MODULAR SOLAR THERMAL DESALINATION SYSTEM WITH FLAT PLATE COLLECTOR

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Abstract

This research article shows the experimental results of a solar desalination system to produce potable water for drinking purposes from either sea or salty ground water. This system has two components: a flat plate solar collector, and a desalination tower with heat recovery mechanism. The flat plate solar collector can be used in either direct or indirect heating mode. In the first case, the water that runs through the collector absorber is the condensate produced in the desalination tower. This condensate flows down on sidewall to a clean water tank at the bottom of the tower. The hot water in the tank evaporates and condenses on the walls of the first stage, directly heating the salty water in this stage. In the indirect heating, solar radiation is absorbed in the collector and transferred to a thermal oil flux, which transport this heat to a mass of salty water in the desalination tower. The heat transfer takes place in a heat exchanger at the lowest level, or the first stage in the desalination tower .Two units were built and tested, one for each heating mode. The desalination tower has six stages and a water circulation system through the stages to avoid salt concentration. The results show the good system thermal performance, and that improvements can be made to reach even higher potable water production rates. The water (polluted sea water and salty well water) laboratory test results show that the desalination process eliminated the Coliform group bacteria, being appropriated for human use.

Keywords: desalination, solar, heat recovery

INTRODUCTION

The shortage of drinkable water in many areas of the world is an old, and seems to be also a future problem. To supply the needed amount of potable water is already a problem that many governments face in developing country. Additionally, some areas also have a limited supply of conventional energy, but with a great potential for solar energy.

Desalination systems that produce potable water from salty water have been studied for quite some years and the use of solar energy to produce potable water remotes to ancient Egypt. Various solar thermal systems have been presented in the literature, (Malik, 1982) and (Löf, 1961). The most studied model is the still type, which is composed of tank with a black floor and a transparent cover. Variations of the basic model, with multiple stages and tank filling material have also been presented. These desalination units have the advantage of low installation cost, but three important disadvantages: low efficiency, problems associated with the accumulation of salt at the basin, and a short lifetime.

The modular solar thermal desalination system with flat plate collector is presented in Figure 1. This unit was operated in direct heating mode, with the condensate as the working fluid. This configuration has the advantage of longer collector lifetime because only clean water runs through the absorber tubes. In direct heating, the condensate is heated up in the solar collector and flows by natural convection to a water tank at the desalination tower. At the upper surface, the water evaporates and condenses at the lower walls of the first stage, transferring its heat to the salty on the other side. The condensate drops back into the tank and is colleted outside, keeping the same level in the tank. The energy received by the salty water in the first stage is used to increase its temperature and in the evaporation process at its surface. The vapor produced condenses at the bottom walls of the next stage, releasing its latent heat to the salty water in this stage, and the heat recovery process is repeated in the next stages. The condensate flows through the sidewall of the desalination tower and drip down into the condensate tank.

The first unit was operated in indirect heating mode and the results are presented in the literature (Hannich, 2000; Lima, 2000; and Coutinho, 2003). In indirect heating, solar energy is absorbed in a flat plate collector and heats up a thermal oil flow, which moves in a closed circuit to the desalination tower. At the tower, the thermal oil flows through a heat exchanger, where it releases heat to a mass of salty water on the other side of a stainless steel wall. After loosing its heat, the thermal oil returns to the solar collector. The heat recovery process in the desalination tower is the same as in direct heating operation, except that the condensate flows through side channels to be collected outside the tower. Because of the heat recovery process, this unit can reach higher thermal performance than the conventional still type solar distiller. Thermal losses through the sidewalls are minimized due to the used of appropriate insulation material. There is a continuous water flow through the stages of the unit avoiding salt accumulation. The condensate that leaves the tower moves a mechanism that feeds salty water into the tower. Also, as the fluids circulate in natural convection, the system is self-pumping and there is no auxiliary energy source. The disadvantage is the higher installation cost when compared to the still type unit.

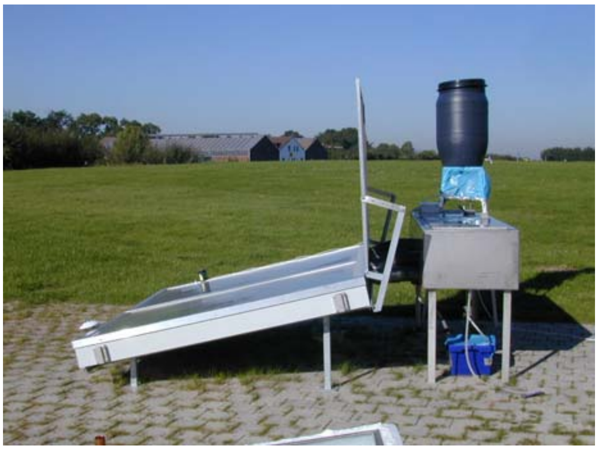

Figure 1. Photograph of the Solar Desalination Unit at the Solar-Institut Jülich in Germany.

The purpose of this work is to present the experimental results and the analytical equations for the modular solar thermal desalination system (Figure 1). Two units were tested, one at the Solar-Institut Jülich [SIJ] in Germany, and the other at the Laboratório de Energia Solar e Gás Natural [LESGN], in Brazil. Thermal measurements (temperature, solar global radiation, water mass, etc) were made as well as the contamination tests (Coliform bacteria group) before and after the desalination process.

APPROACH

To study the performance of the modular solar thermal desalination system, experimental measurements and analytical calculation have been made. The next sections present the energy balance equations, the experimental measurements made during tests, and the bacteria tests.

Energy Balance Equations

Figure 2 shows a schematic drawing of the energy transfer rates in the first stage of the desalination tower for both direct and indirect heating operation. In indirect heating, the thermal oil flow, which was heated in the solar collector, enters a heat exchanger and transfers its sensible energy to the salty water mass on the other side of the stainless steel wall. The temperature of the water mass increases and at the surface, the salty water looses heat to the above stage by evaporation, convection, and radiation. Some energy is also lost to the environment by conduction through the vertical walls and some leakage may also occur. Some sensible energy leaves the desalination tower with a salty water mass flow that circulates through the stages to avoid salt accumulation and keeps the water level in each stage constant. This sensible energy loss can, however, be recovered in another process. In direct heating, the condensate from the collector flows into the water tank at its top, and returns from the bottom.

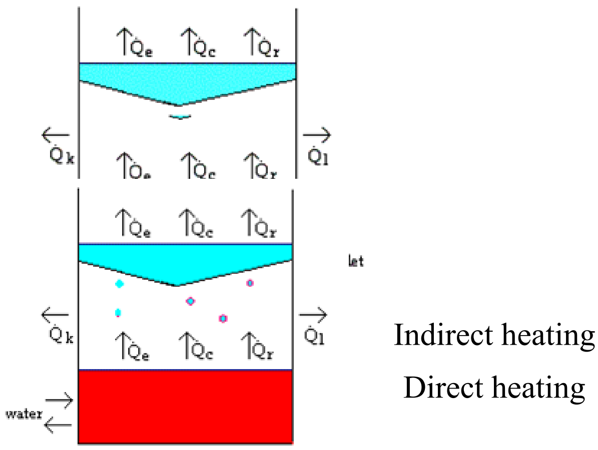

Figure 2. Directions of the energy transfer in the first stage of the desalination tower in direct and in indirect heating operation.

In indirect operation, the energy balance equation for the oil in the heat exchangers is,

$$\left(M_o\, c_{p,o}\right)\frac{dT_o}{dt} = \left(\dot{m}_o\, c_{p,o}\right)\left(T_{o,out} - T_{o,in}\right) - U\,A\left(\overline{T}_o - \overline{T}_w\right) \quad (1)$$

where M_o is the mass of thermal oil that stays in the heat-exchanger, $c_{p,o}$ is the specific heat of the thermal oil, T_o in the oil temperature, t is time, $\dot{m}_o$ is the mass rate of thermal oil through the heat-exchanger, U is the heat transfer coefficient between the oil and the salty water, A is the area, and the subscripts ′out′, ′in′, and ′w′ represent heat-exchanger outlet, inlet, and water, respectively.

For the salty water on the other side, the energy balance equations is,

$$\left(M_w\, c_{p,w}\right)\frac{dT_w}{dt} = U\,A\left(\overline{T}_o - \overline{T}_w\right) - h_e\, A\left(T_1 - T_2\right)\ldots$$

$$\ldots - h_c\, A\left(T_1 - T_2\right) - \varepsilon\,\sigma\, A\left(T_1^4 - T_2^4\right) - \lambda\, A\left(T_1 - T_\infty\right) - \dot{m}_{circ}\, c_p\left(T_1 - T_\infty\right) - \dot{Q}_{leak} \qquad (2)$$

where h_e represents the heat transfer coefficient by evaporation, h_c the heat transfer coefficient by convection, ε the emissivity from the surface of the water, λ the thermal conductivity of the insulation material, $\dot{m}_{circ}$ the rate of mass circulated through the stage, and $\dot{Q}_{leak}$ the rate of heat loss through vapor leakage. The subscripts 1 and 2 are related to the first and second stages in the tower, and ∞ to the ambient air outside the tower.

For direct operation and also for the other stages in the desalination tower, the energy balance equation has the same form as Equation (2), except that the energy that enters the stage by condensation, convection, and radiation from below, instead of convection from the thermal oil flow. In steady state conditions, the mass balance in each stage is presented in Equation (3). This balance states that the amount of water in each tray remains constant, as the amount of water that enters equals the amount that leaves,

$$\dot{m}_{w,in} = \dot{m}_{w,e} + \dot{m}_{w,circ} + \dot{m}_{w,leak}\,. \qquad (3)$$

where $\dot{m}_{w,in}$ represents the rate of water that enter the stage, $\dot{m}_{w,e}$ the rate that leaves, $\dot{m}_{w,circ}$ the rate that circulates through the stage, and $\dot{m}_{w,leak}$ the rate that leaks. The last term in Equation (3) has been experimentally measured and its value is small compared to the other terms. Numerical simulation results estimate the amount of water produced in the desalination system of Figure 1 have been presented in the literature (Schwarzer *et al.*, 2001, Müller and Schwarzer, 2002). To model the performance of the modular solar desalination system, a good knowledge of the rate of heat transfer from the water surface at each stage was necessary. Some papers with information about the convection and evaporation heat transfer coefficient for solar desalination applications have been published in the literature (Clark, 1960; Dunkle, 1961; Adhikari *et al.*, 1990; Shawaqfeh and Farid, 1995). Each of these studies seems to be appropriate for its experimental data at some temperature range, particularly in the interval from 50°C to 70°C, where the solar tank distiller operates. The experimental results for the system presented in Figure 1 show that the water temperature in the first stages can reach values greater than 90°C and therefore, a new correlation for the convection and evaporation heat transfer coefficient was developed and presented.

Experimental Measurements

Temperature measurements were made using type-K thermocouples (± 0.5°C). These measurements were made in the water in each stage. The global solar radiation flux on the tilted plane was measured with a pv-cell type sensor, which has an error of 3% when compared to a precision pyranometer. The instruments are scanned every second and the average values stored at every minute. Two flat plate collectors were used, each with 2 m^2 area, single glazing, and selective surface. For the data shown in this article, no reflectors were used to enhance the radiation on the absorber plate. The desalination tower had six stages, each with three trays. The area of each stage was 1 m^2.

RESULTS AND DISCUSSION

Figure 3 shows the experimental results (temperature in the water, global solar radiation flux, and potable water production) for the desalination unit with flat plate collector, operating in direct heating mode. The experiments were made at the SIJ-Campus, in Germany, on May 6, 2003. For the purpose of comparison, measurements were also made with a 1 m^2 still type distiller.

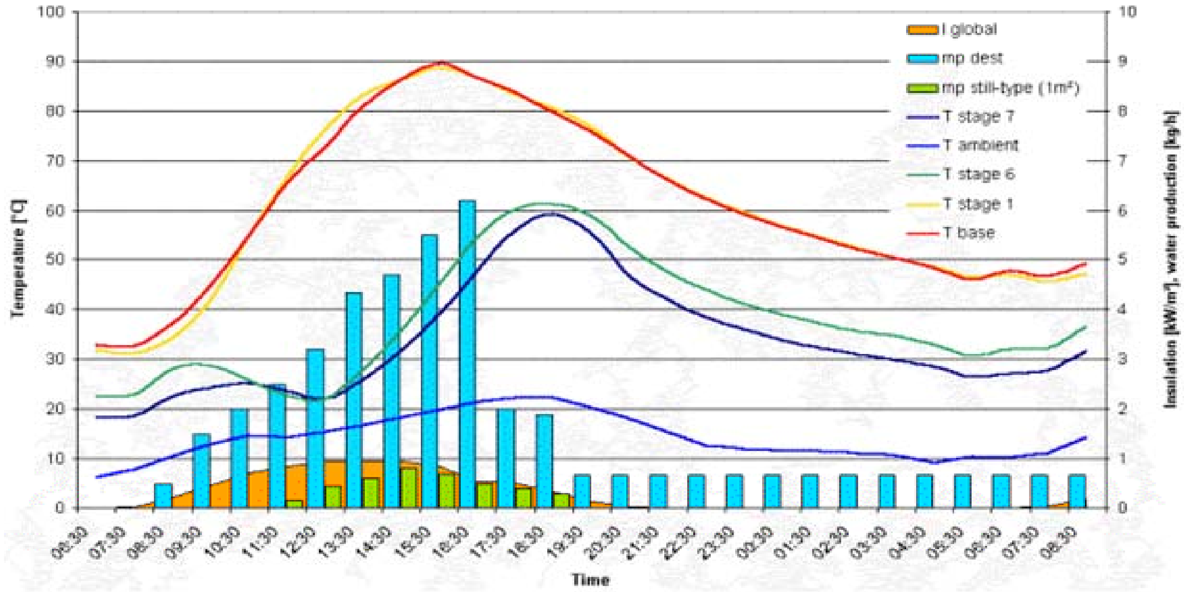

Figure 3. Temperature of the water, solar global radiation flux and amount of potable water produced in the modular solar desalination system installed at the SIJ-Campus in Germany, on May 6, 2003.

The temperature in the first stage was somewhat over 30°C at about 7:00 o'clock and by 15:30h, its value was about 90°C. The stage in the tower (stage 7) is used as a feeding tray, to bring water into the tower. The ambient temperature was above 10°C during the experiment. The total water production for a period of 24 hours (from one day to the same hour the next day) was 43 l for the solar thermal desalination unit, and 4.03 l for the still type distiller.

Table 1 shows the water tests made before and after the desalination process using the system installed at the LESGN-Campus in Brazil, on July 4, 2003. This system has a similar desalination tower to the one installed at the SIJ-Campus, and it uses a heat-exchanger to transfer the heat absorbed in the solar collector to the salty water on the first stage.

Table 1. Coliform bacteria test results before and after the desalination process.

	Polluted sea water		Well water	
Item measured	Before	After	Before	After
Total Coliform group bacteria (NMP/100ml)	311000**	*	*	*
Fecal Coliform group bacteria (NMP/100ml)	146000**	*	*	*
Salinity [ppt]	27.88	0.15	0.10	0.02

** Value greater than the scale for the method used.
* Too small to be measured.

CONCLUSION

The experimental results show the good thermal performance of the modular solar thermal desalination system with heat recovery. As presented in Fig. 3, a production of 43 L of water was measured that day. Even better results can be reached if direct radiation reflector are used with the flat plate collector. This water production represents a rate of 1.49 L/kWh.m^2 of collector area, which is a factor of 2.67 times greater than the tank type distiller in the same day. The salt concentration problem, which always takes place in most solar distellers models, has been taken care by the continous flow of water through the stages of the desalination tower.The water testes presented in Table (1), for very polluted seawater and for well water, shows that the desalination process eliminated the Total Coliform group bacteria and the Coliform group fecal bacteria to such low levels that they could not be detected by the instrument. At the present time, four models are being tested: the first uses a flat plate collector and operates in direct heating mode; the second also uses also a flat plate collector but operates in indirect heating mode, using a thermal oil as the working fluid through the tubes in the absorber plate, the third uses parabolic reflectors and operates in direct heating mode, and the forth uses evacuated tube collectors in direct heating mode. The performance of all these four models can be improved through the use of a heat storage system in the salty water or in the condensate circuit. Three systems are to be tested next year, each with five parallel modelus, to produce 750 L per day per system.

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