Evaluation Study of the Optimal Operational Conditions for Multistage Desalination Plants

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Abstract:

This study evaluates the various operating conditions of the north Benghazi MSF desalination plant under its design constraints to determine the optimal operational conditions. The researchers begin with a discussion of the most important process variables that directly affect the production and performance ratio of the plant such as seawater flow rate, brine recirculating flow rate, make-up feed flow rate, and the temperature of the steam to brine heater. Thus, they constructed a computer code specially developed to simulate the plant's steady state and study the effects of operational variables on the system output. To this end, only one variable is varied whereas all the other variables have the same values as those corresponding to the reference case. The results showed that the brine recirculation flow rate and temperature of steam introduced to the brine heater are of the most important operation variables which have a significant effect on the distillate product and performance ratio of the system. After that, the optimal operating conditions for achieving a stable plant operation were evaluated, and the operation envelope could be constructed. In this envelope, solid lines refer to the constant recirculation brine flow rate, which varies between values corresponding to the allowable limits of velocities through cooling tubes, while the dashed lines represent constant steam temperatures varied between its allowable limits. In summary, we can operate at any point within the envelope and on its borders.

Keywords: Evaluation, Process Variables, Desalination Plants, Optimization, MSF.

الملخص:

تتناول هذه الدراسة تقييم ظروف التشغيل المختلفة لمحطة تحلية شمال بنغازي MSF تحت قيود التصميم الخاصة بها لتحديد ظروف التشغيل المثلى. حيث نبدأ بمناقشة أهم متغيرات العملية التي تؤثر بشكل مباشر على نسبة إنتاج وأداء المحطة؛ مثل معدل تدفق مياه البحر ومعدل تدفق إعادة تدوير المحلول الملحي ومعدل تدفق التغذية ودرجة حرارة البخار إلى سخان المحلول الملحي باستخدام برنامج كمبيوتر. تم إنشاء وتطويرهذا البرنامج خصيصًا لمحاكاة الحالة المستقرة و دراسة تأثير متغيرات التشغيل على مخرجات النظام. للقيام بذلك يتم تغيير متغير واحد وتبقكل المتغيرات الأخرى ثابتة بنفس القيم المناظرة للحالة المرجعية.وقد أظهرت النتائج أن معدل تدفق إعادة تدوير المحلول الملحي ودرجة حرارة البخار الداخل إلى سخان المحلول الملحي من أهم متغيرات التشغيل التي لها تأثير كبير على ناتج التقطير ونسبة أداء النظام. بعد ذلك تم تقييم ظروف التشغيل المثلى لتحقيق عملية تشغيل مستقرة للمحطة، وأمكن إنشاء منحنى التشغيل حيث تشير فيه الخطوط المتصلة إلى معدل التدفق الثابتللمحلول الملحي المعاد تدويره، والذي يتغيرضمن القيم المناظرة للحدود المسموح بها للسرعة عبر أنابيب التبريد، وتمثل الخطوط المتقطعة درجات حرارة ثابتة للبخار تتغيرضمنالحدود المسموح بها له. باختصار يمكننا العمل في أي نقطة داخل المنحنى أو على حدوده.

1. Literature review

Simulating MSF plants provides the ability to optimize designs and predict a plant's performance under the intended operating conditions. It can save much time and money when operating policies have to be altered. Almost all MSF simulations are based on solving the numerous, nonlinear and complex mass and heat balance equations stage to stage calculations.

Optimizing the operation of an existing MSF plant by evaluating the optimal operating conditions for achieving stable plant operation using codes developed for steady state simulation under process constraints. (Abujazyah, 2017)describes the mathematical model developed for evaluating the performance of multistage flash (MSF) desalination plants at steady state operation. The governing equations are linearized and arranged in a tridiagonal matrix form. The solutions of these equations are obtained by a computer code written in visual basic language in a user-friendly format developed for this purpose. This code can predict the plant's productivity with profiles of temperatures and flow rates for all stages in the unit. The present results were compared with some previous results presented in literature, and with the design data of the MSF plant in Benghazi. The comparisons show good agreement with these available data.

(Helal et al. 1986) developed a technique to solve the large system of nonlinear equations which describe the behavior of MSF desalination plants. In his approach, the balance equations and heat transfer relations are linearized using data from previous iterations as well as the present calculations. Using this method, the arrangement of linearized enthalpy balance and heat transfer equations are in a TDM form.

(Husain et al. 1994)described the work done on modeling and simulation of an MSF plant containing 15 recoveries and 3 rejection stages. He used the Fortran program for the steady state simulation based on tridiagonal matrix formulation. Good agreement was achieved by comparing with the vendor supplied as well as actual plant data.

(Rosso et al. 1996) described a steady state mathematical model developed to analyze MSF desalination processes. The model allows to calculate plant productivity together with the profiles of

temperatures and flow rates in all the stages of the unit. They noticed that no attempt was made to optimize the performance parameter.
(El-Dessouky et al. 1995) described a steady state mathematical model developed to analyze the MSF water desalination process. The result obtained from the model developed were compared with data from different MSF plants. Good agreement was reported between the data of these plants and model predictions.

2. Description of the MSF process

Figure 1 shows a schematic diagram of the MSF system. The system involves six main streams: intake seawater, rejected cooling seawater, distillate product, rejected brine, brine recycle and heating steam. The system contains flashing stages, a brine heater, pumping units, venting system, and cooling water control loop. The flashing stages are divided into Two sections: heat recovery and heat rejection. The intake seawater is introduced into the inside of the condenser tubes of the last flashing stage in the heat rejection section. Similarly, the brine recycle stream is introduced into the inside of the condenser tubes of the last flashing stage in the heat recovery section. The flashing brine flows counters to the brine recycle from the first to the last flashing stage (Abujazyah, 2017). To evaluate the optimal operation conditions, we must study the effect of process variables such as (seawater flow rate, make up flow rate, brine recirculation flow rate and temperature of steam introduced to the brine heater) on production and performance ratio of the plant. With the need to take into account, the following process constraints:

- Upper and lower limits of the steam temperature.
- Upper and lower limits of the velocity inside the tubes.
- The makeup feed temperature should be close enough to the flashing temperature in the last stage.

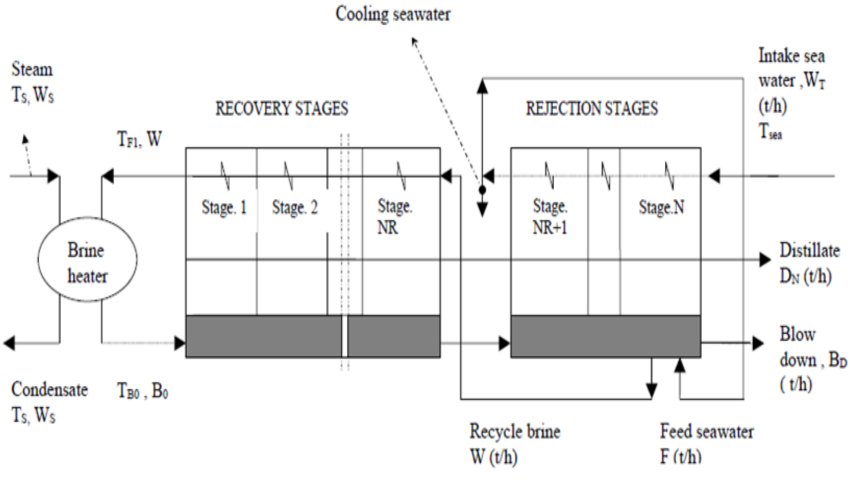

Figure 1. Recirculation brine multistage flash (MSF) desalination plant

3. System performance

Plant performance can be defined as the ratio of the distillate product rate to the rate of steam supplied to the plant. Another way to define the performance is to estimate how much kg of water can be produced by the input of 540 kcal to the brine heater or to the first effect.

$PR = \frac{D_N}{W_S}$ This ratio is dimensionless (1)

The specific heat consumption (q) is defined as being the ratio between the heat flux injected to the brine through brine heater and distillate output.

$q = W_s * \lambda_s / D_N$ (2)

4. Case study

The north Benghazi (Libya) MSF desalination plant as a case study. The capacity of the plant is 6000 tons/day and the total number of stages are 20, 17 in recovery section and 3 in rejection section. The design operational and dimensional data are listed in Tables 1 and 2. The heat balance diagram of the plant presented by the contractor is shown in Figure 2.

Table 1. Design and operational data of North Benghazi desalination plant (ELECTROBEL, 1972)

Processes variables	Units	Specifications
Sea water inlet temperature	° C	27
Distillated produce	t/h	250
Steam flow rate to brine heater	t/h	34.1
Recycle brine flow rate	t/h	2915
Sea water flow rate	t/h	2230
Make-up flow rate	t/h	875
Blow down flow rate	t/h	625
Steam temperature to brine heater	° C	103
Top brine temperature	° C	90

Table 2. Design and dimensional details of North Benghazi desalination plant (ELECTROBEL, 1972)

Variables	Unit	Brine heater	Heat recovery section	Heat rejection section
No. of tubes		1535	1520	1433
Tube (D_I)	mm	18	18	16
Tube (D_O)	mm	20	20	18
Area	m2	842	840	703.33
(U_D)	Kcal/m2. c/hr	1700	2453	2100
F. F	$(Kcal/m2.\ c/hr)^{-1}$	3.5819	1.667	1.945
V of brine	m/s	2.0	2.0	2.1

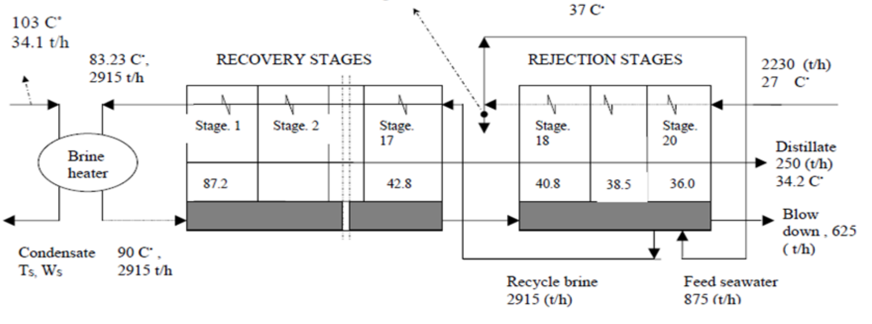

Figure 2. Heat balance diagram for multistage flash desalination plant presented by the contractor

5. The mathematical model

There are many models developed to find a functional relationship between the MSF process design variables and the different operating parameters. The models are well developed from the basic laws of total and component mass balances, enthalpy balance coupled with heat and mass flow rate coefficients. These models must be supported by equations to calculate the thermal and physical properties of fresh and salt waters as functions of temperature and salinity. These models are either simplified or very complicated. The simplified models are based on many assumptions such as a constant temperature drop for each stage, a constant specific heat at constant pressure for water with different salt concentration and at different boiling temperatures, neglecting the thermal losses between the plant and its surroundings, constant heat transfer coefficient in the three different sections of the plant, and the thermodynamic losses inside the flashing chambers. These assumptions cause a larger discrepancy in the result of the models and the actual data (Helal et al. 1986).

The steady state mathematical model of the multi stage flash desalination process illustrated in Figure 2 has been developed under the following simplifying assumptions:

1. The product leaving any stage is salt free.
2. The heat of mixing for brine solutions are negligible.
3. No heat losses.
4. No sub-cooling of condensate leaving the brine heater.

The model equations are constituted of a set of mass and energy balances which are given in the following.

5.1. stage model

Referring to Figure 3 the following equations can be written for stage number J at steady state:

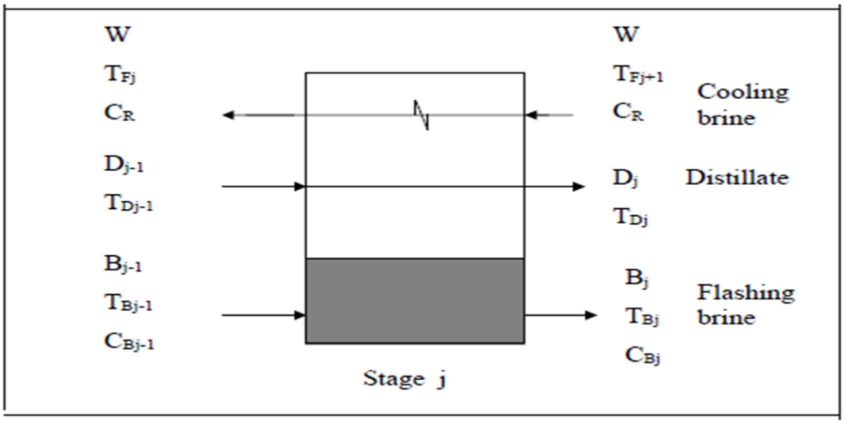

Figure 3. General stage in an MSF plant

Enthalpy balance on flashing brine

$$B_{j-1}h_{B_{j-1}} = B_j h_{B_j} + \left(B_{j-1} - B_j\right) h\, V_j \quad (3)$$

Total material balance

$$B_{j-1} + D_{j-1} = B_j + D_j \quad (4)$$

Salt balance

$$B_{j-1}C_{B_{j-1}} = B_j C_{B_j} \qquad (5)$$

Overall enthalpy balance

$$W\, S_{Rj}\left(T_{Fj} - T_{Fj+1}\right) = D_{j-1}S_{D_{j-1}}\left(T_{D_{j-1}} - T^*\right) + B_{j-1}S_{B_{j-1}}\left(T_{B_{j-1}} - T^*\right) - D_j S_{D_j}\left(T_{D_j} - T^*\right) - B_j S_{B_j}\left(T_{B_j} - T^*\right) \quad (6)$$

Heat transfer equation

$$W\, S_{Rj}\left(T_{Fj} - T_{Fj+1}\right) = U_j A_j\left(T_{Fj} - T_{Fj+1}\right) / Ln\left[\frac{(T_{Dj} - T_{Fj+1})}{(T_{Dj} - T_{Fj})}\right] \quad (7)$$

Distillate and flashing brine temperatures correlation

$$T_{Bj} = T_{Dj} + BPE_j + \delta_j + \Delta_j (8)$$

6. Process variables

To maximize performance ratio and ensure stable operation, the effect of the following process variables on plant performance is investigated:

- Seawater flow rate
- Brine recirculation flow rate
- Make-up feed flow rate
- Temperature of steam to brine heater

6.1 Seawater flow rate (W_T)

The effects of seawater flow rate on plant performance are illustrated in Figures 4 and 5. Figure 4 shows that the distillate flow rate D increases with the increase in W_T. This is due to the increase of H.T.C inside the preheater condenser tubes in the heat rejection section. The specific heat consumption increases with the increase in W_T. This is due to the increase of the flow rate of heating steam. Figure 5 shows that the performance ratio decreases due to the increase in the flow rate of the heating steam.

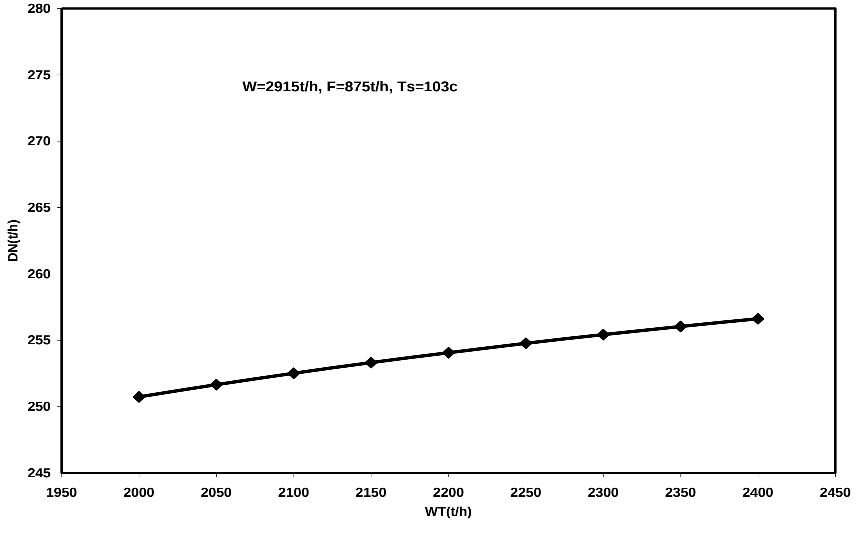

Figure 4. Effect of seawater flow rate on plant productivity

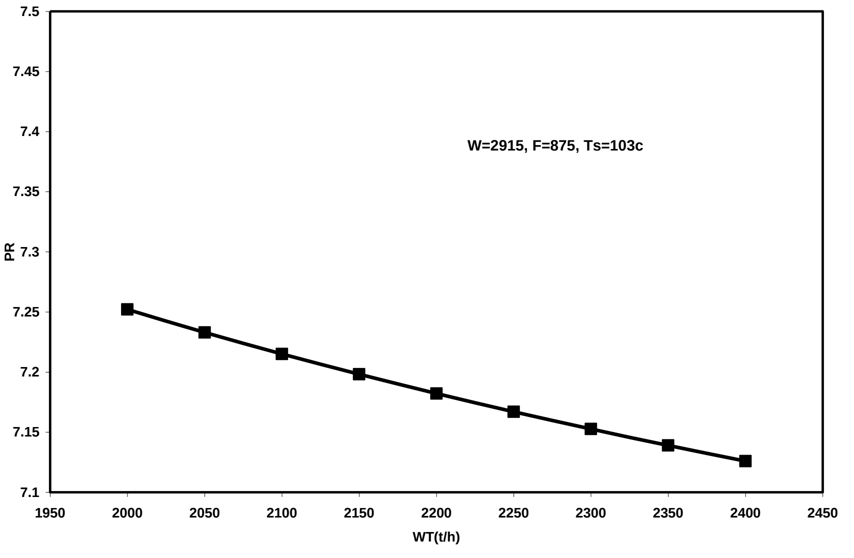

Figure 5. Effect of seawater flow rate on performance ratio

Simulation indicates that; the flow rate has little effect on performance ratio or distillate produced as seen in these Figures.

6.2. Brine recirculating flow rate (W)

Figures 6 and 7 show that; the brine recirculation flow rate has strong effect on performance of the plant. Increasing the recirculation brine increases the distillate production (Figure 6). As steam flow rate to brine heater increases the energy necessary to produce 1.0 kg of fresh water increases. This leads to a decrease in performance ratio (Figure7). The maximum flow rate for the recirculation brine is limited by the maximum allowable velocity in the cooling tubes (ELECTROBEL, 1972). The velocity was chosen of about 2.0 m/s such that to smoothly whip the tubes without eroding them (i.e. not too fast: this will deteriorate the tubes; not too slow: this will allow for deposit).

$$Q = n \times v \times A (9)$$

Where

Q: volume flow rate
n: number of tubes
v: velocity of fluid
A: cross section area of tube

6.3. Make-up brine flow rate (F)

Figures 8 and 9 present the effect of makeup sea water flow rate on the plant performance. Actually, the increase in the make-up flow rate decreases the salt concentration in brine stream. This leads to increases H.T.C inside preheater condenser tubes in the heat recovery section. Consequently, increases the distillate product and the performance ratio. Also, it decreases the energy necessary to produce 1.0 kg of distillate. Usually, the MSF plant operates at a high make-up flow rate.

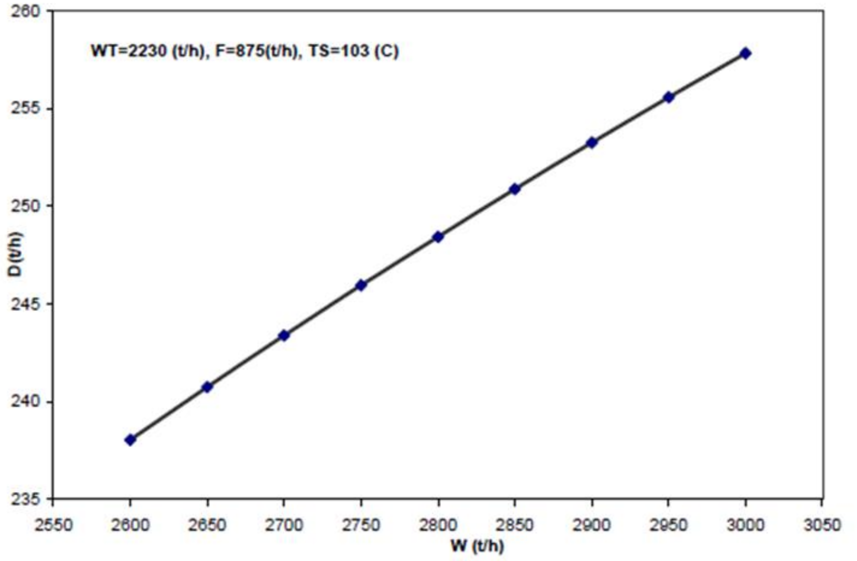

Figure 6. Effect of brine recirculation flow rate on plant productivity

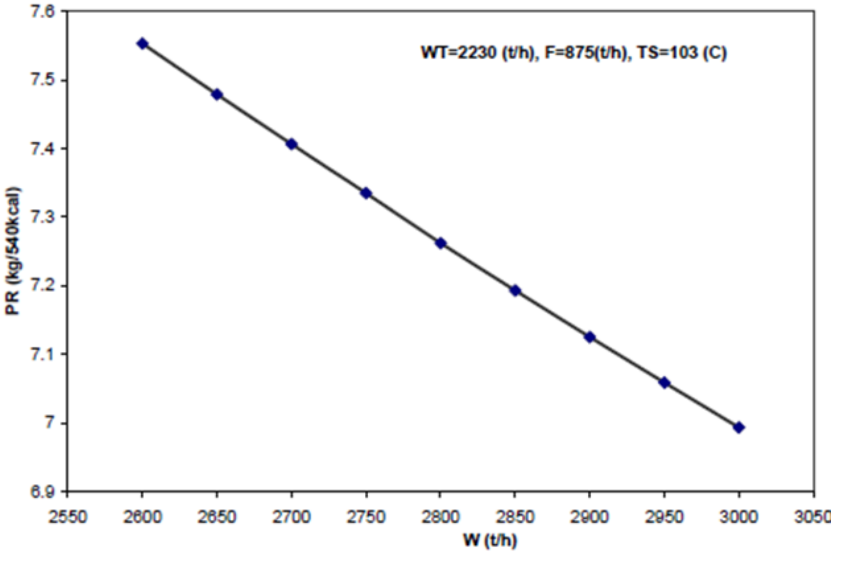

Figure 7. Effect of brine recirculation flow rate on performance ratio

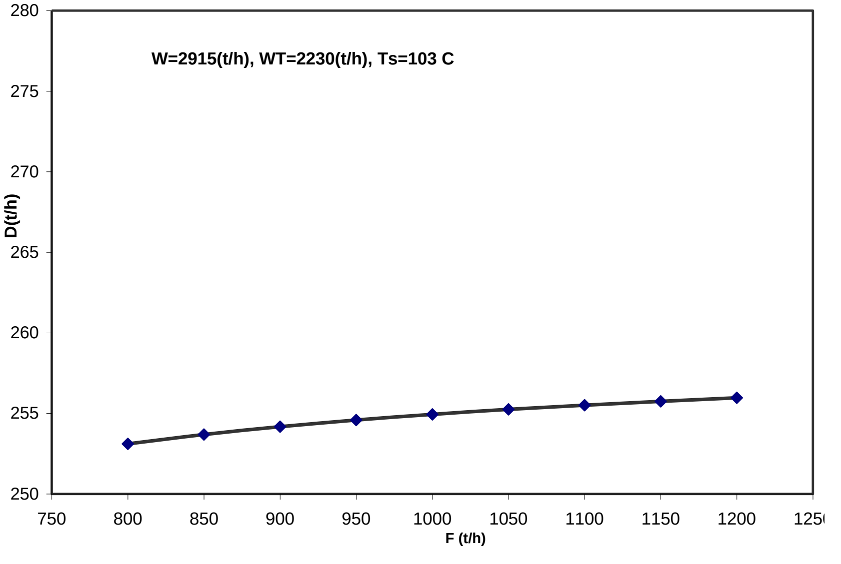

Figure 8. Effect of the make-up flowrate on plant productivity

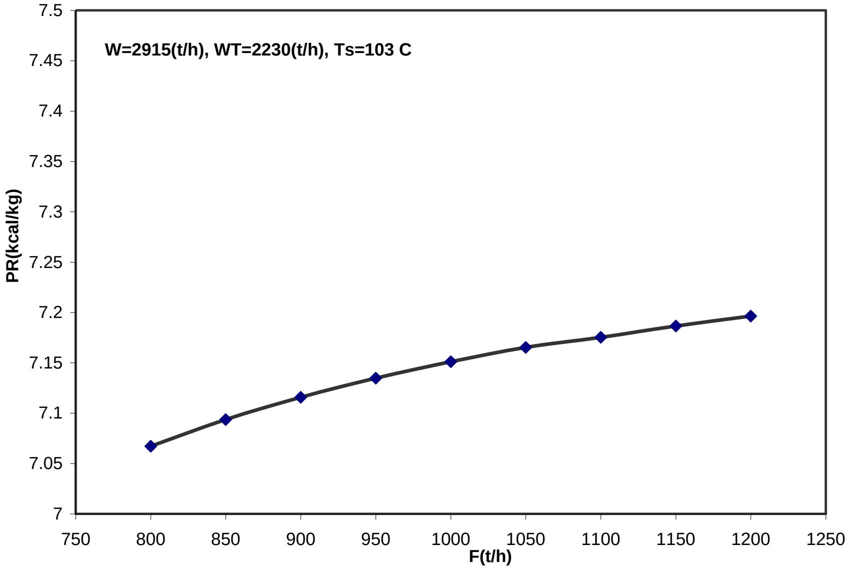

Figure 9. Effect of the make-up flow rate on performance ratio

6.4. Steam temperature (Ts)

One of the most important parameters in the desalination process is the temperature of the heating steam coming from the boiler. The steam temperature depends on the top brine temperature and the steam flow rate introduced to the brine heater. The increase in the steam temperature up to certain critical value yields an increase in steam flow rate due to the decrease in the latent heat of vaporization (the vapor temperature is inversely proportional to its latent heat of vaporization) which results in a increasing the product rate (**D**) and performance ratio (**P.R**). Further increase in the steam temperature over this critical, the rate of increase the product doesn't recover the increase in the steam flow rate (**Ws**). This leads to a decrease in the performance ratio (**P.R**) as shown in Figures 10 and 11. Therefore, the improvement in process performance is dependent on the control in the range of steam temperature.

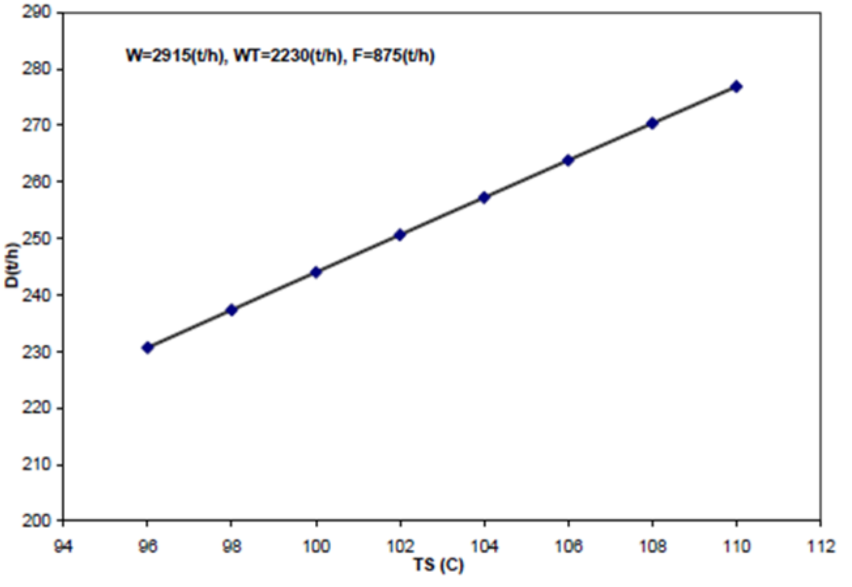

Figure 10. Effect of steam temperature on plant productivity

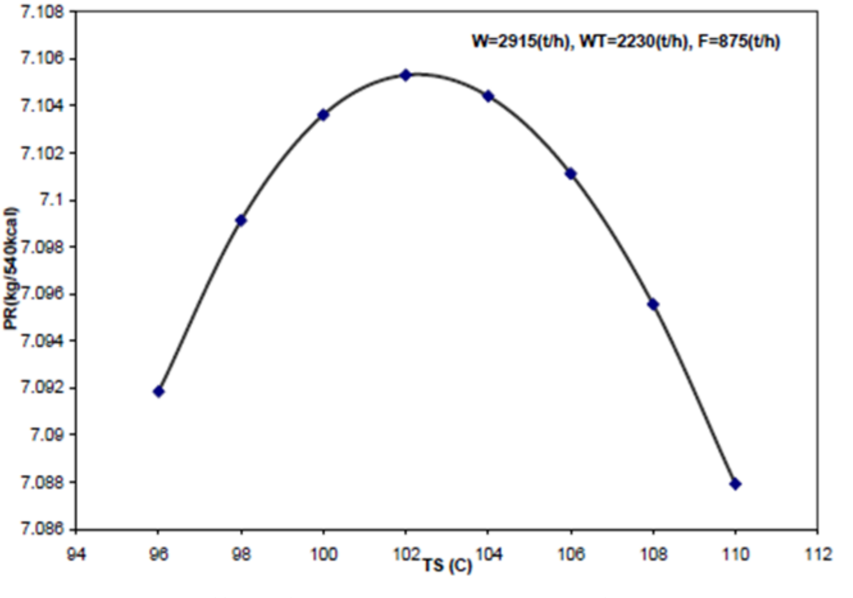

Figure 11. Effect of steam temperature on performance ratio

7. Development of the optimal operation conditions

From the previous sections it is concluded that the steam temperature and recirculating brine flow rate can significantly affect the performance ratio and production rate. Therefore, in order to investigate the optimal operational conditions, these two process variables are changed within the constraints., while fixing the make-up flow rate and seawater flow rate at design values. Running the developed computer code under these constraints the optimal operating conditions can be developed for the seawater temperature at 27 ˚C, make up flow rate 875 t/h and W_T = 2230 t/h.

Figure 12 shows an operating envelope in which solid lines refer to a constant recirculating brine flow rate (W), which decreases from maximum to minimum values of (2600 – 2950 t/h) correspond to the allowable limits of velocities through cooling tubes (1.8 - 2.0 m/s). The dashed lines in Figure represent constant steam temperatures between T_s minimum and T_s maximum values of (96 – 106 ◦C). Table 3 gives the specific operating conditions for points labeled 1 to 20 in Figure 12.

Table 3. Boundary points of the operating envelope shown in Figure 12.

Points	Operating conditions
1-6	**Recirculating brine flow rate constant at a minimum of 2600 t/h at increasing T_S (96, 98, 100, 102, 104, 106 °C).**
7-11	**T_S constant at a maximum of 106 °C and at increasing recirculating brine flow rate (2670, 2740, 2810, 2880, 2950t/h).**
12-16	**Recirculating brine flow rate constant at a maximum of 2950 T/h and at decreasing T_S(104, 102, 100, 98, 96 °C).**
17-20	**T_S constant at a minimum of 96 °C and at decreasing recirculating brine flow rate(2880, 2810, 2740, 2670 t/h).**

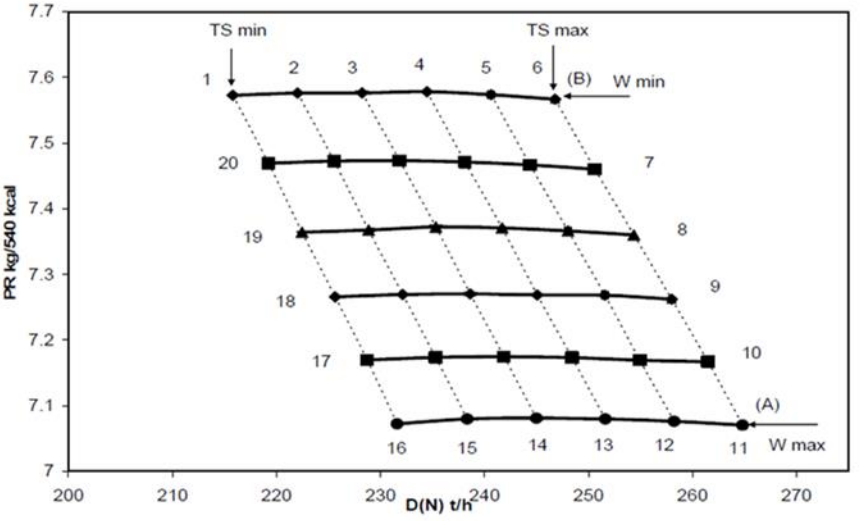

Figure12. Optimal operating conditions for distillate produced and performance ratio

Point (A) in Figure 12 indicates the conditions to attain the maximum production rate at a lower performance ratio. Point (B) in Figure 12 represents the operating conditions to attain the maximum performance rate with a certain loss of production capacity. In principle, we can operate at any point on the borders or within the enveloper.

7. Conclusion

The following conclusions are subtracted from the results which were presented in this study:

1. The brine recirculating flow rate and temperature of steam introduced to the brine heater are the most important operation variables which have a significant effect on the system performance.
2. The developed code can be used for optimizing the plant's performance to ensure stable operation by developing optimal

operating envelopes under the limitation of brine flow rate and steam temperature.

3. The chart shown in figure 12 represents the optimum operating conditions for the studied MSF desalination plant.
4. operating envelope in which solid lines refer to a constant recirculating brine flow rate (W), which decreases from maximum to minimum values of (2600 – 2950 t/h) correspond to the allowable limits of velocities through cooling tubes (1.8 - 2.0 m/s).
5. The dashed lines of operating envelope represent constant steam temperatures varied between 96 and 106 ^{0}C.
6. Point (A) in Figure 12 indicates the conditions to attain the maximum production rate at a lower performance ratio. Point (B) in Figure 12 represents the operating conditions to attain the maximum performance rate with a certain loss of production capacity. In principle, we can operate at any point within the envelope and on the borders.

8. Recommendations for future work

- Extensions to this work can be carried out toinclude the dynamic behavior of the multi stage desalination systems.
- The effect of the H.T.C. local variation on the plant performance can be investigated.
- Optimizing the plant size and thenumber of units can be investigated.

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APPENDIX:Nomenclature

Symbols	**Defined**
A_j	Heat transfer area of stage j
B_D	Blowdown mass flow rate
B_J	Flashing brine mass flow rate leaving stage j
B_0	Flashing brine mass flow rate Leaving the brine heater
BPE_j	Boiling point elevation at stage j
C_W	Rejected sea water mass flow rate
D_j	Distillate flow rate leaving stage j
F	Make-up seawater mass flow rate
h_{Bj}	Specific enthalpy of flashing brine at stage j
h_{Vj}	Specific enthalpy of flashed vapor at stage j
N	Total number of stages, N=NR+NJ
NR	Number of stages in the heat recovery section
T	Temperature
T_{B0}	Temperature of flashing brine leaving the brine heater

T_{Dj}	Temperature of distillate leaving stage j
T_{Fj}	Temperature of cooling brine leaving stage j
T_{Bj}	Temperature of flashing brine leaving stage j
T_{SEA}	Seawater temperature
T_{STEAM}	Steam temperature
U_j	Overall heat transfer coefficient at stage j
W	Recirculating brine mass flow rate to the heat recovery section
W_T	Sea water mass flow rate to the heat rejection section
W_{STEAM}	Steam mass flow rate
Δ_j	Temperaturedrop at stage j
δ_j	Non-equilibrium allowance at stage j
λ_s	Latent heat of steam to brine heater
j	Stage index
*	Reference value