Conference Paper

Evaluation of a Multiple-Effect Distillation Unit under Partial Load Operating Conditions

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The design of a multiple-effect distillation (MED) system is presented, and the results for partial load operation of a single-effect distillation unit are presented. The MED is designed to be driven by solar energy, and thus the dynamic performance and partial load operation production are of interest. Two operating modes are considered in the analysis, with and without the use of a flow distributor. Various tests were performed varying the heating steam flow rate and the intake seawater flow rate. Results are presented as a function of the performance ratio, representing the amount of distillate produced per unit mass of steam input. Results indicate that a higher performance is obtained with the use of the flow distributor.

1. Introduction

The shortage of drinking water is one of the biggest problems in Cyprus, due to insufficient rainfall in the winter, the long lasting hot summers, and the unsustainable rate of fresh water consumption. Furthermore, the observed and recorded climate change over the past few past decades, especially in the Mediterranean region, is another significant factor contributing to the reduction of precipitation. Many global and regional models predict a warming of several degrees in the Mediterranean by the end of the 21st century, with the warming in the summer being larger than the global average [1].

Seawater desalination processes can help alleviate the problem of fresh water scarcity in island communities, such as Cyprus, but these processes require significant amounts of energy. It was estimated that the production of 1 million m³/day requires 10 million tons of oil per year [2].

Thermal desalination processes, such as multiple-effect distillation (MED) or multiple-stage flash (MSF) distillation, utilize thermal energy sources which are used to evaporate

water. While water is heated to boiling, salts, minerals, and pollutants are excluded from the generated steam and therefore remain in the liquid water. The steam is separated and condensed to produce desalinated water [3].

Due to high cost and adverse environmental impacts of conventional energy sources, renewable energy sources have recently received increasing attention since their use in desalination plants will reduce the consumption of fossil fuels and environmental pollution [4].

1.1. Multiple-Effect Distillation. The Multiple-Effect Distillation, or MED, process consists of several consecutive stages (or effects), maintained at decreasing levels of pressure (and temperature), leading from the first (hot) stage to the last one (cold). A schematic of a four-stage MED unit is depicted in Figure 1 [5]; however, typical MED plants can contain as many as 20 effects. Each effect mainly contains a multiphase heat exchanger. Seawater is introduced in the evaporator side and heating steam in the condenser side. As it flows down the evaporator surface, the seawater that does not

FIGURE 1: Four-stage MED schematic with proposed operational conditions.

evaporate concentrates and produces brine at the bottom of each effect. The vapor raised by seawater evaporation is at a lower temperature than the vapor in the condenser. However, it can still be used as heating medium for the next effect where the process is repeated [6, 7].

The vapor raised by the evaporating seawater is at a lower temperature than the vapor in the condenser. However, it can still be used as heating medium for the next effect where the process is repeated [8]. The decreasing pressure from one effect to the next one allows brine and distillate to be drawn to the next effect where they will flash and release additional amounts of vapor at lower pressure [9]. This additional vapor will condense into distillate inside the next effect.

In the last effect, the produced steam condenses on a heat exchanger. This exchanger, called distillate or final condenser, is cooled by seawater [10].

1.2. Concentration Solar Thermal Desalination. Concentrating solar power (CSP) technologies are based on the concept of concentrating solar radiation to provide high temperature heat for electricity generation within convectional power cycles using steam turbines, gas turbines, Stirling engines, or other types of heat engines. For concentrating the solar irradiation, most systems use glass mirrors that continuously track the position of the sun. The four major concentrating solar power technologies are parabolic through linear Fresnel mirror reflector, heliostat-central receiver systems, and dish/engine systems.

1.2.1. Heliostat-Central Receiver Systems. The central receiver falls under the point concentrating type of CSP technologies. The usual realization of this CSP technology is the solar tower system which has a single receiver placed on the top of a tower surrounded by a large number of mirrors (heliostats) which

follow the motion of the sun in the sky and which redirect and focus the sunlight onto the receiver, Figure 2.

The key elements of a solar power system are the heliostats, the receiver, the steam generation system, and the storage system. The number of heliostats will vary according to the particular receiver's thermal cycle and the heliostat design. Radiation is concentrated at the central receiver. The energy is then transported via a heat transfer fluid to a power production cycle. The heat loss from piping and from large absorber surfaces in the distributed design leads to a lower operating temperature for the thermal to electricity conversion cycle [11].

1.2.2. CSP and Desalination. The primary aim of solar thermal plants is to generate electricity, yet a number of configurations enable such plants to be combined with various desalination methods. When compared with other renewable energy sources, such as photovoltaics or wind, CSP could provide a much more consistent power output when combined with either energy storage or hybridization with fossil fuel [12].

Although convectional combined cycle (CC) power plants can be configured in a similar manner for desalination, a fundamental difference exists in the design approach for solar and fossil fuel fired plants [13]. The fuel for the solar plant is free; therefore, the design is not focused on the efficiency but on the capital cost and capacity of the desalination process. In contrast, for the CC power plant, electricity production at the highest possible efficiency is the ultimate goal.

1.3. Single-Effect Distillation. As a precursor to MED, a single-effect distillation system is constructed and tested. In this

FIGURE 2: Schematic of a TVC-MED coupled with a CSP plant (from [11]).

system, the evaporator tank, or effect, is fed by seawater through the saline water pipe. The seawater is heated by passing hot steam through the steam heat exchanger, located in the evaporator tank, until it reaches the boiling temperature. The key components of a single-effect distillation unit are illustrated in Figure 3.

The steam will pass through the tubes of the heat exchanger, condenses, and returns back to the boiler, while the saline water outside the tubes boils and thus evaporates. The water vapor rises and moves towards the condenser tank. In the condenser tank, the water vapor is cooled down by passing cold water through some cooling pipes [14].

Thus, the water vapor will condense into pure liquid water. Subsequently, the distilled water will be collected and stored in the storage tank. To ensure that the heat released from the heating steam, will flow towards the saline water, the condensation temperature of steam has to be higher than the boiling temperature of the saline water. To achieve that, the saline water boiling temperature is reduced by decreasing its vapor pressure.

The vapor pressure is controlled by venting the air from the evaporator tank by a vacuum pump or an ejector. The remaining brine water is removed from the evaporator tank continuously during the distillation process or intermittently at the end of each process.

1.3.1. Research Objectives. In the present paper, we present the design of a MED system and the performance of the first effect of the system. The system is tested under partial load operating conditions. Two operating modes are considered in the analysis, with and without the use of a flow distributor. Various tests were performed varying the heating steam flow rate and the intake seawater flowrate. Results are presented as a function of the performance ratio, representing the amount of distillate produced per unit mass of steam input.

2. Experimental Setup

A small-scale ($\sim 10 \text{ kW}_{\text{th}}$) MED system was designed and built to demonstrate proof of principle of the CSP-DSW system

FIGURE 3: Schematic of the single-stage distillation system (from [14]).

FIGURE 4: Schematic of the single-stage MED experimental setup.

integration. To design and characterize the MED system for this purpose, an understanding of the heat exchanger performance (estimate of the pressure drop and heat transfer coefficient), permeate vapor path, and overall system steady state and transient performance is required. Due to variations in solar radiation, transient response of the MED system between 5 and 20 kW_{th} (with nominal operation at 10 kW_{th}) heat input is considered.

The construction of the MED commenced sequentially, starting with a single-effect distillation unit, as shown in Figure 4. Off the shelf components for use in home potable water distribution systems and sanitary/chemical processing have been employed in the apparatus construction, as many components traditionally used in MED are not commercially available in this scale.

The M3-FG seawater-compatible plate heat exchanger (PHE), rated for up to 20 kW heat input, manufactured by Alfa Laval, and shown in Figure 5(b), was selected. This is similar technology as in state-of-the-art large-scale MED plants. Parallel plate falling film exchangers have been reported to exhibit evaporative heat transfer coefficients up to 4,000 W/m²K, and so they are ideal for use in MED systems providing large heat transfer in compact areas [15]. Modifications to the sealing gaskets to allow for three-phase flow are made, Figure 5(a).

Although the performance correlations of the heat exchangers used in MED are proprietary, two methods to predict the pressure drop and overall heat transfer coefficients for the four-stage design have been used. First, for the M3-FG heat exchanger, Alfa Laval provided overall heat exchanger

FIGURE 5: The Alfa Laval falling film plate heat exchanger and modification to the gasket.

performance estimates for the conditions of a three-stage system with equal stage temperature distribution of 80°C to 35°C . The heat exchanger has a surface of 0.353 m^2 comprised of 13 plates in an alternating pattern of alternating chevrons with 60° corrugation angle and fluid passage gap of 2.2 mm .

2.1. Instrumentation and Data Acquisition. Differential pressure transducers between the heat exchanger inlet and outlet on the steam and seawater sides measure the pressure drop across the condenser and evaporator, respectively. The overall heat transfer coefficient is determined by the change in temperature of the seawater and ratio of permeate to seawater inlet mass flow rates.

Records of the following parameters were acquired: flowrate, pressure, and temperature of steam, seawater mass and temperature, brine mass and temperature, distillate product mass, pressure, and water level within the vessel.

Temperatures were measured again using K-type thermocouples; seawater and brine flow rates were measured using ultralow flow sensors (Omega FTB600B Series). The pressure of the incoming steam and inside the effect was measured using pressure sensors (Omega PX209 Series), and the water level in the vessel was measured using a liquid level sensor (VEGACAL 63 of VEGA). All sensors were connected to a data acquisition system (DAQ), and LabView software was used to record the data.

3. Single-Effect Results

Figure 6 shows typical results obtained during the single-effect characterization experiments. A typical run lasted approximately 1000–1500 seconds, as indicated in the horizontal axis of the figure. A general observation that can be made is the cyclical variation in the steam flow rate (red line of top panel) that is attributed to the thermostatic controller of the steam generator. In contrast, the flow rates of seawater

FIGURE 6: Representative time record of sensor outputs collected from the single-effect MED. The abscissa represents time in seconds. The top panel shows the flowrate of the seawater, steam and brine (in Lpm). The middle panel shows the liquid level inside the effect (in cm). The bottom panel shows the temperature of the seawater (T_{sw}), steam inlet ($T_{s,in}$) and outlet (T_1), and brine (T_b) in degrees C. Note that T_1 and T_b are almost identical.

FIGURE 7: Study of heat exchanger plate wetting by considering the heat exchanger outflow.

(blue curve) and of the brine (green curve) are fairly steady. The middle panel corresponds to the output of the liquid level sensor. A steady depth of approximately 3 cm of brine is maintained within the vessel.

The aim is to achieve a constant line in order to have more accurate calculations regarding the distillate product. The observed peaks are due to electrical noise and are not a real effect. The lower panel shows the temperature at four sensor locations (T_1 , $T_{b,1}$, T_{sw} , and $T_{s,in}$) shown in Figure 4. The incoming steam temperature exhibits the same time variation as the steam flow rate. The temperature of seawater and brine (green line) remains steady. The fact that the steam flow rate variation does not affect the operation of the effect is an indication of the robustness of the MED process.

3.1. Single-Effect without Distributor. Measurements were made in order to characterize the single-effect distillation unit. The variation of the observed steam flow rate was taken into account in our data analysis. The steam generator was set at three different temperatures ($T_s = 140^\circ\text{C}$, $T_s = 150^\circ\text{C}$,

and $T_s = 160^\circ\text{C}$), and measurements were made repeatedly for each temperature. The results obtained are summarized in Figures 8(a), 8(c), and 8(e). It is important to note that the steam input temperature ($T_{s,in}$) is not the temperature quoted above. This was the temperature set on the electrical steam generator but due to thermal losses in the steam line and inefficient operation of the steam generator, the actual steam input temperature to the first effect was lower.

A metric for the efficiency of thermal distillation systems is the performance ratio (PR), defined as the ratio of water product (distillate) mass ($\dot{m}_d$) over the steam mass ($\dot{m}_s$). In Figures 8(a), 8(c), and 8(e), the performance ratio is plotted as a function of the incoming seawater flowrate ($\dot{m}_{sw}$). The seawater flow rate is also nondimensionalized by the steam flowrate. This is done in order to aid comparison between the various cases of thermal input. A maximum in PR is observed for a nondimensional input of 2.

The error bars correspond to an error propagation analysis. A 95% confidence interval was used reflecting a significance level of 0.05. The high variation observed reflects

■ Experiment ($T_s = 140^\circ\text{C}$)

(a) Results for $T_s = 140^\circ\text{C}$ without the distributor

■ Experiment ($T_s = 140^\circ\text{C}$)

■ Theory

(b) Results for $T_s = 140^\circ\text{C}$ with the distributor

■ Experiment ($T_s = 150^\circ\text{C}$)

(c) Results for $T_s = 150^\circ\text{C}$ without the distributor

■ Experiment ($T_s = 150^\circ\text{C}$)

■ Theory

(d) Results for $T_s = 150^\circ\text{C}$ with the distributor

■ Experiment ($T_s = 160^\circ\text{C}$)

(e) Results for $T_s = 160^\circ\text{C}$ without the distributor

■ Experiment ($T_s = 160^\circ\text{C}$)

■ Theory

(f) Results for $T_s = 160^\circ\text{C}$ with the distributor

FIGURE 8: Summary of results for single-effect distillation.

the unstable performance of the steam generator when it performs near to the limiting operating temperature.

3.2. Singel-Effect with Distributor. Complete wetting of the heat exchanger plates is critical for efficient operation of the heat exchanger itself and by extension of the MED unit. During initial testing, it was observed that the plates were not all wetted due to low seawater flow rates. This was asserted by observing the outflow of the heat exchanger, as shown in Figure 7(a). In this figure, the flow exits only from the first 2-3 plates of the heat exchanger.

To remedy this situation, a flow distributor was constructed in order to better distribute the seawater flow over the heat exchanger, Figure 7(b). Several distributor configurations were experimentally evaluated, varying the hole sizing and spacing as shown in Figure 7(c). A configuration with 4 holes, each 3 mm in diameter and spaced 0.85 cm apart, achieved the greatest wetting on the heat exchanger plates, Figure 7(d), as indicated by water exiting the heat exchanger throughout its thickness, and was therefore chosen.

A new set of data was collected on the single-effect unit with the flow distributor in place. The input conditions remained the same. The results recorded are presented in Figures 8(b), 8(d), and 8(f).

3.3. Comparison of Theoretical and Experimental Results. The last step for the single-effect characterization was the comparison of the experimental results with the theoretical results predicted by the control volume model we were using.

The two main conclusions that are presented in Figures 8(b), 8(d), and 8(f) that referred to a constant heat load are as follows.

- (i) Increasing the seawater reduces the amount of distillate product. Increasing the seawater mass results in an increase of the sensible heat. This decreasing slope of the experimental results was capture by the model that we used.
- (ii) Decreasing the seawater reduces the amount of distillate product. The decrease of the seawater results in reduced wetting in heat exchanger. That leads to dry spots that decrease the heat transfer coefficient. This effect was not captured by the model because the overall heat transfer coefficient was set constant during our hypothesis.

4. Conclusion

We presented an experimental characterization of a single-effect distillation unit under partial load operating conditions, in terms of the performance ratio. Performance analysis shows that the best performance is obtained for the flow distributor case. However, a full (four) effect MED system must be designed and evaluated based on the results gained through the characterization of the single-effect MED.

Our results show that a performance ratio (PR) of 0.7 is achieved under various partial load input conditions. The PR exhibits a maximum and decreases with increasing and

decreasing seawater flowrate. The results match well with predictions from a one-dimensional control volume model.

Facing the challenges dealing with the coupling of MED desalination unit to a renewable energy source (CSP), such as operational instabilities, or dynamic range of operation of the MED is the next step of this research.

Nomenclature

Symbols

P : Pressure
 T : Temperature
 $\dot{m}$: Mass flow rate
 N : Number of effects
 PR: Performance ratio.

Subscripts

s : Steam
 sw : Seawater
 in : Inflow condition
 out : Outflow condition
 c : Condensate
 b : Brine/condensate
 v : Vapor
 th : Thermal energy
 l : Condition in effect 1.

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