Thrust Area 4: Solar (Clean Drinking Water)

Low Cost Solar Driven Desalination

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Description: Water and energy scarcity poses a future threat to human activity and societal development around the world. The state of Florida is vulnerable to fresh water shortages. Florida ground water is contaminated in many locations from leaky underground tanks, agricultural pesticides, and other chemicals. Although it is possible to desalinate sea water, conventional systems are energy intensive. Solar energy utilization for desalination systems is being investigated to provide adequate fresh water for the state's needs. Solar diffusion driven desalination (DDD) system has been developed for both bulk water desalination and small community needs/disaster response. The research objective is to examine the best operating condition for the solar diffusion driven desalination (DDD) process using a computer models developed for the transient evaporation and condensation processes. The outcome of the study is the development of cost effective, low power consumption, and low maintenance desalination process that is powered by solar energy. Several operating modes for the solar DDD process have been investigated, and the best operating mode is used to design a small scale distillation unit. In addition, one of the main operational difficulties encountered in thermal distillation processes is the cooling requirement. Cooling is needed to reduce the condensing water temperature in the condenser to increase water production. In this study, the external cooling requirement has been tackled with a unique operating mode.

Budget: $252,000
Universities: UF

Progress Summary

There is significant interest to further explore solar diffusion driven desalination as a potentially low cost and low maintenance alternative to PV-RO systems. In this reporting period, the overall distillation performance of the solar DDD has been investigated under different design and operating conditions. The heat and mass transfer models developed by Alnaimat et al. [1] is used in the analysis. In this study, several operating modes for the solar DDD process have been investigated, and the best operating mode is used to design a small scale distillation unit. In addition, the solar heat input is recycled in a unique transient mode so that it does not require an external source of cooling water. A detailed analytical investigation suggests that this process can potentially produce 100 liters per day distilled water with an average specific electric energy consumption as low as 3.6 kW-hr/m^3 using a total of eight 2 m^2 solar collectors [1]. Water production and energy consumption have been investigated under various design and operating conditions. A unique operating mode has been explored to improve the water production and reduce the specific energy consumption. The study has shown that operation in the delayed mode significantly reduces the specific electric energy consumption compared with operation in the conventional mode. It is believed that the solar DDD process, with its low power consumption and low maintenance requirement is a competitive desalination technology that is well suited for small scale decentralized water production.

[1] F. Alnaimat, J.F. Klausner, R. Mei, Transient Analysis of Direct Contact Evaporation and Condensation Within Packed Beds, *Int. J. Heat Mass Transfer*, 54 (2011), pp. 3381–3393.

The solar DDD performance is primarily dependent on the solar heat input, saline and fresh water tank sizes, and evaporator and condenser inlet water temperatures and flow rates. A parametric study is conducted to examine the influence of these parameters under transient operating conditions. It is found that water production is significantly influenced by the evaporator inlet water temperature. The evaporator water temperature is strongly dependent on the solar heat input, saline water and air flow rates, initial saline water tank size and temperature, and the condenser inlet water temperature. Increasing evaporator inlet water temperature reduces the specific energy consumption.

The process flow diagram is revised to enable a unique operation mode as shown in Fig. 1. Only one saline water tank (Tank 1) is used during operation. Fig. 2 shows the variable solar power input to the system over a twelve hour period, the saline water temperature response into the evaporator, and the corresponding fresh water temperature response into the condenser. The solar thermal input to the system is based on eight solar collectors; each has an aperture area of 2 m^2 and efficiency of 0.85. The total solar thermal input into the system over twelve hours of operation is 98.6 kW-hr. As the solar heat flux decreases, the system still has capacity for desalination due to the stored heat in the system. Further desalination is accomplished by recirculating the fresh water through the heat exchanger. At the same time, ambient saline water (25 °C) is pumped through the heat exchanger and fills the empty saline water tank (Tank 2). Heat is transferred from the fresh water to the saline water which fills the idle tank. During this process, the condenser cools down, and additional fresh water is produced. As shown in Fig. 2, after 8.5 hours saline fill water is directed through the heat exchanger to the idle tank. The feed saline water temperature to the evaporator (from Tank 1) drops as the system is cooled down by the fill water flowing to the idle tank. Operating the solar DDD facility in this manner is denoted as the *standard mode* of operation. Fig. 3 shows the total fresh water production and production rate for the 12 hour period with solar heating operating in the standard mode. It is evident that the fresh water production rate increases as the system increases in temperature. Also, there is a very high initial fresh water production rate when the fill period begins, and the production rate tails off during the three and a half hour fill period.

Fig. 4 shows the electric specific energy consumption during the distillation process operating in the standard mode. Initially the fresh water production rate is low, and thus the specific energy consumption is high. For approximately an 11 hour period after the first hour of operation the specific energy consumption is below 5 kW-hr/m^3 of fresh water, which demonstrates reasonably good performance. From approximately hours 10-12 the specific energy consumption increases because the production rate decreases with decreasing solar flux. At hour 8.5 when the fill process begins, the specific energy consumption is very low because the fresh water production rate is high, and then the specific energy consumption increases as the fresh water production rate decreases. The average specific energy consumption is 5.2 kW-hr/m^3 over the twelve hour desalination cycle. The average specific energy consumption compares well with RO systems, especially sea water PV-RO systems in which the specific energy consumption is typically 10-20 kW-hr/m^3.

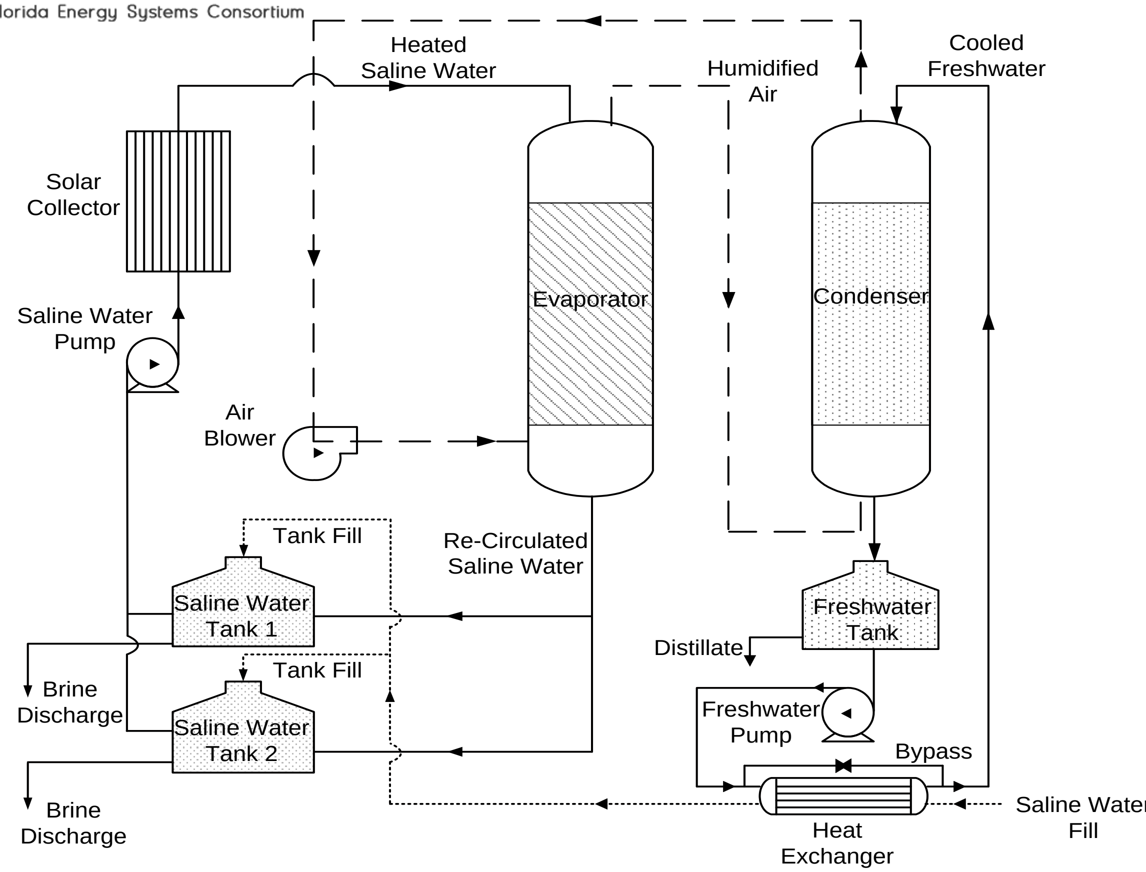

Figure 1: Process flow diagram

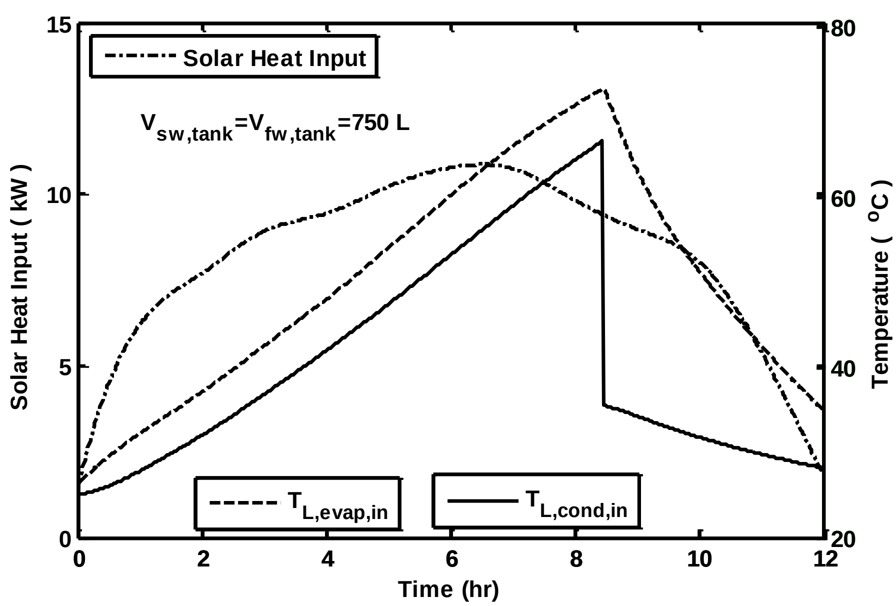

Figure 2: Solar thermal input, evaporator water inlet temperature, and condenser water inlet temperature; standard mode

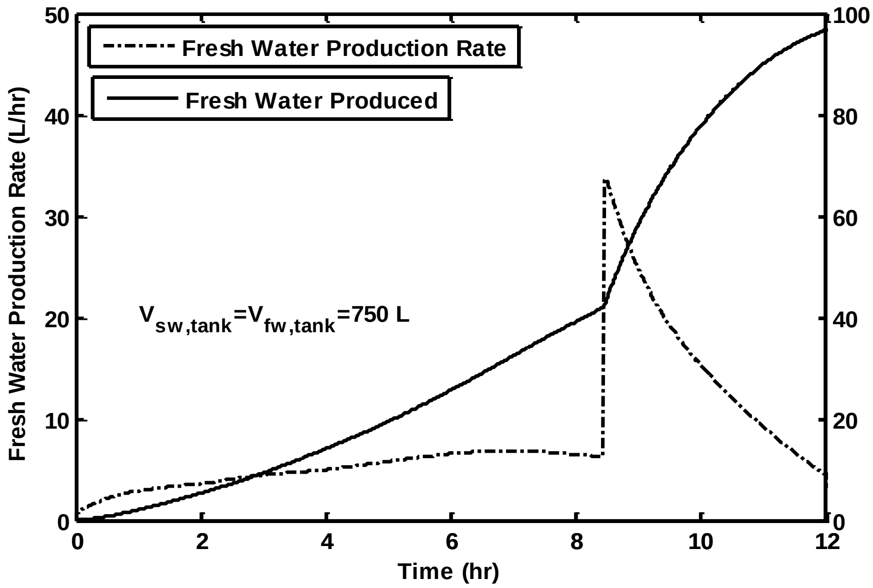

Figure 3: Total fresh water production and production rate; standard mode

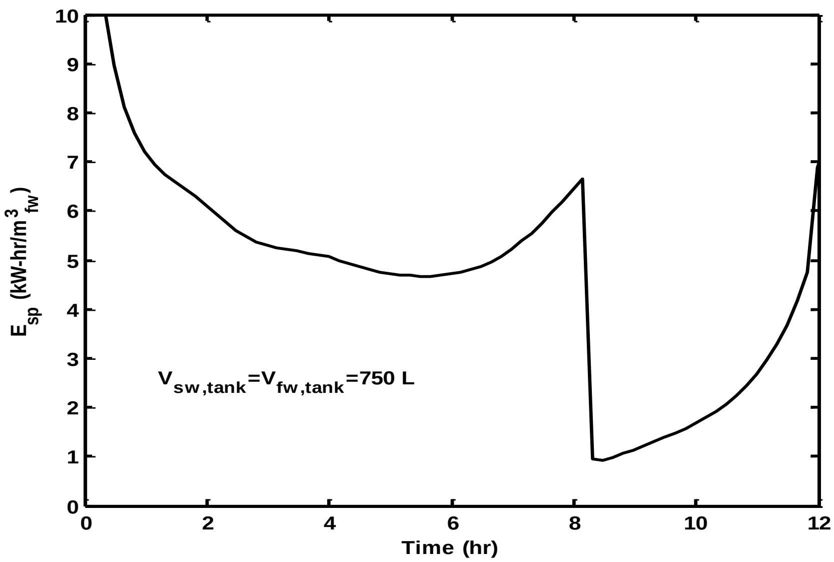

Figure 4: Electric specific energy consumption; standard mode

Examination of Figs. 2 and 3 reveal that the highest fresh water production rate coincides with the highest temperature in the saline water tank. In order to minimize the electric specific energy consumption, the distillation process should only be operational when the temperature of the saline water tank is sufficiently high to yield reasonable fresh water production rates. In order to improve on the specific electric energy consumption to drive the desalination process, it is not necessary to run the system when the solar flux is low and the specific energy consumption is high. Therefore, during the first three hours of operation, the saline water is only circulated through the solar collectors so that it heats up before the distillation cycle begins. The distillation cycle is initiated after three hours of heating the saline water with the solar collectors. At approximately hour 8.5, the heat exchanger is switched into service and the tank refill process is initiated. The idle saline water tank is refilled in 3.5 hours, and the entire system is shut down at hour 12. Operation of the solar DDD facility in this manner is referred to as the *delayed mode* of operation. For operation in this delayed mode, the transient solar heat input, the saline water temperature into the evaporator, and fresh water temperature into the condenser are displayed in Fig. 5. The fresh water production and production rate are shown in Fig. 6, and Fig. 7 shows the corresponding specific electric energy consumption. It is observed that the total daily fresh water production is 100 liters per day (6.3 $l/m^2_{collector}$-day), as is the case for standard operation. However, the specific energy consumption is typically below 5 kW-hr/m^3, and the average specific energy consumption for the entire distillation cycle is 3.6 kW-hr/m^3, which is approximately a 30% reduction compared with the standard mode of operation.

Clearly, the delayed operating mode provides enhanced performance since the specific energy consumption is reduced. Approximately 8 solar collectors with 2 m^2 collector areas will be required to achieve 100 liter per day water production. For more or less production, the size of the system scales approximately linearly. This aforementioned system performance assumes that the system temperature drops back to the ambient temperature (25 °C) at the completion of each distillation cycle. When it is assumed that there is suitable insulation (especially around the saline water tank) to hold the system temperature at a temperature above ambient for the start each distillation cycle, the system performance will be enhanced.

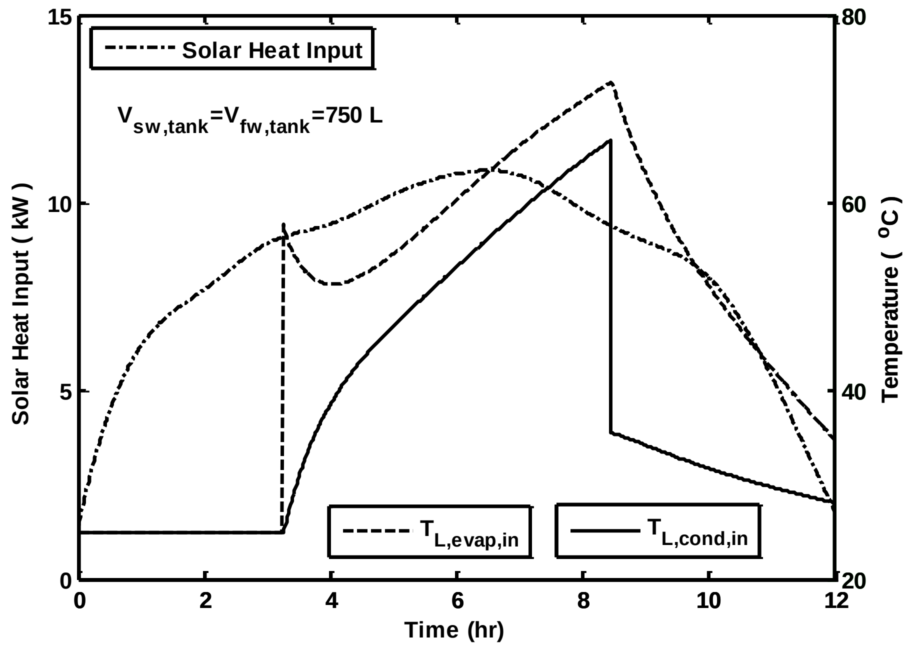

Figure 5: Solar heat input, saline water temperature into evaporator, and fresh water temperature into condenser; delayed mode

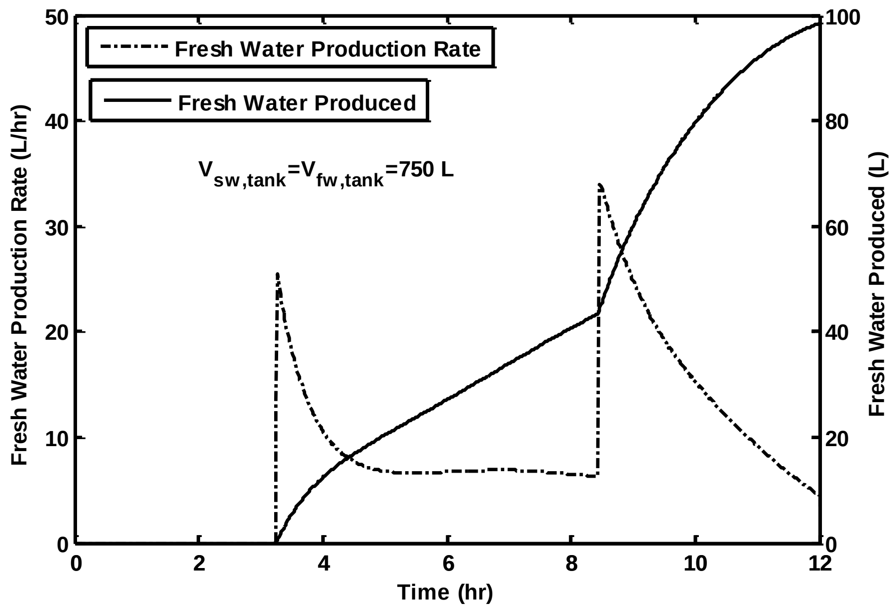

Figure 6: Total fresh water production and production rate; delayed mode

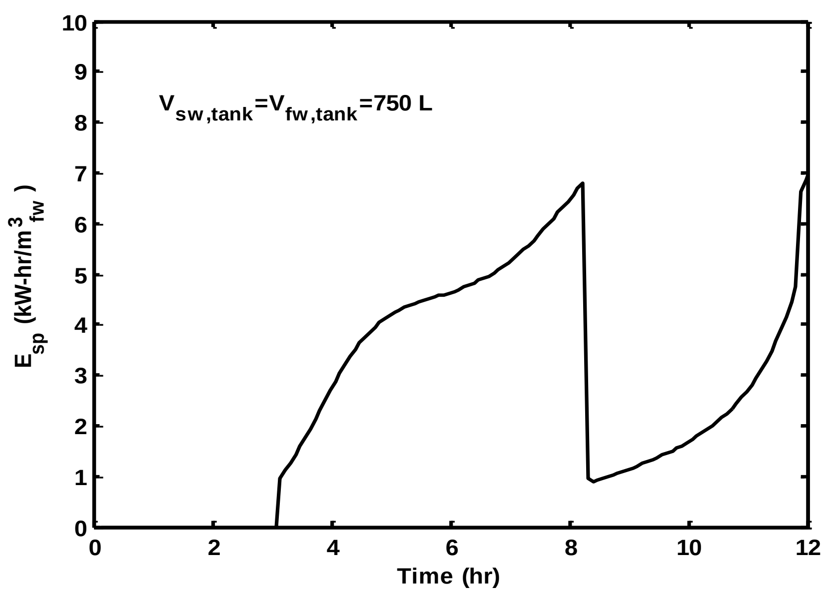

Figure 7: Specific electrical energy consumption; delayed mode

While fresh water production rate and specific energy consumption are essential to evaluate the performance of desalination processes, other factors such as simplicity, ease of operation, and low maintenance requirement are also important practical factors especially for decentralized water production. Clearly, this study has shown that operation in the delayed mode significantly reduces the specific electric energy consumption compared with operation in the conventional mode. It is believed that the solar DDD process, with its low power consumption and low maintenance requirement is a competitive desalination technology that is well suited for small scale decentralized water production.