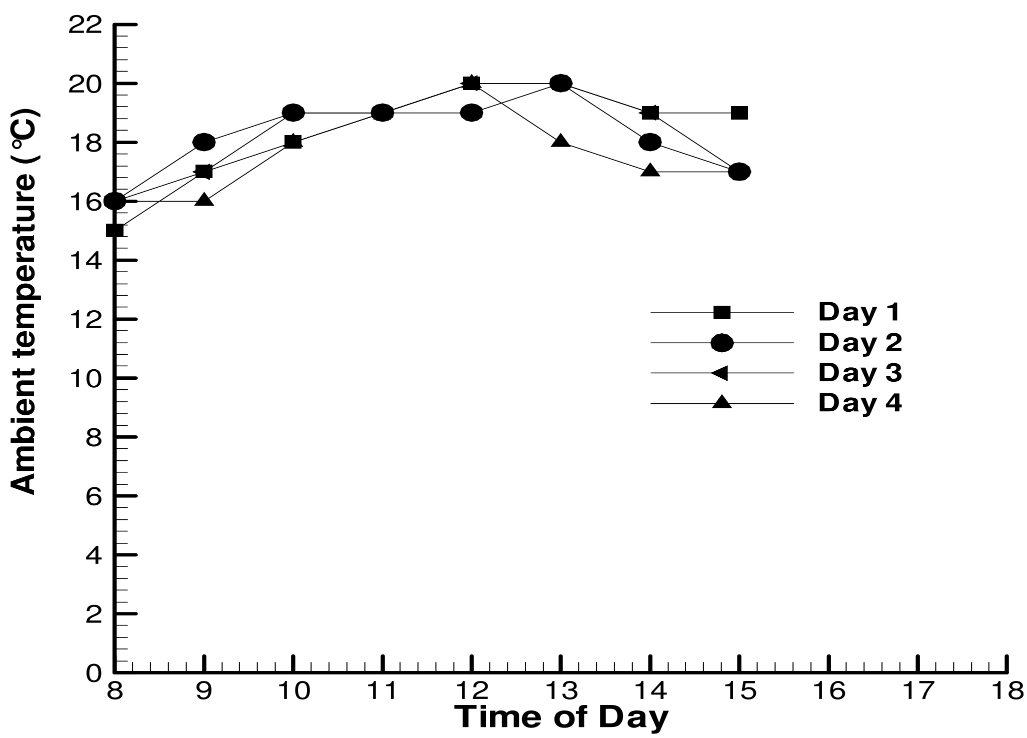

Figure 4b. Hourly variations of ambient temperature for some selected days in winter season.

the daily ambient temperature in both cases ranges from 7 to 9°C.

Figures 5a and b shows the hourly inlet and outlet temperature for typical day in summer and winter. Figure 6 shows the hourly production of fresh water from the improved ISWD for summer and winter. Figure 7

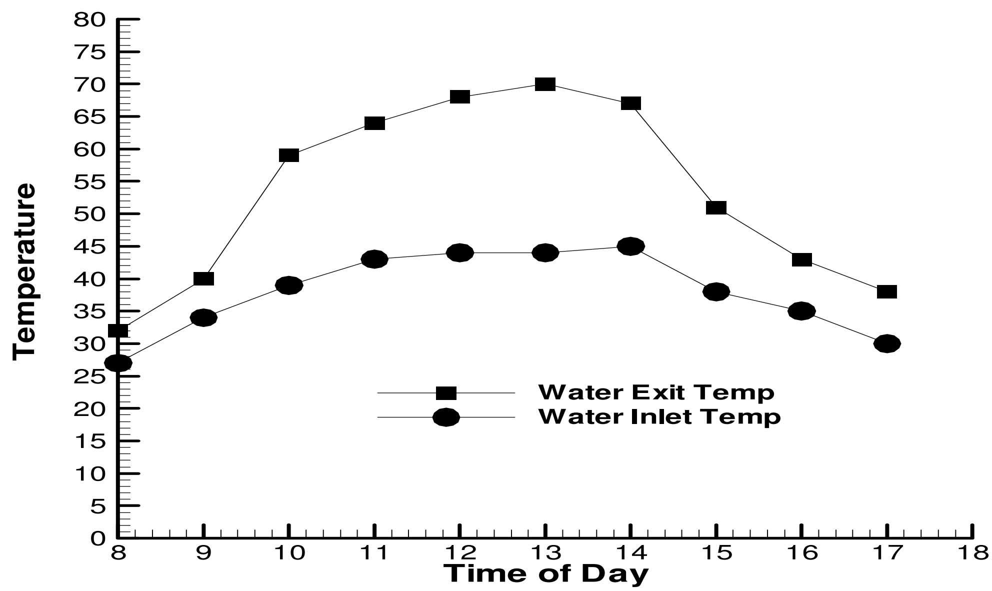

Figure 5a. Inlet and outlet temperature of water on a typical day in summer.

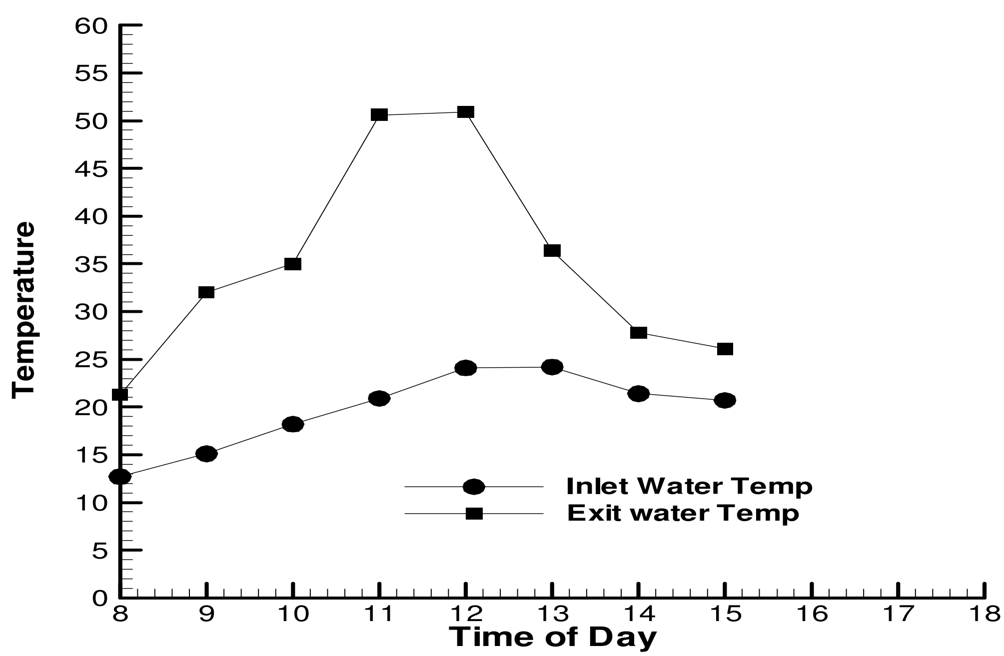

Figure 5b. Inlet and outlet temperature of water on a typical day in winter.

shows the comparison between the hourly daily production of the first type of the ISWD (with bare absorber plate and with wick) with the improved ISWD (with bare absorber plate and with wick).

DISCUSSION

The introduction of jets has significant effect on the daily production of an ISWD unit as tested in this work. The limitation of unevenly feed water distribution in the work of Aybar et al. (2005) was overcome as the jets introduction increases the daily potable water production by 49% when compared to 2.995 kg/m^2 day by Aybar et al. (2005). One major setback in this experiment was that the exit water have to be collected over a period of 1 h before it is re-injected into the inlet feed system thereby losing some heat energy (3 to 5°C) to the surrounding.

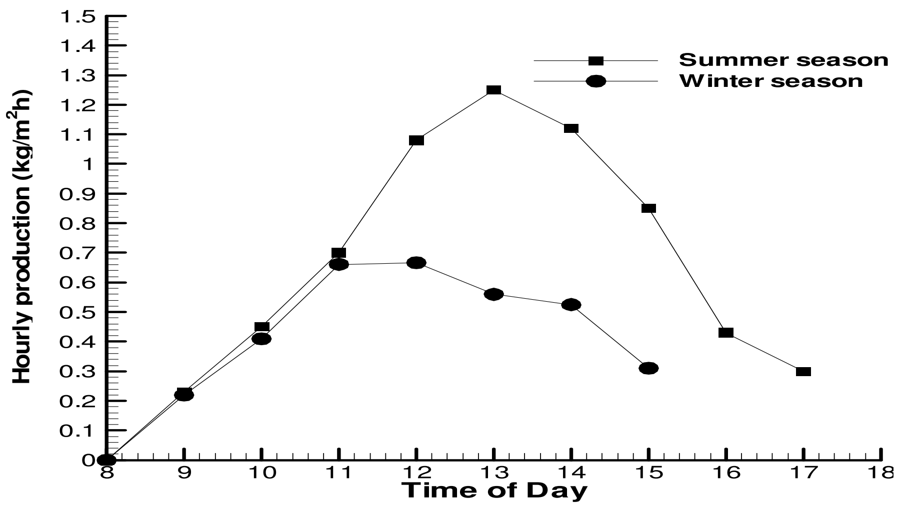

Figure 6. Variations of hourly productivity with time for a typical day in summer and winter season.

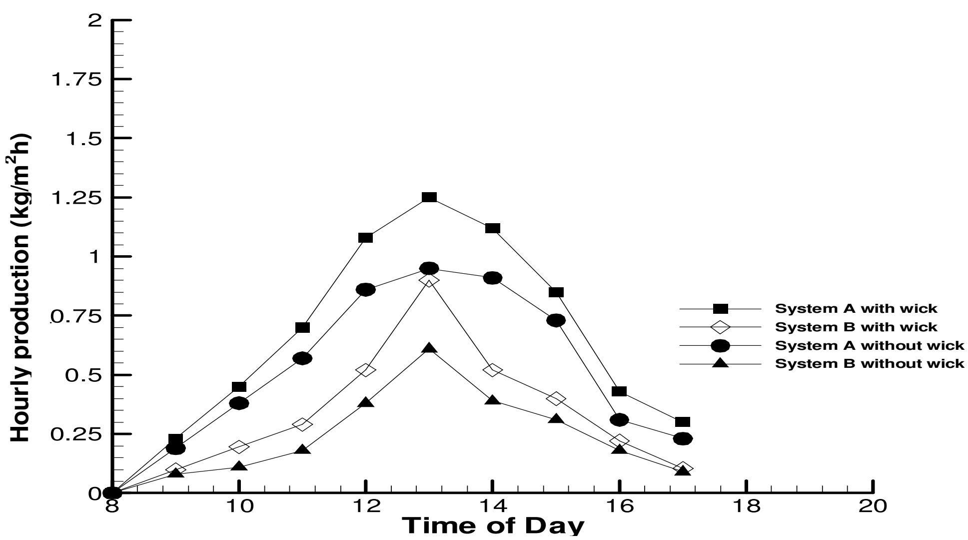

Figure 7. Hourly variations of hourly productivity system A (improved ISWD) and system B (older version of ISWD) during summer when both were exposed to the same experimental conditions.

The feed water used in the experiment was 2000 to 4000 ppm brackish water. The fresh water produced as a result of condensation of the evaporated water in the system were collected and measured while the exit hot water were returned to the in-feed tank to increase the temperature of the water, thereby improving the system's efficiency. Figure 6 shows the hourly production of fresh water from the improved ISWD for summer and winter. The hourly production of fresh water (potable water) between 8:00 am to around 11:00 am are very similar in both summer and winter cases, the only explanation for this could be that the effect of the re-injection of the exit water has little effect during these periods. The wide margin in hourly production was noticeable from 12 noon when the temperature of the exit water had increased substantially for the summer season. The maximum daily productions for the two weather conditions were 6.41 and 3.327 kg/m^2 day respectively as compared to 2.995 kg/m^2 day for summer season by Aybar et al. (2005). The hardness of the fresh water produced ranges from 14 to 40 ppm depending on whether the absorber plate or the wick was used.

The daily production of the system compared with other kind of solar desalination system is presented in Table 4. Figure 7 shows the comparison between the hourly daily production of the first type of the ISWD (with bare

Table 4. Experimental results of selected solar desalination systems.

Name of system	Place	Ambient mean temperature (°C)	Production (kg/m^2.day)	Reference
Double condensing chamber unit	India	13	1.439	Aggarwal and Tiwari (1999)
Double stepped plastic solar still	Italy	30	1.800	Cappelletti (2002)
Single- basin solar still with deep basin	Egypt	28	2.045	Aboul-Enein et al. (1998)
ISWD with wick	N. Cyprus	30	2.995	Aybar et al. (2005)
Single Slope solar still	Jordan	25	3.560	Badran and Abu Khader (2007)
Double basin solar still with insulation	Bahrain	39	3.910	Al-Karaghouli and Alnaser (2004)
Single slope solar still, asphalt cover	Jordan	29	4.120	Badran (2007)
Triple-basin solar still	Jordan	27	4.896	Hamdan et al. (1999)
Distiller with a film in capillary motion	Algeria	40	5.190	Bouchekima et al. (1998)
Solar still coupled to outside condenser	Turkey	30	6.520	El-Bahi and Inan (1999)
Improved ISWD bare absorber plate	N. Cyprus	34	5.130	
Improved ISWD with wick	N. Cyprus	34	6.410	
Improved ISWD with wick	N. Cyprus	19	3.327	

absorber plate and with wick) with the improved ISWD (with bare absorber plate and with wick). It will be clearly observed that the improved ISWD performed better than the ISWD by Aybar et al. (2005) which produce 2.995 kg/m^3 day. Major difference in the system includes a thicker absorber plate and the spray jet. The thickness of the absorber plate play a major role in retaining heat energy and the spray jet in evenly and uniform distribution of the feed water to optimally utilize the thermal area. The efficiency of the improved ISWD system was maximum at 13:00 h. The efficiency of the improved ISWD system with wick was the highest followed by the efficiency of the system with bare plate absorber given as 50.3 and 47.2% respectively. One major difficulty encountered in the system was the high glazing temperature; this problem was minimized by cooling of the glass surface with water in order to increase the condensation under the glazing. The experiments were performed between the hours of 8:00 am and 5:00 pm through the 25th of July to 10th of August, 2010 for the summer when the weather in Famagusta was mostly sunny with clear skies. In wintertime, the experiments were performed between February 13th and March 20th 2011 when sunshine was limited. Gude and Nirmalakhandan (2010) have model a 24 h humidification-dehumidification system (a more complex solar desalination system) to yield 7.5 kg/m^2 day in summer and our system a less complex system yielded 6.41 kg/m^2 day in 8 h which is a good result.

Conclusion

An investigation of the performance of an improved ISWD was carried out experimentally under the climatic condition of Famagusta, Northern Cyprus. The system was tested in various weather conditions (summer and winter) and also with bare absorber plate and absorber plate covered with wick. It was found that the system performance in the two weather conditions is acceptable and the daily productivity and efficiency are reasonable. On a typical summer and winter day in Famagusta, the daily productivities were found to be 6.41 and 3.327 (kg/m^2 day) respectively. In comparison with solar stills the system daily productivity almost doubles the results recorded against different kind of solar still. The pump used in the system for powering the spray jets is of 33 W/h pump and with the pump working for 4 min in 1 h the electricity consumption in this system is highly negligible compare to the effect on the system performance.

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