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Performance Test of a E-Zuetina Sea Water Desalination Plant

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Abstract:
The present study is applied on the seawater multi-stage flash (MSF) desalination plant that is currently under operation in E-Zuetina operations plant located in Libya. The plant contains 21 evaporator stages at capacity of 10025 (ton/day). The presented operating data has been collected during a visit of the plant, a mathematical model for multistage flash (MSF) desalination plants was developed. The model was based on basic principles of physics and chemistry that describe the stages occurring in the desalination process. The input plant parameters that are known to affect the operation of the MSF desalination plant and its performance were taken into account in the construction of the model. These parameters included make-up flow, brine recycle flow, seawater flow, seawater temperature, seawater concentration, steam temperature and the plant load. For each stage, the developed model was used for predicting the temperatures and pressure of the brine, distillate, cooling brine, and the flow rates of brine outlet and distillate production. The developed model was evaluated with the MSF plant vendor simulation results and its actual operating data. The evaluation indicated that model predictions matched well with the vendor simulation results and the plant operating data.
The developed model is sufficiently accurate and model predictions can be relied upon. Therefore, it may be recommended for determining optimum set point of a running MSF desalination plant at different loads to maximize the water production or minimize energy consumption. It can also be used to calculate controller set points for different loads of the plant.

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Keywords:E-Zuetina MSF Desalination Plant, case study, stage model, brine heater.

اختبار أداء محطة تحلية مياه البحر بالزويتينة

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الملخص:

تم تطبيق هذه الدراسة على محطة تحلية مياه البحر متعددة المراحل (MSF) والتي هي قيد التشغيل حاليا في محطة عمليات الزويتينة الواقعة في ليبيا. تحتوي المحطة على 21 مرحلة بقدرة 10,025 (طن/ يوم). تم جمع بيانات التشغيل المقدمة خلال زيارة ميدانية للمحطة.

تم تطوير نموذج رياضي لمحطات التحلية بالفلاش متعدد المراحل (MSF). واعتمد النموذج على المبادئ الأساسية للفيزياء والكيمياء التي تصف المراحل التي تحدث في عملية تحلية المياه. تم الأخذ بعين الاعتبار جميع المغيرات المعروفة بتأثيرها على تشغيل محطة تحلية المياه MSF وأدائها عند بناء النموذج. وشملت هذه المتغيرات التدفق التعويضى، وتدفق إعادة تدوير المحلول الملحي، وتدفق مياه البحر، ودرجة حرارة مياه البحر، وتركيز مياه البحر، ودرجة حرارة البخار، سعة المحطة. ولكل مرحلة تم استخدام النموذج المطور للتنبؤ بدرجات حرارة وضغط المحلول الملحي ونواتج التقطير ومحلول التبريد ومعدلات تدفق خروج المحلول الملحي ونواتج التقطير. تم تقييم النموذج المطور باستخدام نتائج التشغيل التجريبية المقدمة من الشركة المصنعة وبيانات التشغيل الفعلية الخاصة به. وأشار التقييم إلى أن تنبؤات النموذج تتطابق بشكل جيد مع نتائج محاكاة وبيانات تشغيل الشركة المصنعة.

الكلمات المفتاحية: محطة تحلية الزويينة MSF ، دراسة الحالة ، نموذج المرحلة ، سخان المحلول الملحي .

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1. Introduction.

The goals of modeling and simulation in the process industry include improving and optimizing designs, and developing better insight into the working of the process, ultimately leading to the optimal operation and control of the process. A steady-state model consists primarily of algebraic equations that describe system process, mass balance and energy balance through the system cycle. It is mainly applicable for design purposes as well as for parametric studies of existing plants to evaluate their performance and to adjust or optimize operating conditions.

2. Process description of the selected MSF desalination Plant.

The multistage flash (MSF) desalination plant (evaporator) constitutes a number of stages placed in series, each at a successively lower pressure. This pressure is maintaining by operating a vacuum system. The flash evaporation process is repeated in each stage down the line. Each stage consists of two sections: flash chamber and the heat exchanger tube bundle. In the flash chamber, the superheated brine entering the stage (flashing brine) is flash vaporized. The vapor so produced condenses on the outer surface of the tube bundle placed at the top of the flash chamber. The incoming brine (cooling brine) flows inside the cooling tubes as a coolant, counter current to the flashing brine. The condensate product falls into a product tray located below the tube bundle [1,2].

The flow schematic of the selected MSF desalination plant is shown in Figure 1 (recycle brine type plant) with the symbols given to the different variables in this work. It can be seen that the plant consists of three separate sections namely, the heat input section (brine heater), the heat recovery section (HRS) and the heat rejection section (HRJ). Each of HRS and HRJ constitutes of series of stages. The HRS constitutes 18 stages (stages 1–18) whereas the HRJ constitutes three stages (stages 19–21). Connected to the last stage (stage 21) is the deaerator that receives the makeup stream. The function of the HRJ is to reject the surplus thermal energy from the plant; thus, cooling the distillate product and the concentrated brine to the lowest possible temperatures as they emerge from the plant (through stage 21). Dimensional details of the selected MSF

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desalination plant are given in Table 1. The seawater feed to the plant (F_{sea}) is allowed to pass through the tube side of the HRJ (i.e., from stage 21 to 19). On leaving the HRJ (stage 19), the seawater feed stream is split into two parts: the reject seawater (C_w) and the makeup seawater stream (Fm). The reject sea water stream is rejected back to the sea, thus rejecting part of the heat supplied. On the other hand, the makeup stream first enters through the deaerator unit to strip its dissolved air by using steam. It is then combined with the remaining brine stream (R) to form the combined stream (W). This combined stream will be the cooling brine feed for the HRS inlet. The process initiates when the cooling brine (W) flows to the tube side of the HRS (the inlet at stage 18), where it is heated gradually by the flashing brine of each stage as it is proceeding from last to the first of the HRS (at stage 1), finally the cooling brine enters the heat input section (brine heater). In the brine heater, with low-pressure steam as the heating medium, the cooling brine from stage 1 is heated from T_{F1} at the inlet of the brine heater to the maximum temperature T_{B0} that is close to the saturation temperature at the system pressure. At this point, the flashing brine enters stage 1 of HRS through an orifice; thus, reducing the pressure. As the brine was already at its saturation temperature for a higher pressure, the brine will become superheated and starts flashing to produce desalted water vapor in stage 1. This desalted water vapor passes through the tube bundle of the heat exchanger where it is condensed and dripped into the distillate product tray, where the distillate is collected.

As the flashing brine would be still hot enough to boil again at slightly lower pressure, the flashing brine flows into the next stage and the flashing process is then repeated all the way down the plant. This is happened as the flashing brine flows in the consecutive stages where pressure is decreased proceeding from left to right. The distillate in stage 1 then flows to stage 2, and together to stage 3 and so on. The accumulated distillate from all stages is finally collected in a distillate box at the last stage of the HRJ (DN) and is extracted by a distillate pump.

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As it leaves the plant, the concentrated brine (BN) of the last rejection stage (stage 21) is then split into two streams: the blow down stream (BD) and the remaining brine stream (R). The brine blow down stream is discharged back to the sea, whereas the remaining brine is returned back to combine with the makeup seawater stream to form the combined stream (W). This combined stream passes through the HRS inlet (stage 18) to serve as the cooling brine.

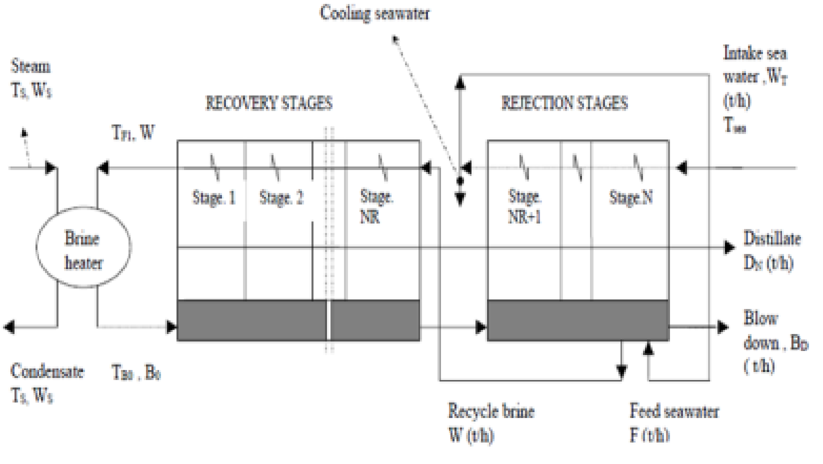

Figure 1. Multi-stage flash desalination process [3,4]

3. Methodology.

1. Collect the process details of the selected MSF desalination plant including its dimensional details and intake seawater conditions. The dimensional details include the number of stages, the number of tubes per stage, the tube internal diameter, the effective tube length, the tube thermal conductivity, the fouling factor, the tube bundle width, the tube material, the overall heat transfer coefficients, the distillate duct height from bottom, the demister height from bottom, the stage length, the stage width, the stage height, the demister specific area and the free volume. The intake seawater

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parameters include the temperature and the salt concentration.

2. Collect the vendor simulation data of the selected plant for various plant loads during summer and winter operations such as seawater flow rate, makeup flow rate, brine recycle flow rate, TBT, steam temperature and steam pressure.
3. Develop the mathematical model that describing the physical phenomena occurring in the flash evaporation stages based on the basic equations of mass balance, enthalpy balance and the equilibrium relations.
4. Select appropriate methods to solve the developed model
5. Check the developed model accuracy with the design/vendor simulation data of the selected MSF plant

4. Model Equations:

The model was based on basic principles of physics and chemistry that describe the process occurring in the MSF plant. The model equations are constituted of a set of mass and energy balance equations (nonlinear algebraic equations) [1,2] that include the following:

- Overall material balance equations.
- Material balance equations for each stage.
- Salt balance equation for each stage.
- Mixing and splitting equations.
- Enthalpy balance equations on flashing brine
- Overall enthalpy balance for any stage
- Heat transfer equation.
- Equilibrium relation
- Brine heater model.

The model was developed with the following assumptions [5]:

- The distillate produced and accumulated in any stage is salt free.
- No heat losses occur at any stage of the process.

- Heat of the mixing of brine solutions is negligible.
- All the saline liquid droplets are retained in the demister.

Linearization of the equations for the MSF plant and tri-diagonal matrix arrangement (TDM formulation) [1,2].

4.1.Overall Material Balance Equations.

The overall material balance for the MSF plant (Figure 2) is given by:

$$F_{sea} = C_w + D + B_D \quad (1)$$

The material balance for the seawater splitter is given by:

$$F_{sea} = F_m + C_w \quad (2)$$

Substituting Equation (2) into Equation (1) yields:

$$F_m = D + B_D \quad (3)$$

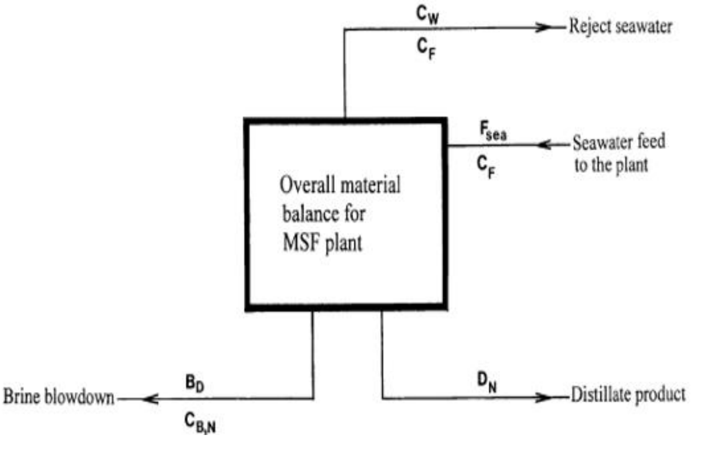

Figure 2. Overall Material Balance for MSF Plants.

As per Equation (3), the overall material balance for the MSF plant has one input stream (the makeup feed seawater, F_m), and two output streams (the distillate product, D, and the brine blow downstream, (B_D). Therefore, the excess energy added to the system in the brine heater is rejected in brine blow down, distillate product and reject seawater streams.

The Overall Salt Balance is Given By:

$$F_m \quad C_F \quad = \quad B_D \quad C_{B\,N} \tag{4}$$

It should be noted that the above equation assumes that the distillate is salt free.

4.2.Material Balance Equation for Each Stage.

For any stage j in the heat recovery or HRJs, except for stage 1, at steady state, the sum of the stage inlet flashing brine and distillate flow rates should be equal to the sum of these steams leaving the stage (Figure 3).

$$B_{J-1} + D_{j-1} = B_J + D_J \tag{5}$$

For stage 1, the mass balance is given by:

$$B_0 = B_1 + D_1 \tag{6}$$

Since no distillate enters the first stage ($D_0 = 0$). It should be noted here that $B_0 = W$.

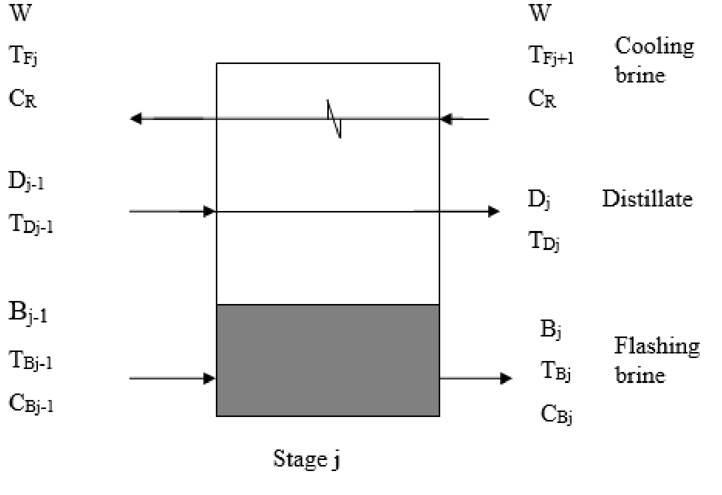

Figure 3.Materail Balance for any Stage j. Except Stage 1.

4.3.SaltBalance Equation for Each Stage.

Similarly, the salt balance equation for any stage j in the heat recovery or HRJs (Fig 3) is given as:

$$B_{j-1}\ C_{B\,j-1} = B_j\ C_{B\,j} \qquad (7)$$

4.4.Mixing and Splitting Equations

Each splitter is described by a mass- balance equation, as well as two temperature equalities and two salt concentration equalities. from Fig1 the following mass- balance equations are written:
Reject seawater splitter [4]

$$Cw = WT - F \qquad (8)$$

Overall salt balance recycle concentration

$$\mathrm{CR} = (\mathrm{F\ CF} + (\mathrm{W} - \mathrm{F})\ \mathrm{CBN})/\mathrm{W} \qquad (9)$$

4.5.Enthalpy Balance Equations on Flashing Brine.

Referring to Figure 3, the enthalpy balance equation on the flashing brine at any stage j, in the heat recovery or HRJs, is given by:

$$B_{J-1}\ h_{BJ-1} = B_J\ h_{BJ-1} + (B_{J-1} - B_J)h_{VJ} \qquad (10)$$

Enthalpy of flashing brine h_B and h_B-j in Equation (10) are calculated by:

$$h_{BJ} = (4.185 - 5.381 \times 10^{-3}\, C_{BJ} + 6.26 \times 10^{-6}\, C_{BJ}^2) \times T_{BJ} - (3.055 \times 10^{-5} + 2.774 \times 10^{-6}\, C_{BJ} - 4.318 \times 10^{-8}\, C_{BJ}^2)T_{BJ}^2 + (8.844 \times 10^{-7} + 6.527 \times 10^{-8}\, C_{BJ}^2 - 4.003 \times 10^{-10}\, C_{BJ}^2)T_{BJ}^3 \qquad (11)$$

4.6.Overall Enthalpy Balance for Any Stage.

The sum of the enthalpies of all the streams entering the stage should be equal to the sum of all those leaving the stage for a steady-state operation, since there is no accumulation or generation of energy

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within the stage. Considering the T* as the reference temperature for all enthalpy evaluation, the enthalpy balance for any stage j, in the heat recovery or HRJs [4], is given by:

$$\begin{aligned} WS_{RJ}\left(T_{FJ} - T_{FJ-1}\right) &= D_{J-1} S_{DJ-1}\left(T_{DJ-1} - T^{*}\right) \\ &+ B_{J-1}S_{BJ-1}\left(T_{BJ-1} - T^{*}\right) - D_J S_{DJ}\left(T_{DJ} - T^{*}\right) \\ &- B_J S_{BJ}\left(T_{BJ} - T^{*}\right) - Q_J \qquad (12) \end{aligned}$$

4.7.Heat Transfer Equation.

The heat transferred due to condensation of the flashed vapor on the cooling tubes in any stage j, in the heat recovery or the HRJs [3], is given by:

$$W\, S_{RJ}\left(T_{FJ} - T_{FJ+1}\right) = \frac{U_J\, A_J\left(T_{FJ} + T_{FJ+1}\right)}{\ln \frac{T_{DJ} - T_{FJ+1}}{T_{DJ} - T_{FJ}}} \qquad (13)$$

4.8.Equilibrium Equation.

The flashing brine temperature (TB j) and the distillate temperature (TD j) in any stage j are related by the following equation accounting for the boiling point elevation, the non-equilibrium allowance and the temperature loss due to pressure drops through demister and the condenser tube bundle.

$$T_{BJ} = T_{DJ} + \Delta T_{PBR\,J} + \Delta T_{NONE\,J} + \Delta T_{DEM\,J} + \Delta T_{TB\,J} \qquad (14)$$

4.9.Brine Heater Model.

Referring to Figure 4, the total mass balance for brine heater is given by:

$$B_0 = W \qquad (15)$$

Since $B_0 = W$, then the salt balance gives:

$$C_{B0} = C_R \tag{16}$$

For making enthalpy balance of the brine heater figure 4, two assumptions are made; steam condensate does not sub-cool and heat loss to surroundings is negligible. Therefore, the enthalpy balance can be written as:

$$W\,S_{R,H}(T_{B0} - T_{F1}) = W\,\lambda_s \tag{17}$$

The heat transfer equation for brine heater can be described by:

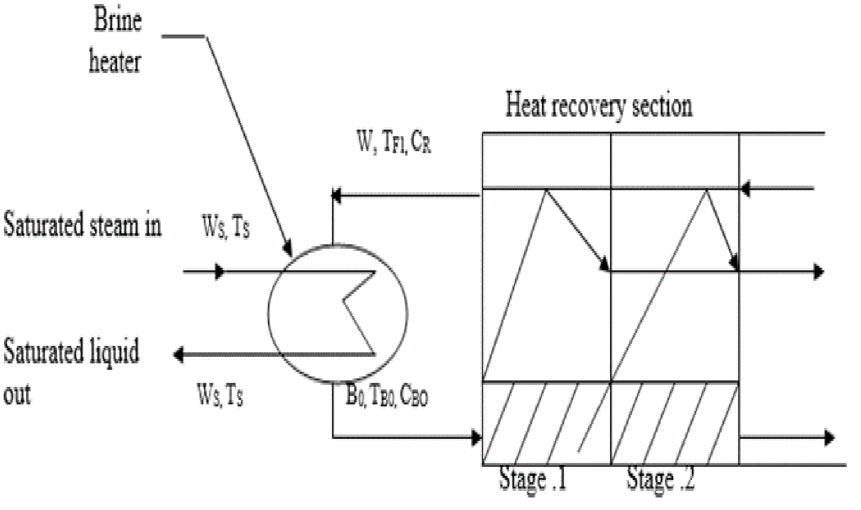

Figure 4. Heat Input Section [4].

$$W\,S_{RH}\left(T_{B0} - T_{F1}\right) = \frac{U_H\;A_H\;(T_{B0} + T_{F1})}{\ln\frac{T_S - T_{F1}}{T_S - T_{B0}}} \tag{18}$$

5. Computation procedure.

Evaluation of production rate, temperature and flow rate profiles for the specified operating conditions in agiven plant is the basic objective to be fulfilled by a computation module for any MSF study. The stepwise procedure for such a module is described below [5].

Step 1: Specify the following data:

- Dimensional parameters for the flash chambers, heat exchanger bundle and brine heater (number of stages, number of tubes per stage, tubes thermal conductivity, fouling factors, tubes materials) (Table 1).
- Seawater: Temperature (T_{sea}), salt concentration (C_F) and flow rate (F_{sea}).
- Makeup flow rate (Fm). Recycle brine flow rate (W).
- Steam to brine heater: temperature (Ts).

These data can be obtained from vendor simulation manual as well as from plant.

Step 2: Assume suitable brine levels in all stages.

Step 3: Estimate initial temperature profiles for the flashing brine ($T_{B\,j}$) distillate ($T_{D\,j}$), and cooling brine. (T_{Fj}), in all stages. An initial guess for flashing brine temperature (T_{Bj}) is obtained by linear interpolation between the TBT and the seawater temperature (T_{sea}) as follows:

$$T_{BJ} = TBT - J\Delta TB \quad (19)$$

Where:

$$\Delta\ TB = \frac{TBT - T_{SEA}}{N} \quad (20)$$

A profile for cooling brine ($T_{F\,j}$) is obtained using the following interpolation relations [4,5]:

$$T_{FJ} = T_{BN} + (N - i)\,\Delta TB - (J - 1)\,\Delta TB \quad (21)$$

This is for cooling brine in HRS, where i is the number of stages in the HRJ. The cooling brine temperature at HRJ is calculated as follows [4,5]:

$$T_{FJ} = T_{SEA} + (N + 1 - J)\,\Delta T_{diff} \tag{22}$$

Where:

$$\Delta T_{diff} = \frac{T_{BN} - T_{SEA}}{i} \tag{23}$$

Step 4: Assume the makeup feed temperature (T_F). The makeup feed enters the flashing chamber of the last stage. Part of the brine from the last stage of HRJ is discharged to sea as blow down and the other part is mixed with the makeup feed and this mixed stream is pumped to the last stage of HRS as cooling brine. It is worth noting that the temperature of the exiting makeup feed from first stage of heat rejection should be same as stream entering the last stage of HRS.
Step 5: Calculate the flashing brine flow rate in all stages (B j) using flashing brine enthalpy balance, starting from the first stage. The flashing brine flow rate is calculated using the enthalpy balance equations. The flashing brine flow rate for the stage 0 or brine heater is equal to the recycle flow rate. Whereas for the last stage, flashing brine flow rate (B_N) is equal to the remaining brine (R) plus blow down (B_D) flow rates.
Step 6: Calculate distillate flow rate in all stages (D j) using material balance for flashing brine. The amount of distillate in last stage (D_N) is the accumulated sum of the distillate produced in each separately.
Step 7: Update the salt concentration in flashing brine by salt balance in all stages.
Step 8: Evaluate the coefficients of TDM matrix and solve it to update the cooling brine temperature profile ($T_{F\,j}$).
Step 9: Use the new ($T_{F\,j}$) profile obtained in the above step to update the distillate temperature profile ($T_{D\,j}$).
Step 10: Update the flashing brine temperature profile ($T_{B\,j}$) using converging criteria [2],
Step 11: If the convergence criteria for $T_{B\,j}$ profile are satisfied, go to step 12, otherwise repeat the procedure from step 5.
Step 12: If the makeup temperature (T_F) is equal to exit cooling brine temperature from first rejection stage then calculate brine levels, otherwise repeat from step 5.

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6. Case study.

To check the accuracy of the developed model, Ez-zuetina MSF desalination plant selected as case study [6]. The capacity of the plant is 10,000 ton/day and the total numbers of stages are 21, 18 in recovery section and 3 in rejection section. The dimensional data of the selected plant were given in Table 1. Vendor- simulated data of the plant given in Table 2 is used to check the accuracy of the developed model predictions.

Table 1. Dimensional Details of the Selected MSF Desalination Plant.

Variables	Unit	Brine heater	Heat-recovery section	Heat –rejection section
Number of tubes		1302	1313	1410
Tube length – stage width	mm	13090	9000	9400
Tube inside diameter	mm	22	22	18
Area of heat transfer	m^2	1274	891	791
Coefficient of heat transfer at 100 clean٪	$W / m^2 k$	3740	3971	3346
Coefficient of heat transfer at design point	$W / m^2 k$	2652	3323	2106
Fouling factor at design point	$m^2 \ k / w$	0.000178	0.00009	0.000178

Table 2. Design Operational Details of the Selected MSF Plant.

Process variables	Units	Specification
Sea water inlet temperature	C°	28
Distillated produced	t/h	416.7
Steam flow rate to brine heater	t/h	52.2
Recycle brine flow rate	t/h	3313
Sea water flow rate	t/h	2800
Make-up flow rate	t/h	1049
Blowdown flow rate	t/h	632.5
Steam temperature to brine heater	C°	124.4

The model-predicted results for the same vendor-simulated conditions are presented in Table 3. A comparison of the vendor-simulated results with the developed model predictions indicates that the agreement between the two is excellent in Table 4.

Table 3. Model Predictions for Given Operation Conditions.

Stage No.	Flashing brine flow rate B_j t/h	Distillate flow rate D_j t/h	Flashing brine concentration mass fraction	Cooling brine Temp TF C°	Distillate Temp TD C°	Flashing Brine Temp TB C°
0	3313	0	0.06145	0	0	117.853
1	3286.5	26.517	0.06194	109.442	112.709	113.334
2	3266.3	46.681	0.06232	105.885	109.21	109.832
3	3245.9	67.042	0.06272	102.259	105.637	106.254
4	3225.4	87.562	0.06311	98.566	101.993	102.607
5	3204.8	108.201	0.06352	94.814	98.285	98.895
6	3184.9	128.923	0.06393	91.006	94.517	95.154
7	3163.3	149.69	0.06435	87.15	90.695	91.300
8	3142.5	170.466	0.06478	83.249	86.825	87.428
9	3121.8	191.218	0.06521	79.309	82.911	83.515
10	3101.1	211.913	0.06565	75.336	78.959	79.565
11	3080.5	232.52	0.06608	71.335	74.975	75.585
12	3060.0	253.01	0.06653	67.311	70.964	71.579
13	3039.6	273.357	0.06697	63.268	66.931	67.554
14	3019.5	293.535	0.06742	59.212	62.880	63.515
15	2999.5	313.519	0.06787	55.147	58.816	59.468
16	2979.7	333.286	0.06832	51.078	54.745	55.417
17	2960.2	352.812	0.06877	47.009	50.670	51.363
18	2940.9	372.075	0.06922	42.947	46.596	47.329
19	2927.4	385.573	0.06954	38.894	43.686	44.469
20	2913.1	399.885	0.06988	35.489	40.593	41.412
21	2898.0	414.983	0.07025	31.861	37.293	38.159

of Various Parameters of Vendor Simulation Results withModel Predictions.

Parameter	unit	Vendor simulation	Model predictions
Steam flow rate	t/h	52	54.1
Distillate flow	t/h	416.7	414.98
Average distillate production	t/h	19.84	19.76
Blowdown flow	t/h	632.5	634.3
Inlet temp in recovery section	C °	38.2	38.89
Out let temp from recovery section T_{F1}	C °	109.3	109.44
Total temp rise in recovery stages	C °	71.1	71.28
Temp of last stage	C °	38.2	38.16
Inlet / outlet temp in brine heater	C °	109.3 / 118	109.3 / 117.85
Blowdown temp	C °	38.5	38.16
Distillate temp	C °	37.0	37.29
Total salinity in recovery section	mg / l	0.06038	0.06145
Salinity of blowdown	mg/l	0.06780	0.07025
Press 1st stage	Bar (abs)	1.59	1.55
Press last stage	Bar (abs)	0.064	0.064
Average velocity In tubes (recovery S & brine heater)	m/s	1.81	1.82
Average velocity In tubes (rejection s)	m/s	2.16	2.12

7. Conclusion:

In this paper, a steady-state mathematical model was developed to study the performance of the selected MSF desalination plant. The developed model is based on basic principles of physics and chemistry to describe the physical phenomena occurring in the

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process. It was constructed after considering all limitations of the desalination unit from construction, operation and capability angles**.** The developed model predictions were compared with vendor simulation results and the actual operating data for the MSF desalination plant, and matching was found very well. Thus, the developed model was considered to be sufficiently accurate. It is safe to assume that the model predictions would be reliable over complete operating plant range since the models are based on basic principles of physics and chemistry; not empirical model**.**

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