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Thermodynamic Modelling of an Industrial Scale Solar Desalination Plant with Low-Concentration CPC Collectors and Multiple-Effect Thermal Distillation (MED) in India

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Abstract. A solar seawater desalination plant with glass-covered compound parabolic (CPC) collectors, flash evaporation chamber and multiple-effect distillation (MED) with 8 stages, operating in Vallur, India, is modeled in the Ebsilon thermodynamic simulation software. Standard equations from literature for solar collectors and for saltwater heat exchangers are selected and implemented as scripts. Model results are a distillate/steam ratio of 7.0 and average temperature steps of 2.8 K between effects. With the simulations it has been possible to identify performance-relevant deviations of the mass flow in solar field loops and in a saltwater preheater during the trial operation period. It is shown that the implementation of current state-of-the-art equations into the proven modeling software already including physical properties of saltwater and calculation of solar plants with time series provides a viable basis for a digital twin of the commercial plant.

INTRODUCTION

A solar desalination plant uses the energy from solar irradiation for the production of fresh demineralized water from seawater as feedstock. NTPC operates a new commercial scale solar desalination plant in the vicinity of a thermal power station on the coast in Vallur near Chennai, India. The plant consists of a solar collector field with glazed CPC solar collectors, and a multiple-effect distillation (MED) system, top brine temperature of around 70°C and a nominal production rate of 5 tons of distillate per hour. For periods without sunshine there is an auxiliary heater operated with 4-bar-steam from the adjacent thermal power station.

The solar field supplies hot water as energy source to the MED system. The MED is operating at relatively low temperature of 70-75°C or lower due to the sub-atmospheric pressure inside the evaporator stages (effects). This low temperature reduces negative effects of fouling/scaling of the saltwater on the heat exchanger tubes and makes solar hot water an attractive energy source for this process for water production.

For the purpose of verifying the operation and performance of the solar desalination plant, NETRA and DLR both use Ebsilon Professional software for simulation of thermodynamic cycles, processes and systems, and the model is set up in this powerful engineering software environment (www.ebsilon.com). Ebsilon has the typical thermodynamic process components integrated in the library, including turbines, heat exchangers, pumps, and piping, and also concentrating solar collectors, piping manifolds etc., as well as saltwater thermodynamic properties. Missing components in Ebsilon are however: CPC solar collector, steam-driven evaporator for saltwater, flash evaporation for saltwater, and steam-driven preheater and condenser for saltwater.

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Solar Energy from CPC collectors

Solar CPC collectors consist of evacuated absorber tubes with linear-curved mirrors behind the tubes in order to reflect and slightly concentrate solar irradiation onto the absorber tube. The absorber tubes are evacuated heat pipes with water/steam or organic fluid at low pressure as heat transfer medium to transport the collected heat by evaporation and condensation to a collecting manifold at the top of the collector, where the heat is transferred from the condenser bulb of the heat pipe in the dry socket connector to the water of the solar circuit. The collector is specified as Apricus Solar Co. Ltd model ETC-CPC-24, with 24 absorber tubes of about 1.7 m length, and a gross aperture of 5.12 m² per collector (Figure 1). The collector has an additional glass cover. Performance data is taken from the Solar Keymark certificate SC0064-19, reported in 2019 by Intertek Testing Services Shenzhen Ltd. Guangzhou.

The collectors are installed in the field, close to the ground, tilted by 20° to south, at a latitude of 13°14'N. The solar field is configured in 5 parallel subfields (bays), each subfield consisting of 22 parallel rows of 5 collectors in series each, resulting in a total collector gross area of 2816 m². For the plant modelling, piping lengths, diameters, and insulation thickness are extracted from drawings and implemented in the model for heat loss and pressure loss estimates.

FIGURE 1. CPC collector ETC-CPC-24 with glass cover in NTPC solar field (photo: NTPC)

The hot water from the solar field flows to a flash chamber at sub-atmospheric pressure to partly evaporate to low-pressure steam flowing into the first effect of the MED system ("motive steam"), where it condensates releasing its energy to the first stage (effect) of the desalination process. The nominal temperature and pressure in the flash chamber are 72°C and 0.34 bar respectively. A pump feeds the remaining saturated water and the condensate from the first effect back to the solar circuit, thus requiring a geodesic height difference to avoid cavitation in the pump.

Multiple-Effect Distillation

Distillation at industrial scale is widely used in many processes, and the most common way for desalination of seawater to produce demineralized or drinking water, beside high-pressure membrane processes. The high amount of thermal energy needed to evaporate water of around 2.26 kJ/kg (630 kWh/ton) makes this process only economically efficient, if the condensation energy is recovered in subsequent stages by recovering it for evaporation at decreased pressure, and if the energy source is sufficiently cheap and available. In the multiple-effect distillation the saltwater preheated close to boiling temperature at the respective stage pressure level is sprayed onto the horizontal heat exchanger tubes of the so-called effect (Figure 2 and 3). The evaporation takes place on the heat exchanger surface under vacuum conditions and with excess liquid. The heat transfer from the condensing distillate inside the tubes to the boiling saltwater in the shell side is very high under these phase-change conditions (2 kW/m²K) which is advantageous for low temperature gradients between the stages and allows for good energy recovery. The formed vapor is fed to the condensing side (inside tube) of the next stage as heat source, and distillate is collected from the individual stages. Brine at increased salt concentration remaining after the evaporation flows in the same direction (from higher to lower temperature) through the stages allowing for flash evaporation in the subsequent stages at lower pressure generating some additional distillate vapor. Part of the distillate vapor generated in the stages is used for preheating the entering feed of saltwater to boiling temperature in separate preheaters. Behind the last (coolest) stage a condenser condenses the vapor from the last stage by cooling with excess seawater stream. Part of the brine with increased salt concentration is recycled together with fresh seawater input into the evaporation stages, which saves some thermal energy because the brine from the last stage is still at elevated temperature, and reduces the amount of rejected brine. A higher number of stages reduces the specific thermal energy consumption (kWh/m³), but the number of stages is limited by the temperature difference between motive steam temperature and condenser, and by the cost associated to the heat exchangers. Pumps and pumping (electric) energy are needed to pump distillate and brine from the sub-atmospheric pressure level at the condenser pressure out of the system.

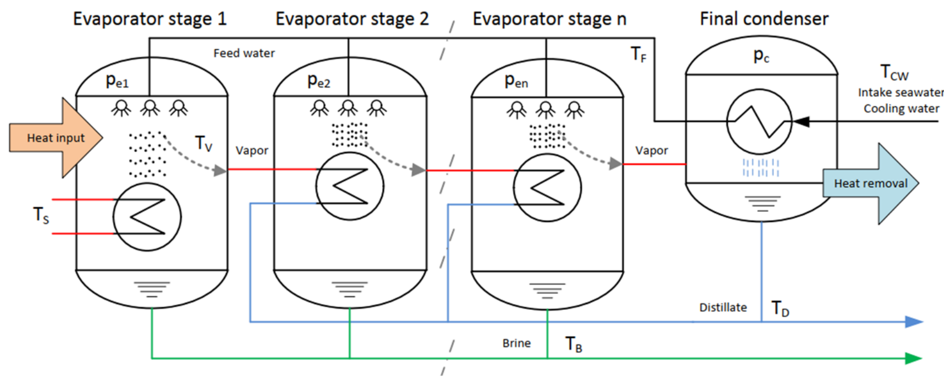


FIGURE 2. Simplified scheme of parallel/cross feed multi-effect distillation (Wellmann [6])

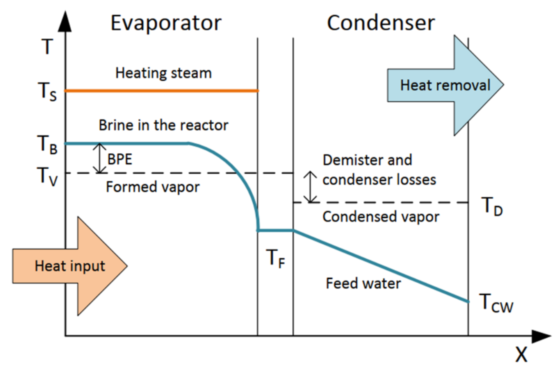


FIGURE 3. Temperature profile of saltwater distillation: one effect and condenser (Wellmann [6])

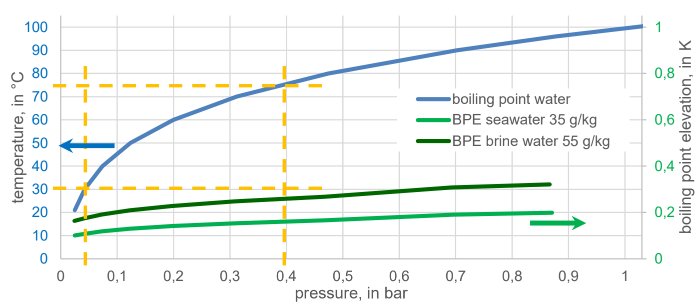


FIGURE 4. Boiling temperature versus pressure of pure water (blue) and boiling point elevation (BPE, green) of saltwater (35 and 55 g/kg)

Figure 4 shows the relation between temperature and pressure at the boiling/condensation point of water and the "boiling point elevation", the increase of boiling temperature due to the dissolved salt in seawater and brine. The relevant temperature range for the MED is 75 to 30°C, and the related effect and condenser pressure range is 0.39 to 0.04 bar.

The NTPC installation in Vallur has eight effects and three intermediate seawater preheaters. It uses steam from the solar field formed in the flash chamber as heat source for the first effect. The cold end in the condenser is cooled by excess seawater, part of which becomes preheated seawater to the feed of the effects. According to design a fraction of 2/3 of the total brine flow from the last effect, at elevated temperature, is recirculated together with preheated fresh seawater as feed into the effects. In addition to the condensation in consecutive effect stages, fractions of the distillate vapor from effects 2, 4 and 6 are used to preheat the feed water.

MODEL IMPLEMENTATION

For practical reasons in development and simulation, the Ebsilon model for the solar desalination is originally separated into two blocks. The solar field including pump and including backup steam supply is one block, that can be simulated separately and in time-series mode. The second block comprises the whole MED system including energy supply in form of hot water to the flash chamber. This block can be used to simulate the operation parameters of the MED separately. Figure 5 shows the complete model.

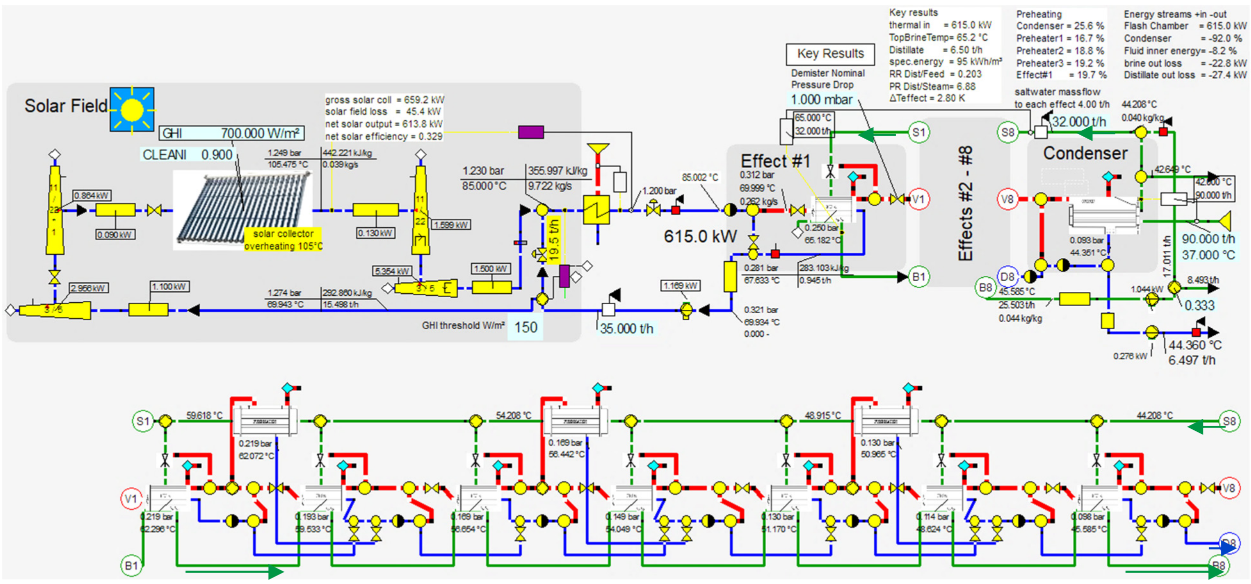


FIGURE 5. Ebsilon model for CPC solar field (top left) and MED in parallel/cross flow configuration, 8 effects, 3 preheaters, and condenser, heated with hot water from the solar field (right and bottom) green lines: saltwater, blue line: water, red line: vapor, upper right side: cooler outlet, seawater feed, brine outlet, distillate outlet

Implementing CPC Field

The model block for the solar collector field, piping, controls, auxiliary heating and its water circuit is prepared for fast modelling with time series as data input for parameters such as solar irradiance, time (for sun position), and ambient temperature. The direct and diffuse irradiation on the CPC collectors is modelled on the basis of global irradiance (GHI) values with NREL-Maxwell equations [1]. Standardized collector equations and performance parameters are used for modelling the thermal collector output. Piping heat loss is a relevant aspect and included in the model, for which Ebsilon provides the necessary components.

Irradiance on the tilted collector, composed of direct, diffuse and ground-reflected parts, is calculated according to Liu-Jordan's isotropic approach (2) with

$$E = E_{dir} + E_{diff} + E_{refl} = DNI\ \cos\theta_{long} \tan\theta_{tran} + (GHI - DNI \sin\alpha)\frac{(1+\cos\beta)}{2} + GHI\ albedo\,\frac{1-\cos\beta}{2} \quad (1)$$

applying the interpolated longitudinal and transversal IAM coefficients on direct irradiance, and the diffuse IAM K_d on diffuse and ground-reflected irradiance for determining the absorbed solar power. The typical ground *albedo* value of 0.2 is used. The influence of ground reflected irradiance is very low, could be negligible, under the conditions of this application and low tilt angle. For completeness the equation has been fully implemented.

Following collector performance equations are implemented:

$$\mathrm{E_{abs}} = \eta_{0b}\,\chi\left[E_{dir}\ K_{\theta\mathrm{Long,coll}}(\theta_{long})\ K_{\theta\mathrm{Trans,coll}}(\theta_{tran}) + (E_{diff}+E_{refl})\ K_{\mathrm{d}}\right] \qquad \text{optical gains (2)}$$

$$E_{loss} = a_1\,\Delta T + a_2\,\Delta T^2 \qquad \text{thermal loss (3)}$$

$$Q_{out} = \mathrm{ncoll}\ A_{\mathrm{G}}\ (E_{abs} - E_{loss}) \qquad \text{field thermal output (4)}$$

with ΔT as difference between mean collector temperature and ambient temperature. The collector output power can be negative in periods without solar irradiance if fluid temperature is higher than ambient temperature. The applicable parameters and symbols are listed in table 1.

The concept of collector cleanliness χ is implemented in this model. This parameter specifies optical loss on the collector glass (between incoming solar irradiation and absorber) that is not considered in the collector efficiency under clean test conditions. Dust is depositing on the collectors every day (can be additional 1-2% per day), also called soiling, and has to be cleaned off by washing with water spray and brush regularly to maintain performance. Cleanliness varies strongly depending on the ambient conditions (wind, dust, dew) and the cleaning frequency and intensity. In field application this parameter can be measured on flat glass with a reflectometer, but this is not a common technique. In the modelling this parameter is foreseen to be used as overall factor for performance reduction of any type.

TABLE 1. CPC collector and field parameters (Apricus model ETC-CPC-24)
Block 1 and 4: Solar Keymark Certificate data, block 2: solar field layout data, block 3: cleanliness effect on optical performance

	Name	variable	value	unit
1	collector gross aperture	A_G	5.12	m²
	optical efficiency	η_{0b}	0.54	-
	thermal loss coefficient 1st order	a_1	1.21	W/(m²K)
	thermal loss coefficient 2nd order	a_2	0.004	W/(m²K²)
	IAM for diffuse irradiance	K_d	0.98	-
2	number of collectors per collector row	ncoll	5 / 110	loop / field
	collector field azimuth (to south)	Cazim	0	°
	collector installation tilt angle to south	β	20	°
	sun elevation angle	α	variable	°
3	collector cleanliness	χ	0.9	-

	angle θ	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°
4	iam $K_{\theta \text{Trans,coll}}$	1.00	1.02	1.03	1.04	1.05	1.12	1.18	0.79	0.39	0.00
	iam $K_{\theta \text{Long,coll}}$	1.00	1.00	0.99	0.99	0.97	0.95	0.91	0.83	0.57	0.00

TABLE 2. Process parameters for design point of the solar field

Design case solar field temperature inlet	70°C
Design case feed temperature outlet	85°C
Solar field water mass flow	35 t/h
Pressure at solar field outlet / before control valve	1.4 / 1.2 bar
Estimated solar field piping thermal loss	42 kW
Global solar irradiance GHI	750 W/m²
Direct solar irradiance DNI	calculated [1]
Calculated thermal power	611 kW
Auxiliary steam	144°C (1.03 t/h)

Table 2 presents the design parameters for the whole solar field as modeled with the mentioned parameters.

Implementing MED

The second Ebsilon model block simulates the MED system fed by hot water on the hot end and cooled by seawater on the cold end of the process. Information from the specific plant layout and from the literature [3 - 8] has been used to implement the details of such system. Inlet stream apart from the solar circuit is the seawater, outlet streams are cooling seawater, brine, distillate product (Figure 5 right end).

To implement the solar desalination plant as stationary simulation model in Ebsilon, there are conventional components used, such as valves, pipes, manifolds, pumps, control units, sun. Several specific units of the system however are not available as components in Ebsilon, in particular not for saltwater, and have been programmed as macro components with EbsScript code. These are:

1. the condensing tubular heat exchangers with specified heat transfer coefficients for preheaters and condenser
2. the tubular evaporators with phase change on both sides of the tubes and saltwater spray evaporation with specified heat transfer coefficients, and
3. the flash evaporation of saltwater.

Each component has the specific balances (equations) on energy, water mass, and salt mass and pressure boundary conditions at the respective boiling points of the specific saltwater/brine conditions or water(distillate) to be fulfilled.

Design sea water mass flow in each evaporator and condenser is 4 t/h and 90 t/h respectively. Design heat transfer area of three preheaters varies in the range 4 m² to 16 m². Design heat transfer area of condenser and evaporator are around 75 m² and 100 m² respectively.

According to the most common reference work by El-Dessouky [4], the overall heat transfer coefficient U in each effect, preheater and condenser is a function of condensation temperature. The values are determined for a fouled condenser, including a fouling resistance of 0.08 m²K/kW, with the equations [4]:

condenser/preheater: $$U = 1617.5 + 0.1537\, T_{sat} + 0.1825\, T_{sat}^{\;2} - 0.00008026\, T_{sat}^{\;3} \quad (5)$$

evaporator (effect): $$U = 1939.1 + 1.40562\, T_{sat} - 0.0207525\, T_{sat}^{\;2} + 0.0023186\, T_{sat}^{\;3} \quad (6)$$

where saturation temperature T_{sat} is in °C, and U is in W/m²K. Typical results are in the range of 1800 and 2800 W/m²K, for condenser and 1st effect respectively, directly determining the resulting temperature difference between hot (condensing) and cold (liquid or boiling at lower pressure) side of the heat exchangers.

Pressure loss of the steam side is neglected (set to 0). Pressure loss of the saltwater side is not calculated, as there is no influence on thermal performance of the system. Vapor loss with the non-condensable gases (NCG) to the vacuum system is set to 0. Non-condensable gases, which might influence heat transfer coefficients, are not considered in the model [5]. Non-equilibrium allowance in the effects is neglected [3, 9].

The condenser and the preheater components use the same equations and the identical program code.

Heat transfer is limited to the full condensation of the heating vapor (no subcooling). The effect of possible further scaling on the evaporator tubes can be accounted for by a fouling factor, that reduces the heat transfer coefficient U.

Further Model Adaptation

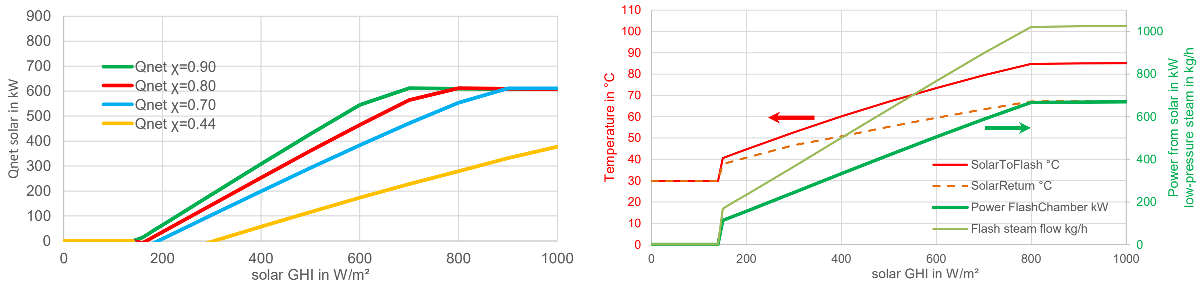
Both model blocks include performance figures to be easily read after a simulation. For both blocks further adaptation of process parameters in the model is possible in order to adapt it to operation data of the real plant. These are the control strategies of mass flow and pressure, heat transfer coefficient modifiers, or solar collector cleanliness. The separate blocks for solar field and MED have been joined to one full model of the plant. The model is prepared for quasi-stationary simulation. In particular start-up and shut-down operation procedures or other transient behaviour of the MED are not implemented at this stage.

RESULTS

The plant in its design configuration reaches modelling results according to table 3. The results show that there is some design margin for the production of the desalination plant, which is specified to 5 t/h of distillate with the specified solar field net power.

TABLE 3. Modelling results of solar MED plant performance

Net power from solar field	611 kW
Top brine temperature	65°C
Distillate production	6.6 t/h
Specific thermal energy for distillation	93 kWh/t
Recovery ratio distillate/feed	0.21
Performance ratio distillate/steam	7.0
Temperature step between effects	2.8 K



(a) (b)

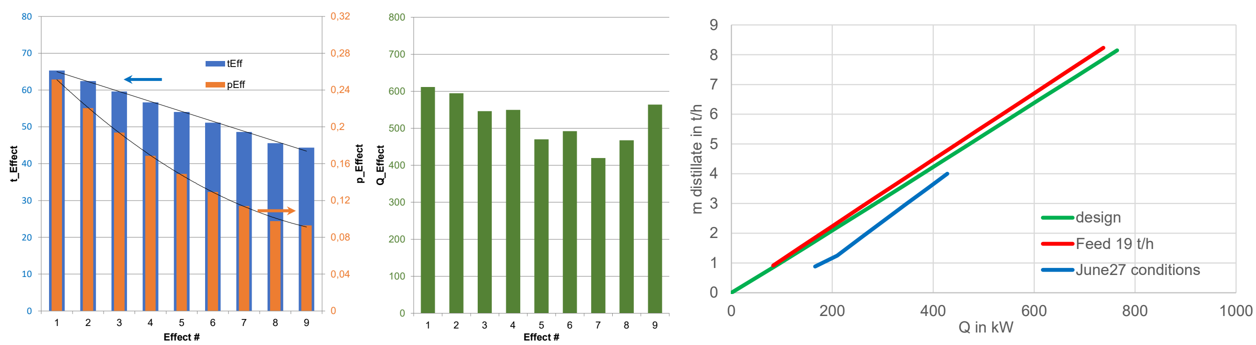
FIGURE 6. (a) Solar field net outlet power for cleanliness of 0.90 to 0.44, simulation results with flow rate 35 t/h and solar field inlet temperature 70°C
(b) Flash chamber inlet and outlet temperature and power depending on solar GHI for design mass flow 35 t/h, for sun position on 27-June 13:00h, simulation results of combined model with cleanliness χ=0.80, T_{amb}=30°C, $T_{seawater}$=29.4°C

For the combined model of solar field and MED it results that flash chamber and top brine temperatures are directly related to the amount of energy coming from the solar field. With the maximum specified feed temperature of the solar part to the flash chamber, the power is limited at 611 kW. Figure 6 shows this relation.

The model component parameterization has been adapted to also reproduce operation data with lower specific distillate production. The model parameters for tuning the Ebsilon model with the objective of good agreement with the operation data include in particular demister pressure loss, condenser pressure and preheater steam mass flow.

Parameters such as feed flow rate and brine recirculation ratio are apparently of low influence on the performance.

The simulation with the model and design parameters shows a good agreement with the available design data. Distillate production rate under ideal design conditions is above the design value, according to expectations. The comparison of the process engineering and design data and plant data from 7 days of trial operation with solar heating in June 2020 helps to identify the cause of deviating performance and to suggest solutions to improve heat collection in the solar field. The model has been validated with operation data from June 2020. The MED process operation data comparison to the model shows principally good agreement. In detail it reveals that the preheating train of feed saltwater of the plant is underperforming in comparison to the model, leading to increased specific steam demand and thus reduced distillate production (Fig.1c). The data shows deviations of temperature and pressure in the flash chamber before the first effect and in the condenser that could be due to trapped air (non-condensable gas) in the system.



(a) (b) (c)

FIGURE 7. MED effects model results: (a) pressure in bar and temperature in °C, (b) power in kW for the design point, (c) desalinated water production rate simulated for design (green, red) and operation data (blue)

The models can be applied for simulation of the solar field alone and the MED plant alone. The combination of both model blocks into one single model is demonstrated to simulate the entire plant with specific operating parameters or as time series, in particular concerning the solar irradiation input data variation.

Simulation results of the combined model show that the flash chamber temperature strongly depends on the amount of energy from the solar field, determining also the top brine temperature in the first effect of the MED. Other control parameters of the plant have only low influence on this top brine temperature level.

The models are set up and prepared with components and process parameters for a specific commercial project, but the new components can be flexibly used with other parameters or modified programs for different configuration of a solar desalination with multiple-effect distillation.

CONCLUSION

The model in Ebsilon introduces new components for the solar collector rows, for saltwater flash evaporation, saltwater evaporators, preheaters and condenser. Technical data has been implemented as specification values for components and streams. With the provided variations in parameters such as condenser and flash pressure, preheater steam flow and demister pressure loss it is possible to reproduce trial operation data of the plant from June 2020. This serves as validation of the developed model.

The simulation shows for the solar field that at high irradiance the temperature limitation at 85°C in combination with the mixing valve control leads to collector temperatures above 140°C. To maintain flow through the collectors, elevated pressure behind the pump would be required, otherwise the collectors (or some of them) go into stagnation and no energy will be delivered from the affected loops to the solar circuit.

Further observation concerns the saltwater feed preheaters. According to the operation data, the transferred heat in the preheaters is too low in comparison to the model results. In order to reproduce the lower performance of the preheaters in the model, the mass flow split to the preheater from the respective effect can be set in the model. The reason for the low performance of the preheaters must be a too low steam-side mass flow and is probably the steam-side pressure level which could be influenced by some valve or other pressure drop or by geodesic height difference to the effects. This reduces the production rate and increases the specific energy consumption.

The Ebsilon model can be used as digital twin for the physical plant to analyze the influence of operation parameters such as mass flow and temperature of solar circuit, seawater to condenser, feed to MED, and brine recirculation under different solar energy input levels on the distillate production and the key performance parameters. The parametric studies are suggested to be performed in particular with the MED part of the model and using the time series function of Ebsilon to produce tables of calculation results. The performance of the solar field can be analyzed by relatively simple energy balance or with support of the solar field part of the Ebsilon model.

ACKNOWLEDGMENTS

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