USING TRNSYS SIMULATION TO OPTIMIZE THE DESIGN OF A SOLAR WATER DISTILLATION SYSTEM

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1. 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 tower, 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 nearly to 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 surface 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 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.

The described system was modeled in the simulation platform TRNSYS, which incorporated modeling of 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.

2. INTRODUCTION

Water is an essential element for all life forms. In order to be consumed by people, however, it must be treated to eliminate particles and organisms that could be harmful to human health [Bouchekima, 2003]. 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 transitions from liquid to gaseous state it leaves all impurities in the liquid phase [Bermudez, et al., 2008]. However, it is important to note that distillation depends on the great amount of thermal energy required to evaporate water.

At present, most thermal energy worldwide is obtained from burning fossil fuels. These are limited resources, however, the use of which 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 [Jiang, 2010; Peidong, *et al.*, 2009].

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 evaporate significant quantities of water vapor out of a saltwater source, and then condenses this moisture out of the air and onto a colder surface. Stills are characterized by performing the entire HDH method in a single enclosed space, which is a relatively inexpensive design for small systems but becomes very expensive for large ones [Thomas, 1997]. Stills are made very inefficient by their defining feature. Given that condensation and evaporation happen in the same enclosed space, they also happen at temperatures that are very close to each other, which results in a system efficiency far removed from the theoretical and practical maxima.

An alternative HDH configuration separates the evaporation and condensation processes, optimizing the conditions for each. The productivity of these HDH systems is significantly greater than that of solar stills working under the same conditions [Orfi, *et al*., 2004]. They can produce as much as five times more water than a solar still receiving the same amount of energy [Amara, *et al*., 2004].Thus, HDH can be an environmentally sound, technically and economically feasible water purification method, but only if the system performing it is adequately designed [Bermudez, *et al*., 2008].

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.

2.1 Justification

There exist "integral" solar distillation systems, 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 another. 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. Still distillers have been proven to have low distillation efficiency, and are limited to small capacities due to their steep cost scaling (Thomas, 1997).

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 detected that the most important variable to achieve a high operation efficiency is the temperature of the water flow entering the tower. This is due to the fact that 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 (Figure 1). The present work reports the results obtained by modifying the design by Escobedo-Bretado (2010) to control the temperature of the water feed to the evaporation tower and thus maximize distillate production.

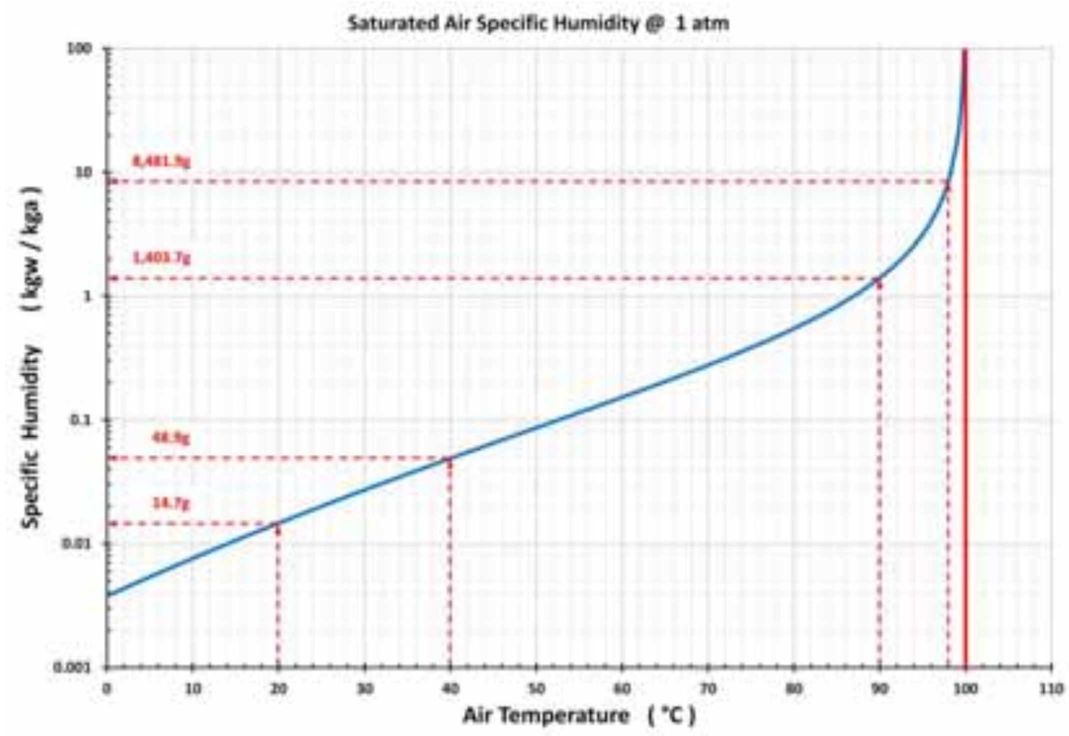

Figure 1. Air saturation curve as a function of temperature

3. METHODS

3.1 Description of the system

The proposed design consists of a field of vacuum-tube solar collectors, a thermal oil storage tank, two heat exchangers for heating water and air, a direct-contact evaporation column, and a condenser (Figure 2). In this design, thermal oil is heated in the collector field, stored in the thermal tank, and then used in the heat exchangers to heat the water and air currents entering the evaporation tower. We use a flow controller to maintain at 90°C the temperature of the water entering the evaporation column. The tower works at counter-flow, with hot water entering the top of the column and hot air entering the bottom. A flow of hot, saturated air leaves the tower and is directed to a condenser, from which distillate is obtained.

3.2 Parametric analysis

We performed a parametric analysis, considering systems with different numbers of solar collectors, different thermal storage volumes, and different water feed 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/(year · m^2). 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.

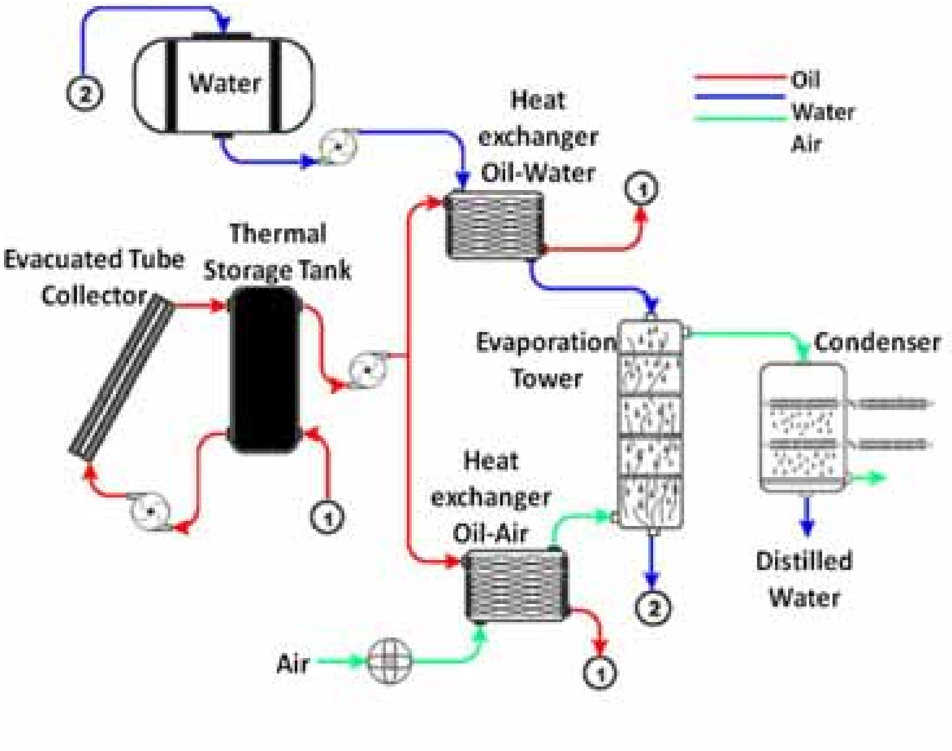

Figure 2. Distillation system.

Table 1. 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

4. RESULTS

The TRNSYS implementation of this system is shown in Figure 3, including the equipment and all its connections. The figure also shows and differentiates between the subsystems for distillation and heat storage.

Our results confirm that vacuum-tube solar collectors are capable of producing the thermal oil temperatures necessary to continuously maintain the feed-water to the column at the desired 90°C. Figure 4 shows the cyclic variation of the oil temperature in the thermal storage tank. This temperature variation is due to a combination of a) the cyclic variation in solar radiation reaching the collectors, and b) the controlled variation of the water-flow, needed to keep stable air and water temperatures in the heat exchangers.

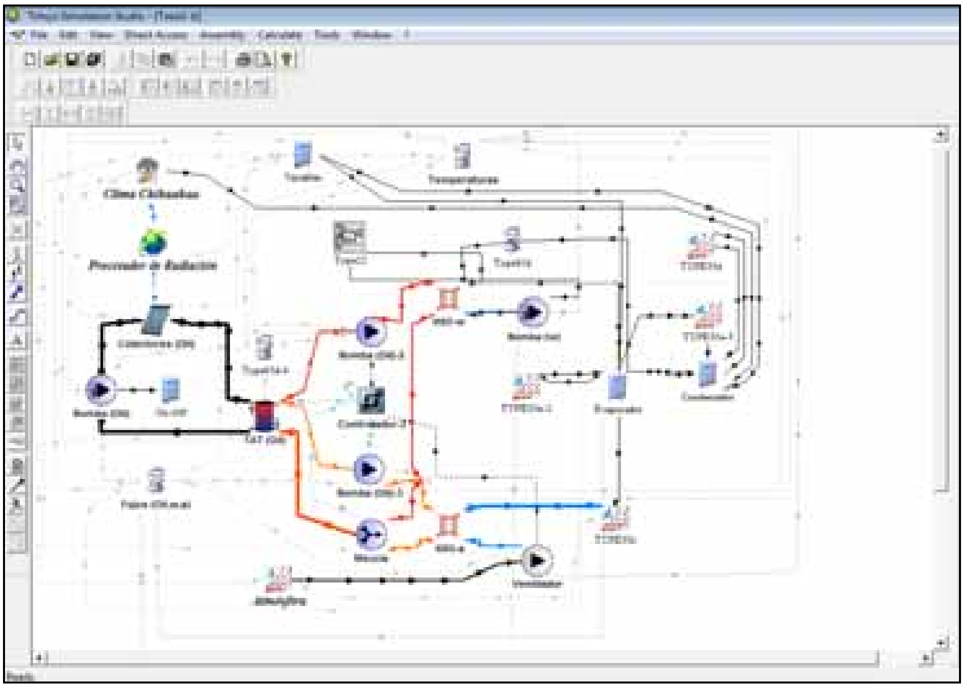

Figure 3. TRNSYS diagram of the desalination system

The amount of water fed to the heat exchanger is varied by the control system, such that its exit temperature (the feed to the column) is always 90°C. Since the oil temperature in the storage tank varies during the day, so does the flow of feed water. This is shown in Figure 4.

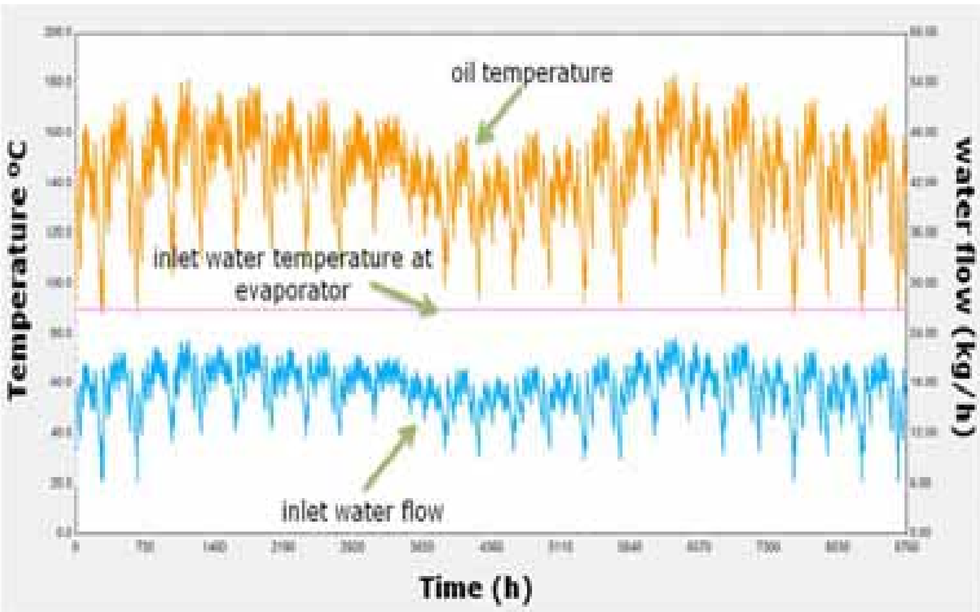

Figure 4. Temperature of the thermal oil and the heated water, as well as the feed rate of water to the evaporation tower.

The temperature reached by the water in the heat exchanger is so closely controlled because it has an enormous effect on the system's distillate production capacity. This temperature, and not the amount of total solar energy gathered by the system, is the governing variable. Therefore, keeping the water entering the tower as close as possible to the boiling point produces the highest distillation rate (Figure 5).

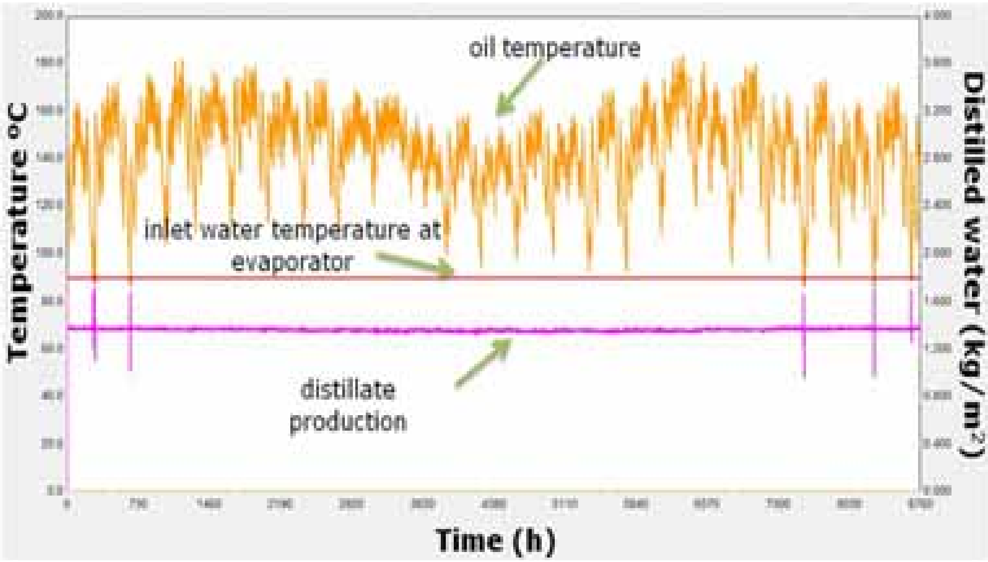

Figure 5. Distillate production and temperatures of the oil and feed water.

Despite the importance of feed-water temperature, annual distillate production is still dependent on the total amount of collected solar energy. This collection occurs during the day, but the evaporation subsystem works as long as the thermal storage system still has available heat. With favorable weather conditions, sufficient heat can be available 24 hours a day. Figure 6 shows how distillate production increases substantially with a greater thermal storage volume and number of collectors. This figure also shows how, for a small number of collectors (2, 4, and 6), increasing the thermal storage volume in fact decreases distillate production. This happens because a greater thermal storage volume requires more energy to maintain its temperature, and few collectors may not be enough to provide it.

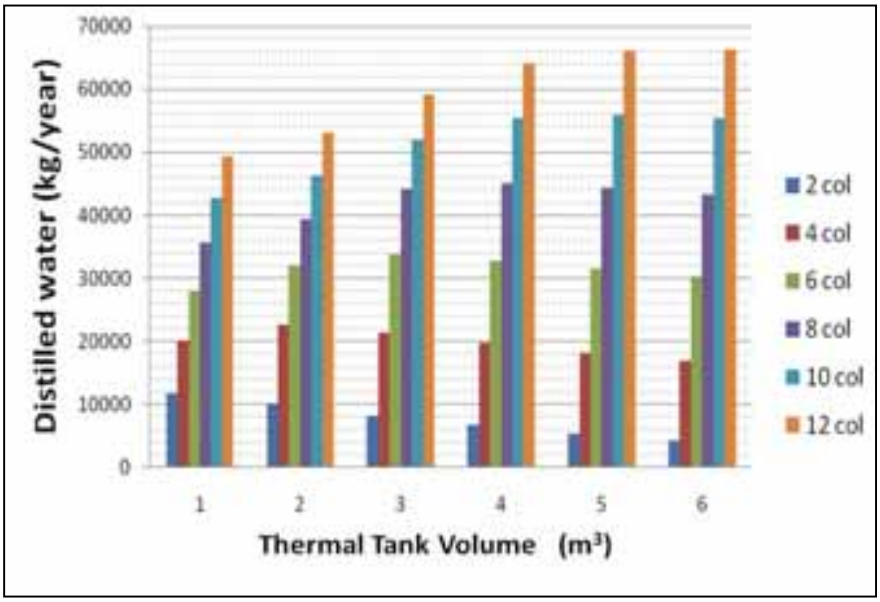

Figure 6. Annual distillate production

Distillation efficiency is defined as the amount of distillate produced per square meter of solar collector. Figure 7 shows how a given thermal storage volume corresponds to an optimal number of solar collectors. As the former increases, so does the latter. For example, a volume of 6 m^3 corresponds to an optimal number of collectors between 10 and 12. An important thing to note is that *maximum* distillate production, per m^2, is similar for any combination of thermal storage volume and number of collectors. Volumes of 3, 4, and 5 m^3 have optimal collector counts of 6, 8, and 10, respectively, but the annual distillate production in all cases is still 2,800 kg/(year·m^2). Which of these combinations to use depends on which represents the best economic option.

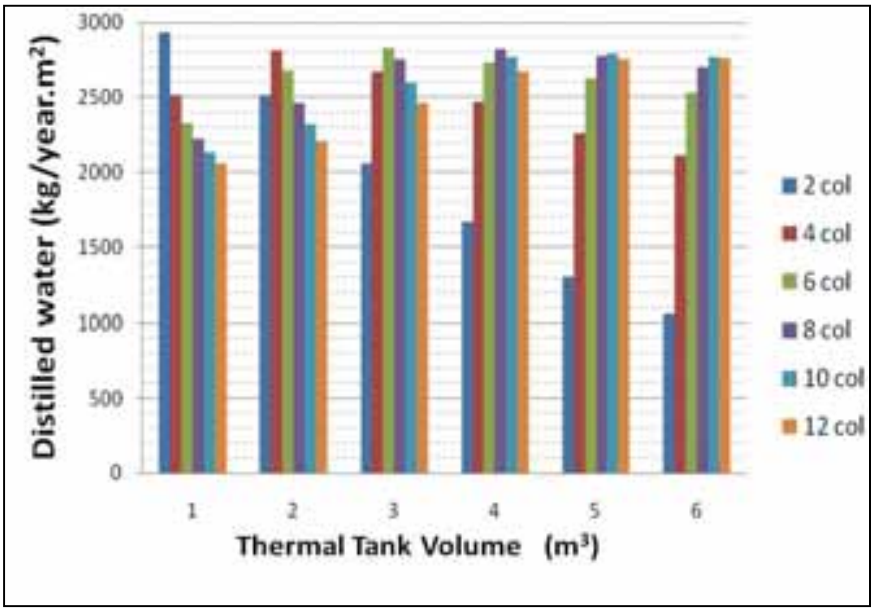

Figure 7. Annual distillate production per square meter of solar collection

Another factor that influences distillate production is the amount of water fed to the evaporation tower. One might think that feeding more water to the evaporation tower would result in more distillate, but this is not the case. Figure 8 shows that a given number of collectors corresponds to an optimal feed water flow, as marked by the maxima in the graph. Too much water in the system will cause its temperature to drop, along with its distillate production. For a storage volume of 6 m^3, for example, the optimal combination is 70 kg/h of feed-water and 12 solar collectors. A greater flow results in a significantly lower distillate production.

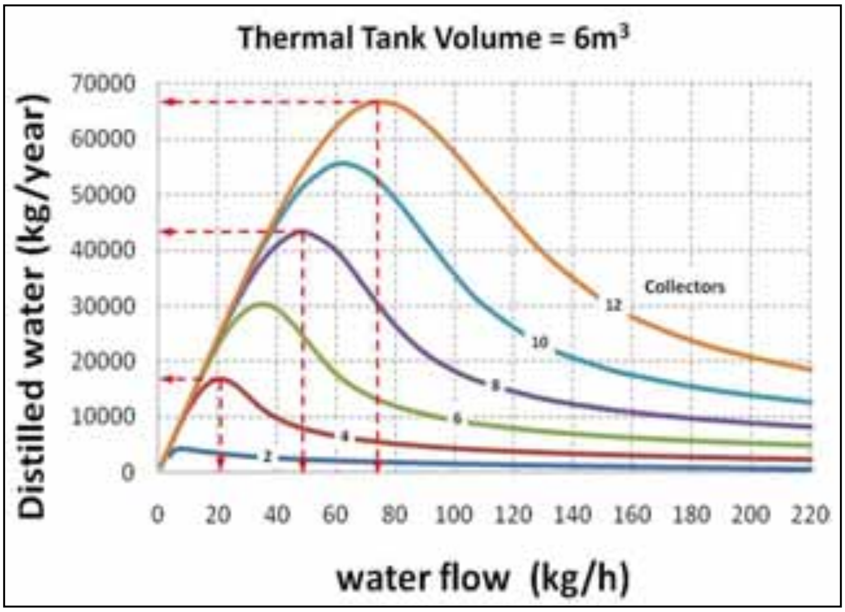

Figure 8. Annual distillate production for a thermal storage volume of 6 cubic meters

In order to obtain large volumes of distilled water, it is necessary for the system to be properly dimensioned. Small systems will use few collectors have small storage volumes, and produce little distillate. The only way to efficiently increase that production is to scale the entire system. Figure 9 shows the effect of using different numbers of solar collectors for a given storage volume. As the number of collectors increases, distillate production maxima occur at higher flow-rates and maximum distillate production plateaus. For 6 m^3 of storage volume and 10 collectors, for example, the optimal water feed is 60 kg/h and distillate production is 2,770 kg/m^2.

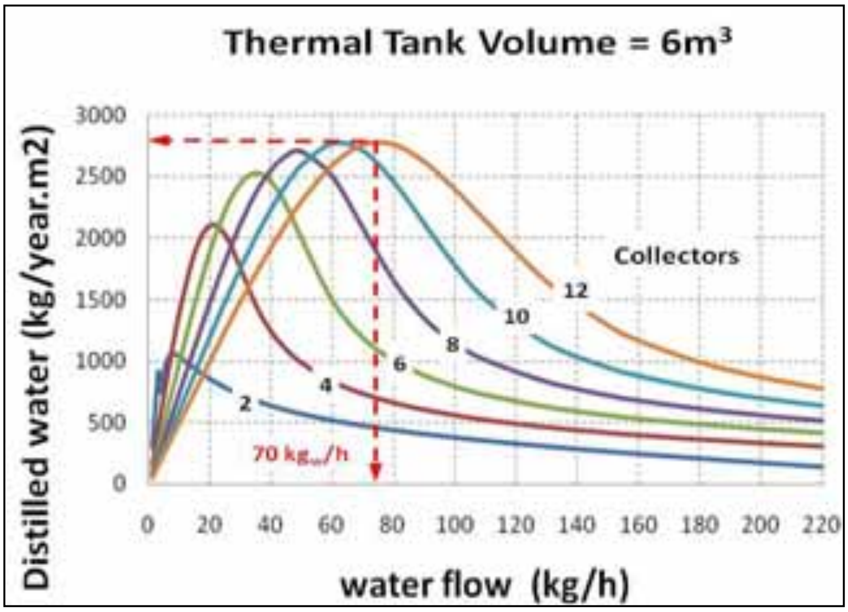

Figure 9. Annual distillate production per square meter for a thermal storage volume of 6 cubic meters.

These results show that the simulation tool presented here makes it possible to dimension and optimize solar distillation systems with a higher theoretical efficiency than any reported in literature until now. Table 2 shows several combinations of optimal parameters for such distillation systems.

Table 2. Parameter combinations for several optimally efficient distillation systems

Solar collectors	Thermal tank volume (m^3)	Water flow rate (kg / h)	Distillate production (kg_w / m^2 year)	Annual water production (kg_w / year)
2	1	15	2,932	11,731
4	2	25	2,814	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

5. CONCLUSIONS

A solar desalination system can be thoroughly studied through simulation. The parameters affecting its behavior, such as ambient temperature and solar radiation, are intrinsically variable. Specialized computer simulation is the only way to follow the thermal behavior of these systems over extended periods of time.

We show that dynamic simulation can be used to determine the long-term behavior of any thermal system, and based on this knowledge it is possible to make design changes to optimize the systems' behavior. When designing thermal systems, the behavior of the working substance must be the main focus of attention. Physical components must be selected and dimensioned to permit the work substance to behave as desired, not vice versa.

Solar energy offers a promising alternative for meeting the fundamental drinking water needs of remote populations. The availability of fossil fuels or access to the electrical grid are not necessarily requisite for access to safe drinking water. With dynamic simulation, these technologies have greater potential than ever.

6. ACKNOWLEDGEMENTS

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