MATHEMATICAL SIMULATION OF A SOLAR DESALINATION PLANT

Ali M. El-Nashar
Water and Electricity Department, Abu Dhabi, UAE

Keywords : Absorber plate, Atmospheric transmissivity, Diffuse radiation, Evacuated tube, Extraterrestrial, Setpoint, Solar azimuth, Transmissivity

Contents

Summary

This chapter presents some of the details concerning the development of a special-purpose, user oriented, interactive computer program which can be used to model solar desalination plants using the multiple-effect boiling seawater distillation plants of the MES type and utilizing evacuated tube collectors. The program, named "SOLDES", includes mathematical models to simulate the performance under different loads of the main plant components such as collectors, heat accumulator and evaporator as well as pumps, valves and controllers. Other (non-physical) component models include: solar radiation model, ambient temperature model, dust effect model and shadow effect model. The program was tested for accuracy by validating the simulation results with those from an existing solar desalination plant currently in operation in Abu Dhabi, UAE. The plant is identical in design configuration to the system being simulated. With measured hourly solar radiation and ambient temperature data, initial accumulator temperatures and setpoint temperatures being provided as input to the program, the program output is compared to the actual plant data. It was found that the program can predict actual plant data quite accurately and can thus be used as a tool for the design of

new plants and for the optimization of operating conditions of existing plants.

1. Introduction

The utilization of solar radiation as the energy source for desalination plants in remote areas seems to offer a good alternative when compared with those which use conventional fuel supplies particularly for those regions with abundant solar radiation. The reason is that the transportation of fossil liquid fuel to remote areas involves substantial expense and is fraught with logistical problems that make the supply of such fuel to remote areas both expensive and highly unreliable.

The design and performance prediction of solar desalination plants are generally more complicated than for desalination plants utilizing fossil fuels as the energy source. This is because the operating conditions of a solar desalination plant are highly variable and continuously changing depending on the prevailing weather conditions such as solar radiation, ambient temperature and wind speed - unlike conventional desalination plants which usually operate at constant load. The use of computer simulation to predict the operating conditions of a solar desalination plant becomes an unavoidable exercise in the design stage. This simulation involves the use of mathematical models to predict the performance of each plant component under different operating conditions. Those models could be integrated into a computer program to predict the plant performance under different weather conditions. The well known simulation program TRNSYS (Klein 1977) was developed as a general-purpose, user-oriented, flexible simulation program capable of analyzing forced flow solar systems. However, an important distinction exits between TRNSYS and the current program, namely, the current program is developed for a particular collector geometry, namely, evacuated tube type collectors in which shading and dust effect models are incorporated in the program.

This paper describes the mathematical model for the main components used to simulate the operational performance of solar desalination plants that utilize evacuated tube collectors and thermally-stratified heat accumulators to provide thermal energy to multiple-effect seawater evaporators. A special-purpose computer program called SOLDES was developed for two purposes: (1) to assist in optimizing the design parameters; and (2) to optimize the operating parameters of existing solar desalination plants by maximizing the annual production rate or minimizing water cost.

2. System Description

Figure 1 is a schematic diagram of the solar desalination system under investigation (El-Nashar and Ishi 1985). A field of evacuated tube collectors is used to provide the thermal energy required by a multiple-effect, vertically-stacked seawater evaporator. A heat accumulator is provided between the collector field and the evaporator in order to allow the evaporator to achieve continuous running throughout day and night and during overcast periods.

The collector field has a bypass line to allow the fluid discharged from the field to return back for further heating when the fluid temperature is too low. Two motorized valves are used in the collector field to control the temperature of water entering the heat accumulator, one valve installed in the bypass line and the other in the supply line to the accumulator. When one valve is open the other will be closed. A temperature sensor (RTD) installed in the discharge line of the collector field monitors the water temperature leaving the collectors and if it is below a set point the bypass valve will be open and the accumulator supply valve will be closed. If the temperature is above the set point, the bypass valve will close and the supply valve will open. This will ensure that the water temperature entering the accumulator tank will always be above a set point.

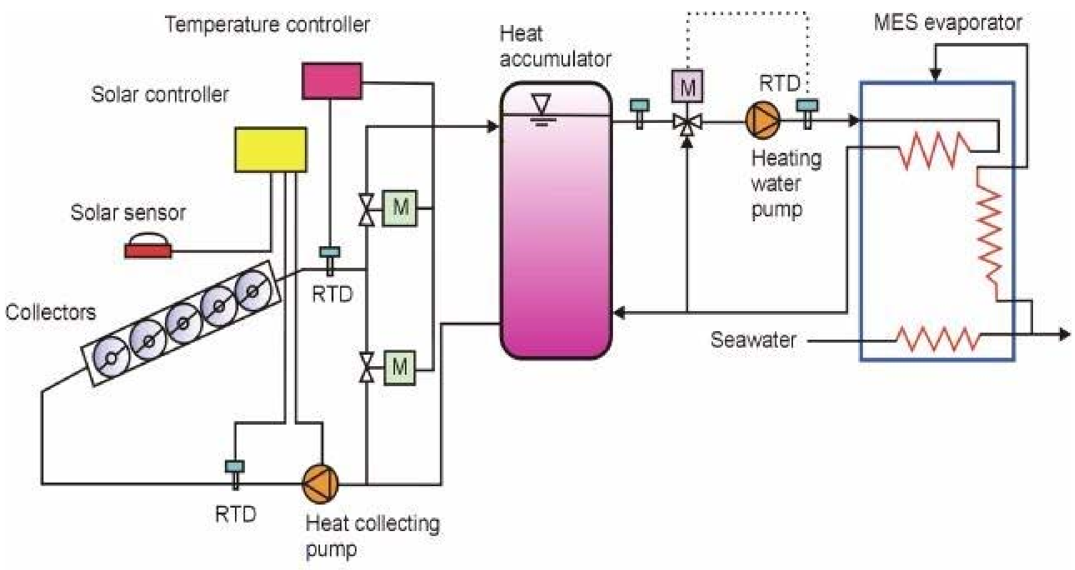

Figure 1. Schematic of solar desalination system.

The operation of the solar collector pump is controlled by a solar controller which provide a startup (when pump is shutdown) or shutdown (when pump is operating) signal to the pump depending on the intensity of solar radiation measured by a solar sensor. After sunrise, as soon as the solar radiation intensity reaches a certain value (which depends on the water temperature at the bottom of the accumulator) the controller sends a startup signal to the pump to begin pumping water through the collectors. Just before sunset and soon as the radiation intensity reaches another low value, the controller sends a shutdown signal to the pump to stop operation.

The heat accumulator used in this system is simply a thermally stratified water tank. By virtue of density variation between the top and bottom layers, the higher temperature water is located in the upper region of the accumulator tank while the lower temperature water occupies the lower region. The lower temperature water is drawn from the bottom of the tank and pumped through the collector field by the heat-collecting pump. The hot water returning from the collector field is forced to flow to the top of the tank. The hot water from the top region of the accumulator is drawn from the top region by another pump - called the heating water pump - which supplies this water to the first effect of the multiple-effect evaporator. As this water flows through the tube bundle of the first effect, it will cool down thus providing the thermal energy required by the evaporator.

The return water from the first effect flows to the bottom of the accumulator tank.

The MES evaporator has a number of effects that can be varied by the designer according to the desired performance ratio and top brine temperature. Each effect, with the exception of the first, consist of a tube bundle where vapor which was generated in the previous effect flows through the tubes. The first effect, as was mentioned earlier, has heating water from the accumulator flowing through the tubes. In addition to the effects, the evaporator has a number of feed water preheaters - equal to the number of effects minus one - and a condenser. The absolute pressure to be maintained in the final condenser is designed to be 50 mm Hg. The pressure to be maintained in each effect varies from slightly below atmospheric in the first effect to about 50 mm Hg in the last effect.

Seawater is used to condense the vapor generated in the last effect. Part of the discharged warm seawater leaving the final condenser returns to the sea, while the other part constitutes the evaporator feedwater. The feedwater flows through all the preheaters before being admitted to the first effect.

3. System Operating Conditions

The program was designed to simulate the different plant operating conditions as faithfully as possible particularly for the start-up and shutdown conditions of the solar heat collection subsystem and evaporator subsystem. It is possible for the user to specify the start-up and shutdown set-point temperatures for both subsystems or, alternatively, the program can select appropriate values for these temperatures based on actual system performance criteria obtained from the operation data of the Abu Dhabi plant.

3.1. Solar Heat Collecting Subsystem

The operation of the solar heat collecting subsystem is controlled by the solar controller whose function is to switch the heat collecting pump on or off at the appropriate time. The judgement regarding whether or not heat can be effectively collected by the solar collector field is dependent on the water supply temperature (lower temperature of heat accumulator) to the field, the ambient temperature and the solar radiation intensity prevailing at the time.

Figure 2 shows the start-up procedure for the heat collecting subsystem. The minimum solar radiation required for heat collecting pump start-up, I_{start}, is estimated by the solar controller and a signal to start-up the pump is issued if the solar radiation $I \geq I_{start}$. Before the pump starts, the accumulator by-pass valve should be open and the inlet valve closed so that during start-up the operation is in recirculation mode. As recirculation continues, the collector outlet water temperature increases until it reaches a "high" set-point which can be specified by the program user or selected by the program. At this time, the by-pass closes and the inlet valve open thus allowing hot water from the collector to enter the accumulator and start the energy storage mode. If, during this mode, the collector outlet temperature drops below a "low" setpoint the recirculation mode is entered again by opening the by-pass valve and closing the input valve. This procedure takes place daily after sunrise but can also happen during cloudy days in which there is substantial fluctuations in solar radiation.

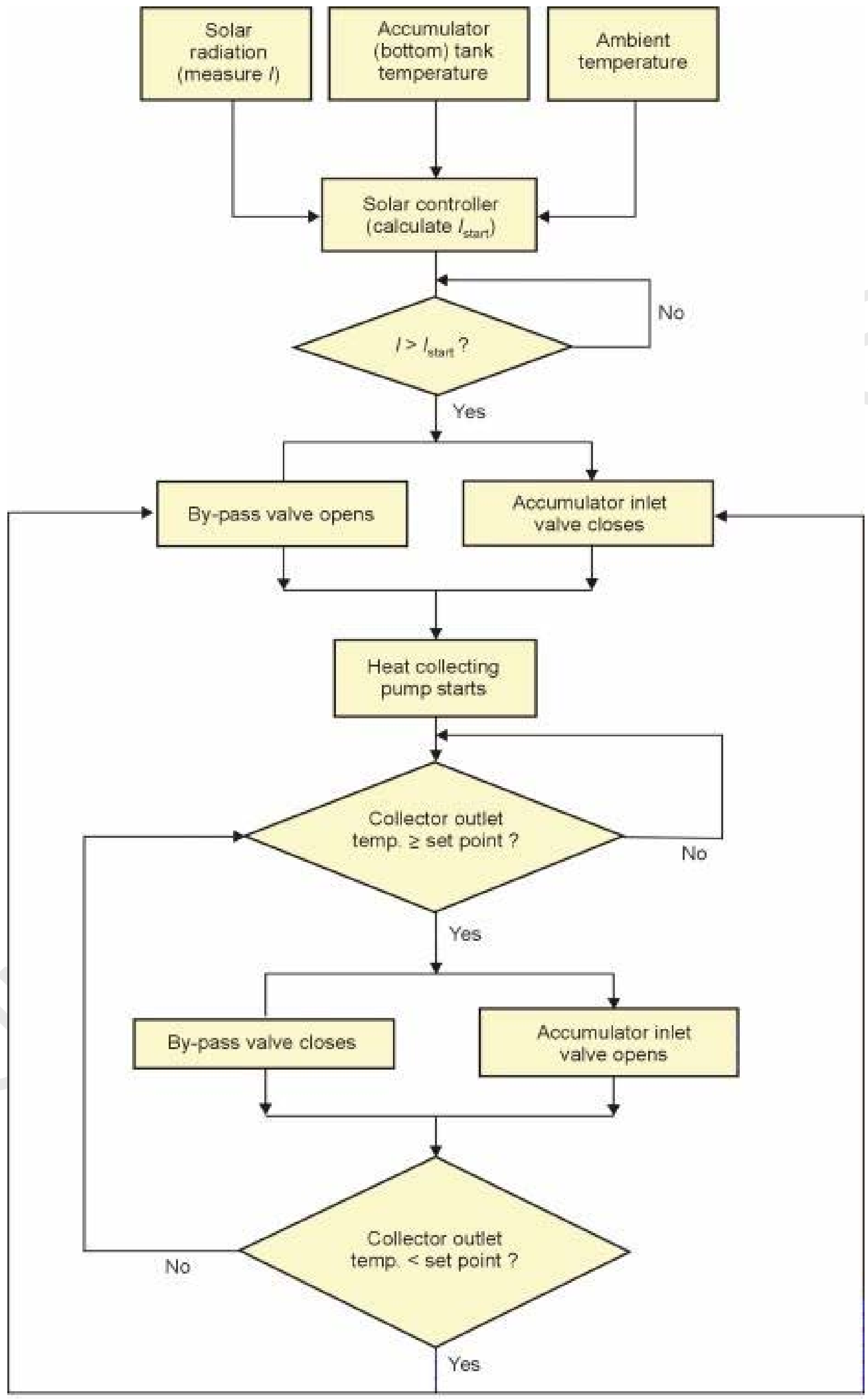

Figure 2. Start-up procedure for heat collecting subsystem.

The shutdown procedure takes place just before sunset and is essentially the reverse of that during start-up. As the solar radiation drops to a level below I_{stop} (which is estimated by the solar controller) a shutdown signal is issued to stop the pump and the by-pass valve is opened and inlet valve closed.

3.2. Evaporator Subsystem

Figure 3 shows the start-up procedure for the MEB evaporator. The start-up of the evaporator depends essentially on the state of charge of the accumulator as specified by the middle water temperature (start-up) setpoint. If the measured water temperature in the middle layers of the accumulator tank is above setpoint, the evaporator start-up sequence will begin and the vacuum pump will start operating. When the pressure inside the evaporator shell drops below 110 mmHg, the heating water pump starts operation thus pumping hot accumulator water to the first effect. When the brine temperature in the first effect reaches that value corresponding to 80 per cent load, normal operating condition is considered reached.

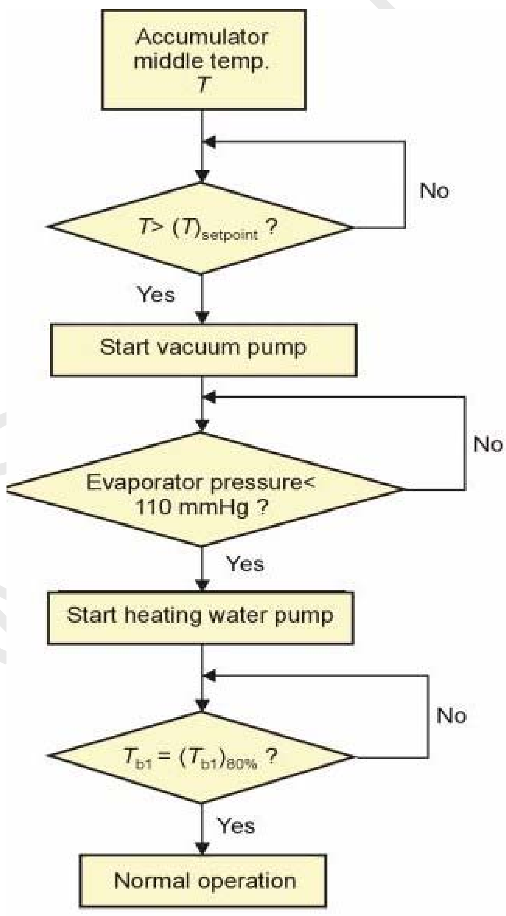

Figure 3. Start-up procedure for the MEB evaporator.

The shutdown sequence is initiated by the temperature of the upper layers of the accumulator. If this temperature is below the (shutdown) setpoint which corresponds to 60 per cent load, the evaporator will stop.

4. Mathematical Modeling of System Components

Models were developed to describe mathematically the characteristics of the major plant components as well as the environmental variables that are important to the simulation program (Duffie and Beckman 1980, El-Nashar 1990). This section describes these models in some detail.

4.1. Solar radiation model

The global solar radiation on a tilted surface making an angle α with the horizontal, I_t, can be expressed by the equation:

$$I_t = I_{tD} + I_{td} \quad (1)$$

where I_{tD} is the direct solar radiation component and I_{td} is the diffuse component in kcal m^{-2} per h.

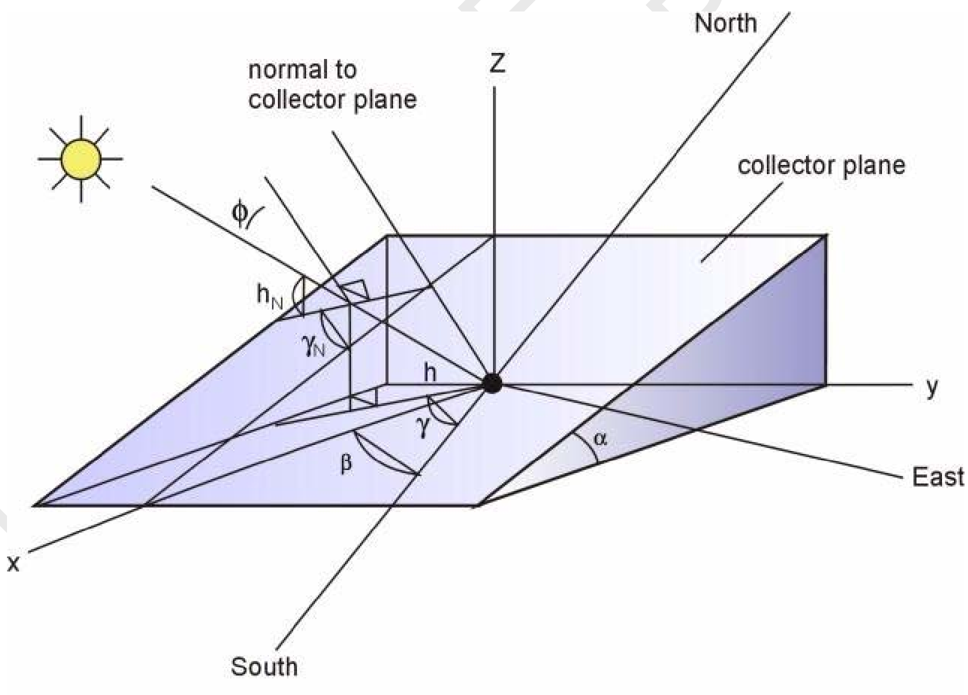

Figure 4. Angles on a tilted plane.

Each of the two radiation components can be expressed in terms of the atmospheric transmissivity, *P*, the solar altitude, *h*, the incidence angle of the solar beam on the tilted plane, θ, and the angle of the tilted plane with the ground, α (ENAA and WED 1986) as follows:

$$I_{\mathrm{tD}} = I_{\mathrm{o}} \cdot P^{\frac{1}{\sinh}} \cdot \cos\theta$$

$$I_{\mathrm{td}} = 0.5 I_{\mathrm{o}} \cdot \sin h \cdot \frac{1 - P^{\frac{1}{\sin h}}}{1 - 1.4 \ln(P)} \cdot \frac{1 + \cos\alpha}{2} \qquad (2)$$

These equations are developed by Bouger and Berlage (ENAA and WED 1986). The angles h, θ and α as well as the azimuth angle of the tilted surface, γ, are shown in Figure 4.

The atmospheric transmissivity, P, is a measure of the extent of attenuation of direct radiation due to scattering and absorption as it passes through the layers of the atmosphere. Assuming that the direct radiation normal to a surface on the ground is I_{n} and the solar radiation intensity just outside of the earth's atmosphere is I_{o} where the sun is at the zenith, the atmospheric transmissivity is defined as

$$P = \frac{I_{\mathrm{n}}}{I_{\mathrm{o}}} \qquad (3)$$

The value of P is usually greater than zero and less than one. A value of P in the vicinity of 1.0 means that the sky is clear whereas a value near zero means that the sky is overcast. The value of P fluctuates depending upon the region, season and weather condition. The value has to be known in order to estimate the hourly values of the direct and diffuse components of the global solar radiation on any tilted surface which is necessary for the plant simulation program. Since the hourly global solar radiation on a horizontal surface, I_{h}, at a particular site is usually available or can be estimated, it is possible to calculate the hourly values of transmissivity, P, by an iterative method using the following equation,

$$I_{\mathrm{h}} = I_{\mathrm{o}} \cdot P^{\frac{1}{\sin h}} \cdot \sin h + 0.5 I_{\mathrm{o}} \cdot \sinh \cdot \frac{1 - P^{\frac{1}{\sin h}}}{1 - 1.4 \ln P} \qquad (4)$$

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Biographical Sketch

Ali M. El-Nashar received the B.Sc. (Mech. Eng.) from Alexandria University (Egypt) in 1961 and Ph.D. (Nuclear Engineering) from London University (UK) in 1968. He has been a faculty member at several universities in Egypt, UK and USA and was appointed professor of mechanical engineering at Florida Institute of Technology (USA) and Mansoura University (Egypt). He was a research fellow at Clemson University (USA) during the period 1971 to 1976. He has worked as consultant for different industrial and UN organizations among which Dow Chemical Co. (USA), Ch2M-Hill Co. (USA), Science Application Co. (USA), UNEP, Technology International Co. (USA). He is member of the ASME, ISES and IDA and editor of the International Desalination and Energy journals. He has worked at the Research Center of the Abu Dhabi Water and Electricity Authority (UAE) as manager of the desalination and cogeneration section which pioneered development work on solar desalination for ADWEA for 20 years. He has been associated with the International Centre for Water and Energy Systems, Abu Dhabi, UAE.