Improved Inclined Solar Water Desalination System

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Abstract

The rapid urbanization, industrialization, developments in agriculture and increase in population are responsible for the growing demand of freshwater around the world. In most part of the world, potable water shortage is a growing concern. North Cyprus lack edible water source due to seawater intrusion into its main aquifers due to over withdrawing. In addition, the low precipitation is adversely affecting the surface water sources. Desalination technology can provide a new source of freshwater accessible to the populace for either domestic or agriculture use. The use of convectional desalination technology comes with the growing concern of fossil fuel price fluctuations and the environmental issues. Therefore, solar desalination technology will be one viable option for the freshwater sources in North Cyprus due to the high solar radiation in the area. This study continues a research in the field of solar desalination within the Mediterranean region. The economic and thermodynamics performance of an improved inclined solar water desalination systems were experimentally investigated. The performances of IISWD with 2, 4 and 6 spray jets were studied. In addition, the effect of wick on absorber plate and porous media (wire mesh) on the performance of the system was investigated. The result of the investigation revealed that the introduction of spray jets to inclined solar water desalination was significant. Three different configurations IISWD, IISWDW and IISWDWM were tested. Each of the configurations was tested concurrently with ISWD (a control system without the spray jets) to effectively monitor the contribution of the spray jets. The maximum daily production of ISWD, IISWD, IISWDW and IISWDWM are 3.25 kg/m2 with daily efficiency of 40.10%, 5.46 kg/m2 with daily efficiency of 48.30%, 6.41 kg/m2 with daily 50.30% efficiency and 3.03 kg/m2 with daily efficiency 32.60% respectively. The distilled water cost price analysis also shows that IISWDW with 2 spray jet is the most economically viable among all the system while the IISWDW with 6 spray jets was the most expensive.

Keywords: Edible water, inclined solar water desalination, thermal efficiency, spray jets, Daily production
1. INTRODUCTION

1.1 Types of Desalination Methods

Desalination process can be categorized into two main methods: Thermal Desalination process and Membrane Desalination process as seen in Figure 1. The thermal process mimic the hydrological cycle while the membrane process mimic the biological membranes. The thermal separation technique can be subdivided into two main categories; the first is evaporation followed by condensation of the formed water vapour. The second involves freezing following melting of the formed water ice crystals. The evaporation-condensation technique is the most common in desalination systems. The Thermal separation techniques include two main categories; the first is evaporation followed by condensation of the formed water vapour and the second involves freezing followed by melting of the formed water ice crystals. The former process is the most common in desalination and nearly at all cases it is coupled with power generation units, which may be based on steam or gas turbine systems. The evaporation process may take place over a heat transfer area and is termed as boiling or within the liquid bulk and is defined as flashing. International Desalination Association (IDA) in 2009 estimated the number of desalination plants in operation to be 14,451 worldwide, producing about 60 million cubic meters per day [1,2,3,4].

1.2. Solar Desalination

Solar desalination systems are systems that utilize the sun energy (Solar radiation) for the separation of water and salt. Classification of solar desalination varies depending on techniques and energy supply. The most common type of solar desalination systems is the solar stills. Solar stills can be categorized into Passive solar stills and Active solar stills. Solar desalination systems can also be categorized by techniques and design of the systems. This can be categories as direct collection system or indirect collection system. The direct collection systems are the systems with all parts integrated into one system. The system uses the heat energy from the sun to produced water vapour that later condensed on the glass cover of the system. The indirect collection systems are the ones with two sub-systems. The solar energy is collected in one sub-system and the desalination takes place in the other. This work focuses on the direct type of solar desalination system.

1.3. Objectives and Organization

The literature review on solar stills shows that there are extensive works on the system yet there is room for more modification to optimize the performance of a solar still. On the other hand, inclined solar water desalination is not as well studied. There are similar studies close to the principle of inclined solar water desalination but none have considered the use of spray jets. There are no experimental works in solar desalination in that involves the use of spray jets for the inlet water of a direct solar desalination system. The main objective of this work is to design, construct and test an inclined solar water desalination system with spray jets under the climatic condition of Famagusta, North Cyprus. The effect of the spray jets
on the economic and thermal performance of the systems will be investigated. The research aims to explore and document the findings of the use of spray jets on the temperature profiles of the absorber plate, the cover glass, the cavity air and the daily productivity of the system. In addition, for accurate investigation of the performance an inclined solar desalination with spray jets, convective inclined solar water desalination as designed by Aybar et al (2005) [5] will be constructed and tested along concurrently under the same climatic condition.

2. EXPERIMENTAL PROCEDURES

The experimental procedure presented is for the improved inclined solar water desalination (IISWD) systems, and a control system as ISWD. These systems all investigated the influence of design (certain inclusions) on the daily fresh water production. The experimental set up of the IISWD’s and ISWD will be discussed in this chapter. In order to measure the performance of the systems external apparatus were used for data retrieval. Each system has a number of constituents’ component that makes it differ from the other. In all the experimental, to measure effectively the effect of design or some major inclusion a control system was tested concurrently along the new designs. In the case of an improved ISWD the design by [5] was used as control system and was tested alongside the new design. The use of jets to spray water evenly on the absorber plate was to improve the first version of the IWSD system by Aybar et al. (2005) [7].

In order to investigate the effect of design and certain material inclusion in the IISWD three types of set up were used:

1. Improved Inclined Solar Water Desalination with bare absorber plate (IISWD)
2. Improved Inclined Solar Water Desalination with wick on absorber plate (IISWDW)
3. Improved Inclined Solar Water Desalination with wire mesh on absorber plate (IISWDWM)

The schematic of ISWD, IISWD, IISWDW and IISWDWM are shown in Figure 2a,b,c- Figure 3 respectively.

3. Inclined Solar Water Desalination Efficiency

The instantaneous efficiency (\(\eta_i\)) of improved inclined solar water desalination is defined as the ratio of the energy used for water production to the total solar radiation rate given by[8,9,10]:

\[
\eta_i = \frac{Q_{es}}{H_A} 
\]  

(1,2)
\[ Q_{ev} M_{ev} L \times 3600 = 1 \]

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 IISWD surface (W/m \(^2\)). IISWD daily efficiency, \( \eta_{di} \), 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 [12,13,14]:

\[
\eta_{di} = \frac{\int_{0}^{t} m_{ev} L dt}{3600 A_b \int_{0}^{t} H dt}
\]

Where \( t \) is the time.

4. Effect of Solar radiation and ambient Temperature on IISWD system

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 [5]. The weather conditions were not perfect for all the days, there were days with cloudy skies which resulted into huge solar radiation fluctuations. High wind speeds days and days with fluctuating ambient temperature were neglected in this research work. The temperatures of the systems constituents increase with the time of day when the solar radiation 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 temperatures achieved by the absorber plate, cavity air temperature, glass cover temperature and ambient temperature occurred around 1:00 pm in summer and shifter backward to around 12 noon in winter seasons. In each testing of the IISWD, IISWDW and IISWDWM set-ups a parallel ISWD design by Aybar et al (2005) was tested as a control system. it will be observed that the hourly solar radiations are consisten over the period of the experiment. Figure 6 shows the ambient temperature against the local time of the day.

5. System Temperature Distributions

The introduction of spray jets has significant effect on the daily production of an IISWD unit as tested in this work. The limitation of unevenly feed water distribution in the work of Aybar et al. (2005) [5] was overcome as the spray jets introduction increases the daily potable water production by 114.38% when compared to 2.995 kg/m2 day by Aybar et al. (2005)[6,15,16]. One major setback in this experiment was that the exit water have to be collected over a period of an hour before it is re-injected into the inlet feed system.
thereby losing some heat energy (3 to 5°C) to the surrounding. 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. The absorber plate temperature, cavity air temperature, glass surface temperature for the IISWD, IISWDW and IISWDWM systems are shown in comparison with the ISWD in Figures 8,10. Figures 8 a&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 minutes interval. Figure 12 shows the hourly inlet and outlet temperature for typical day for ISWDW and ISWD and shows the same for IISWD and ISWD. Figure 13,15 shows the effect of number of spray jets on the daily distilled water production of ISWDW. Figure 16 shows the hourly production of distilled water from the ISWD. Figure 17 shows the comparison between the hourly daily productions of all the systems.

6. Discussion of Experimental Result

Theoretically, it is expected that for a clear day solar radiation graph should follow the curses as shown in Figure 4,5. At an inclined angle of 30° the maximum solar radiation is collected over the 1m² 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 1000w/m² while the maximum ambient temperature recorded was around 38°C (see Figure 6,7). The solar radiation and ambient temperature factors are necessary for a high yield of distilled water. As 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 Figures 4,5 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. In Figure 8 a&b, the temperature distribution of IISWDW and ISWD was shown. In Figure 8a the early hours of the experiment shows a close temperature result for the cavity air temperature and the cover glass temperature. This can explained 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 profile of the two systems in Figure 8a&b one can see that the IISWDW have higher temperature profiles intern of cavity air and the
absorber plate temperature. Figure 9 show similar temperature with Figure 8. In Figure 10 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 inclusion 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 condensation. 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 Figure 11 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. Since, the work is more interested in distilled water production; the hot water derived from the system was used to increase the temperature of the feed water. The daily productions of the systems with variation in spray jets were shown in Figure 13,16. In Figure 13, the IISWDW with 2 spray jets, 4 spray and 6 sprays jets produced the 6.41kg/m²/day, 4.55kg/m²/day and 3.33kg/m²/day respectively. IISWDW with 2 spray jets performed the best. In Figure 14 IISWDWM with 2,4,6 productions are 3.03 kg/m² day, 2.07 kg/m²/day and 1.80 kg/m²/day respectively. Figure 15 gives 5.46 kg/m²/day, 4.36 kg/m²/day and 3.35 kg/m²/day respectively. The control system ISWD gives 3.25 kg/m²/day as the maximum daily production. Figure 17 compares all the systems together. Figure 18 show that the IISWDW performed better than the ISWD system.

7. CONCLUSION

This research work presents experimental results of four (4) different configurations of inclined solar water desalination system.

1. ISWD
2. IISWD
3. IISWDW
4. IISWDWM

The improved designs was tested with bare absorber plate, wick on absorber plate and wire mesh on absorber plate. Also the different spray jets arrangement was tested on the designs for optimum performance. The effect of spray jets on inclined solar water desalination was investigated while running the Aybar et al designs at the control system. The results obtained shows that solar radiation, wick material and the jets variation are the main factors that influences the system. The daily production of the ISWD system is given as 3.25 kg/m² and with daily efficiency of 40.1% while the daily production of IISWD System is
given as 5.46 with daily efficiency of 48.3%. The IISWDW system performed the best with 6.41 kg/m$^2$/day with 50.3% efficiency. The IISWDWM performed the worse with 3.03 kg/m$^2$/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 2 spray jet is the most economically viable among all the system while the IISWDW with 6 spray jets was the most expensive. The pump used in the IISWDS, IISWDW and IISWDWM for powering the spray jets is of 33W per hour pump, and with the pump works for 4 minutes in one hour. The electricity consumption in this system is high negligible compare to the effect on the system performance.

REFERENCES


Appendix

Figure Caption

Figure 1 Thermal and Membrane Desalination Processes
Figure 2a. Schematic Diagram of the Inclined Solar Water Desalination System (ISWD)

Figure 2b. Schematic Diagram of Improved Incline Solar Water Desalination System
Figure 2c. Schematic Diagram of Improved Incline Solar Water Desalination System with Wick (IISWDW)

Figure 3. Schematic Diagram of the Improved Inclined Solar Water Desalination System with Wire Mesh (IISWDWM)
Figure 4. Hourly variation of Solar Intensity versus Local Time in Summer Season
for (a) IISWDW with 2 spray jets (b) ISWD (control system)
Figure 5. Hourly variation of Solar Intensity versus Local Time in Summer Season

for (a) IISWD and (b) ISWD
Figure 6. Ambient Temperature versus Local Time of the Day(s) for (a) IISWDW with 2 spray jets for (b) ISWD
Figure 7. Ambient Temperature versus Local Time of the Day(s) for (a) IISWD and (b) ISWD
Figure 8. A typical Temperature distribution of (a) IIISWDW and (b) ISWD
Figure 9. A typical Temperature distribution of (a) IISWD and (b) ISWD
Figure 10. A typical Temperature distribution of (a) IISWDWM and (b) ISWD
Figure 11. Inlet and outlet temperature for (a) the IISWDW and (b) ISWD
Figure 12. Water inlet Temperature and Water Exit Temperature for the IISWD

Figure 13. Effects of number of spray Nozzles on Production rate of IISWDW
Figure 14. Effects of number of spray Nozzles on Production rate of IISWDWM

Figure 15. Effects of number of spray Nozzles on Production rate of IISWD
Figure 16. Daily Production rate for ISWD

Figure 17. Daily Production of all the systems
Figure 18. Comparison of Daily production between IISWDW and ISWD