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Using TRNSYS Simulation to Optimize the Design of a Solar Water Distillation System

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Abstract

We present the modeling, TRNSYS simulation, and parametric analysis of a solar water distillation system based on a humidification-dehumidification cycle. The thermal processes that constitute the cycle are carried out in devices designed for maximum individual efficiency. In order to achieve this, it is necessary for the evaporative process (in which an air current is humidified) to happen at the highest temperature attainable without boiling. This maximizes the amount of vapor that can be carried by the air current. This process is performed in a vertical packed column, where a stream of hot water falls as a current of hot air ascends in countercurrent and directly contacts the water. The air at the exit of the tower is saturated with vapor at the same temperature as the entering water, thus maximizing the amount of moisture carried. The hot and humid air then passes through a condenser that releases heat to the atmosphere, bringing air to nearly ambient temperature and maximizing distillate condensation. In order to achieve the previous, it is necessary for the thermal capture and storage system to work with thermal oil, an insulated storage tank, and evacuated-tube solar collectors. The system must maintain a steady oil temperature of 110°C. We propose a condenser based on heat pipes and with excess heat transfer area for dumping heat to the atmosphere, in order for the condensation temperature to be as close as possible to atmospheric. The efficiency of the distiller is substantially increased by forcing the process to occur between the described temperature limits, not unlike what happens in the power cycles of heat engines. The thermal oil transfers energy to the air and water currents through two heat exchangers, and the insulated storage tank makes it possible to operate the system at night for as long as sufficiently hot oil is still available. A flow control system regulates the temperature reached by the water that flows to the evaporation tower.

We used the simulation platform TRNSYS to model this system, including the evaporation tower and condenser. Using the climatic conditions of the city of Chihuahua, Mexico, we performed a parametric study of the system and determined the effect of varying the number of solar collectors, volume of the thermal tank, and flow rate of water. We simulated the behavior of the system over a year of continued operation, measuring the amount of condensate produced during that period. The objective of this analysis was to determine the variation of distillate production, in kilograms of water distilled per year per square meter of solar collector, and per cubic meter of thermal tank. This was used to determine the optimal characteristics of the proposed distillation system.

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1. Introduction

Water is an essential element for all life forms. In order to be consumed by people, however, it must be treated to eliminate substances and organisms that could be harmful to human health [1]. The process of water purification requires an energy source to separate contaminants from water, and a system that can efficiently use this energy. Distillation is a highly effective method for purification, given that when water changes from liquid to gaseous state it leaves all impurities in the liquid phase [2]. However, it is important to note that distillation requires a great amount of thermal energy to evaporate the water.

At the present time, most thermal energy worldwide is obtained burning fossil fuels. However, these are limited resources, and its use also contributes to local air pollution and global climate change. A sustainable alternative is the use of renewable resources like solar energy, which conveniently is most available in the places that are in greatest need of drinking water [3], [4].

Perhaps the most common method for solar distillation is the simple solar still, which is an application of the solar humidification-dehumidification (HDH) method. HDH uses air to allow the evaporation of water out of a saltwater source at temperatures below the boiling point, and then condenses this moisture out of the air, onto a colder surface. Solar stills are characterized by performing the entire HDH cycle in a single enclosed space, which is a relatively inexpensive design for small systems but becomes very expensive for large ones [5]. Solar stills are made very inefficient by their defining feature, that condensation and evaporation occur in the same enclosed space. Evaporation and condensation occur at temperatures that are very close to each other, and therefore the amount of moisture transported in the air is very low. Since the amount of air moving inside the still is also small, the overall efficiency is very low.

An alternative HDH configuration separates the evaporation and condensation processes, optimizing the working conditions for each. The achieved productivity is significantly larger than that of solar stills working under the same conditions [6]. These systems can produce as much as five times more water than a solar still receiving the same amount of solar energy [7]. Thus, HDH can be an environmentally sound, technically and economically feasible water purification method when the system is properly designed [2].

The objective of this work is to use numerical simulation in TRNSYS to design a more efficient solar water distillation system based on the HDH method.

1.1. Justification

"Integral" solar distillation systems are those in which two or more different thermodynamic processes occur in a single physical component of the system. Any design modification introduced to this component will simultaneously affect two or more processes, hopefully benefitting one but possibly damaging the others. This design causes the efficiency of each process to be lower than what could be reached if it happened in a device specifically designed for it, and makes the system inherently difficult to improve. Solar stills have been proven to have low distillation efficiency, and are limited to small capacities due to their steep scaling costs [5].

Escobedo-Bretado (2010) analyzed the behavior of a distillation system fitted with an evaporation tower, in which each thermodynamic process occurred in a component designed specifically for it. They determined that the most important variable to achieve high operation efficiency is the temperature of the water flow entering the column. This is because the air exiting the column will match the temperature of

the feed water, and the capacity of said air to carry moisture depends exponentially on its temperature. Higher feed water—and thus process air—temperatures lead to a dramatically higher rate of water transport to the condenser (Fig. 1). We present the result of modifying the design by Escobedo-Bretado (2010) to control the temperature of the water feed to the evaporation column and thus maximize distillate production.



Fig. 1. Air-water vapor saturation curve as a function of temperature.

2. Methods

2.1. Description of the System

The proposed design consists of a field of evacuated-tube solar collectors, a thermal oil storage tank, two heat exchangers for heating water and air, a direct-contact evaporation column, and a condenser (Fig. 2).

In this design, thermal oil is heated in the field of solar collectors, stored in the thermal tank, and then used in the heat exchangers to heat the water and air currents entering the evaporation column. In the simulation, we use a flow controller to maintain the temperature of the water entering the evaporation column at 90°C. The column works as a counter-flow direct-contact heat and mass exchanger, with hot water entering the top of the column and hot air entering the bottom. A flow of hot and saturated air leaves the column and is directed to a condenser, from which distillate is obtained.



Fig. 2. Distillation System.

2.2. Parametric Analysis

We performed a parametric analysis, considering systems with different numbers of solar collectors, different thermal storage volumes, and different feed water flows. We modeled this system in the software platform TRNSYS, analyzing each design variation during a continuous simulated year of operation at 15-minute intervals. The climatic conditions used in this study correspond to the city of Chihuahua, Mexico. The variable we sought to optimize was annual distillate production per unit area of solar collection, kg/(m² year). Table 1 shows the analyzed parameters and their ranges of variation. The number of studied design configurations results directly from the number of possible combinations of the considered parameters. From these results we determined the optimal solar water distillation system.

Table1. Analyzed Parameters.

Number of collectors	2, 4, 6, 8, 10 and 12
Thermal storage volume (m ³)	1, 2, 3, 4, 5 and 6
Feed-water flow rate to the evaporator (kg/h)	From 1 to 220

3. Results

The simulation model of the distillation system was implemented in TRNSYS, as shown in Figure 3, in which the equipment used and all their interconnections are depicted.



Fig. 3. TRNSYS diagram of the distillation system.

From the simulation results, it is possible to observe that the most important parameters in the distillation system are the type of solar collectors, volume of thermal storage, and flow rates of air and water. Figure 4 shows the effect that solar radiation availability has over the temperature of thermal oil flowing out of solar collectors.



Fig.4. Solar radiation and temperature of the oil in the collectors.

Our main goal in the proposed system was to maintain the temperature of the water flowing into the evaporation column constant at 90°C for as long as possible. Figure 5 shows that even when oil temperature fluctuates continuously, a constant water flow temperature can be obtained by controlling its flow rate in the heat exchanger. (The same result could either be achieved by controlling the flow rate of hot oil). By using evacuated-tube solar collectors, oil temperatures up to 180°C can be obtained, and the

required oil-water temperature gradient is therefore always present. If enough hot oil storage volume is provided, the system may run continuously 24/7, year around, maximizing distillate production for a given system size.

The main characteristics of our proposed system are:

- Evacuated-tube solar collectors operating with thermal oil (or other solar collector technologies capable of maintaining similar process temperatures).
- Insulated storage for the thermal oil.
- Inlet water flow temperature controlled at 90°C (basically just shy of boiling).
- Year around continuous operation.

TRNSYS simulation shows that this combination leads to the optimum thermodynamic design. The true optimum can then be found by including economic factors in the analysis.



Fig. 5. Temperature of the thermal oil and the heated water, as well as the feed rate of water to evaporation tower.

For a given system size (number of solar collectors, thermal storage volume), distillate production rate strongly depends on inlet water flow temperature, as shown in Figure 6. Small temperature drops below the controlled value translate to relatively large drops in distillate production. This is consequence of air's specific humidity behavior, as shown in Figure 1. Therefore, annual cumulative production is very sensitive to the system's ability to continuously maintain water flow temperature as high as possible.



Fig. 6. Distillate production and temperatures of the oil and feed water.

Figure 7 shows the results of a parametric analysis. The annual accumulated distillate production depends both on the amount of energy collected, which is proportional to the number of solar collectors used, and on the available hot oil temperature. By using only 2 solar collectors, the maximum distillate production is reached having a 1 m³ thermal storage volume. An increase in storage volume results in smaller annual distillate production, since the thermal oil temperature decreases. By using more solar collectors, the distillate production first increases with storage until a maximum is reached, then decreases. With 12 collectors its maximum production is achieved when the storage volume is 5 m³. This indicates that there is an optimum combination of solar collection area for a given thermal storage volume.



Fig. 7. Annual distillate production.

Distillation efficiency can be obtained by dividing the annual distillate production by the solar collection area used. Figure 8 shows that the maximum efficiency is attained with the smallest system simulated, 2 collectors and 1 m³ of storage volume. Almost equivalent values of the maximum efficiency $(2,800 \text{ kg}/\text{m}^2 \text{ year})$ were obtained with larger systems, but at different combinations of storage volume and collector number. This behavior indicates that the maximum thermodynamic efficiency of the system,

at the simulated conditions, was reached at the various combinations of storage volume and collection area. The constant lesson from these observations is that lowering the water inlet flow temperature dramatically reduces system efficiency.

For a given system size, there is an optimum feed water flow rate. Figure 8 shows that for a given thermal storage volume and number of solar collectors, the maximum rate of distillate production is achieved with certain feed water flow rate. The graph shows that system performance strongly depends on the proper dimensioning of the main design parameters. For a fixed storage tank volume and number of solar collectors, if the optimum feed water flow rate is exceeded, operational temperature is reduced and distillate production is also reduced. For a thermal storage volume of 6 m³, for instance, the optimum combination is 70 kg/h feed water flow rate and 12 solar collectors.



Fig. 8. Annual distillate production per square meter of solar collection.

Figure 9 shows the cumulative distillate production for one year of operation. Figure 10 shows the cumulative distillate production divided by solar collector area. The former graph shows that for a given thermal storage volume there is an optimum combination of collector number and feed water flow rate that yields the maximum rate of distillate production. For 6 m^3 of thermal storage, 12 collectors and 70 kg/h of feed water flow rate produce 2,770 kg/m² year of distillate.



Fig. 9. Annual distillate production for a thermal storage volume of 6 m³.



Fig. 10. Annual distillate production per square meter for a thermal storage volume of 6 m³.

Figure 10 shows that there is a thermodynamic, or capacity, limit to distillate production per unit area of solar collector. For a given climate and feed water temperature (90°C, in this work), that limit will be a constant value achievable with a certain combination of thermal storage volume, number of solar collectors and feed water flow rate, and that limiter is around 2,800 kg/m² year. This can be observed on Table 2, where the optimized results of several system sizes are presented. The results correspond to year-long simulated operation of different-size systems. Parameters were varied with finite steeps, so not all possible results were obtained (solar collectors are integer numbers, thermal storage volume was varied in 1 m³ increments, etc.).

Our simulation results show theoretical distillation efficiencies much higher than any other reported in the literature. We attribute this to the high and sustained operational temperature we selected for the system.

Solar Collectors	Thermal Tank Volume (m ³)	Water Flow Rate (kg/h)	Distillate Production (kg/m ² .year)	Annual Water Production (kg/year)
2	1	15	2 932	11 731
4	2	25	2814	22 513
6	3	40	2 826	33 915
8	4	50	2 818	45 095
10	5, 6	60	2 793	55 862
12	5, 6	70	2 762	66 310

Table 2. Parameter combinations for several optimally efficient solar distillation systems.

4. Conclusions

Dynamic simulation is a very useful analysis and design tool to understand the behavior of solar desalination systems. The intrinsic variability (temporal, seasonal, geographic) of the driving variables, such as solar radiation and ambient temperature, forces the use of specialized computer simulation tools like TRNSYS. Dynamic simulation and parametric analysis makes it possible to both design functional systems and optimize the design.

We observed that a high feed water temperature was the most important factor for obtaining higher rates of distillate production. Near-boiling water feed to the distillation column and a condensation temperature as close as possible to ambient maximize the net humidity transported per mass unit of air circulating in the HDH system. Evacuated tube solar collectors can maintain thermal oil temperatures above 180°C, making it possible to keep feed water close to 90°C and maximizing distillate production.

References

[1] Bouchekima B., (2003). A small solar desalination plant for the production of drinking water in remote arid areas of southern Algeria. Desalination, v.159, n.2, pp.197-204.

[2] Bermudez C., Thomson M., Infield D., (2008). Renewable energy powered desalination in Baja California Sur, Mexico. Desalination, v.220, n.1-3, pp.431-440.

[3] Jiang H., (2010). Promotional policy for renewable energy development in Taiwan, Renewable and Sustainable Energy Reviews, v.14, n.3, pp.1079-1087.

[4] Peidong Z., Yanli Y., Jin S., Yonghung Z., Lisheng W., Xinrong L., (2009). Opportunities and challenges for renewable energy policy in China. Renewable and Sustainable Energy Reviews, v.13, pp.439–449.

[5] Thomas, K.E. (1997). Overview of village scale, renewable energy powered desalination. National Renewable Energy Technical Report NREL/TP-440-22083. UC Category: 1210. DE97000240.

[6] Orfi J., Laplante M., Marmouch H., Galanis N., Benhamou B., Nasrallah S. and Nguyen C.,

Experimental and theoretical study of a humidification– dehumidification water desalination system using solar energy, Desalination, 168 (2004) 151–159.

[7] Amara M., Houcine I., Guizani A. and Mfialej M., Experimental study of a multiple-effect humidification solar desalination technique, Desalination, 170 (2004) 209–221.

[8] Escobedo-Bretado, J.A. (2010). Desalinización solar de agua por humidificación-dehumidificación de aire simulado en TRNSYS. Tesis de Maestría. Centro de Investigación en Materiales Avanzados, S.C.