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Modelling and Simulation of Multistage Flash Desalination Plants

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ABSTRACT

This study 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 are arranged in a tridiagonal matrix form. The solution of these equations are obtained by a computer code written in visual basic language with friendly user format developed for this purpose. This code can predict the plant 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 MSF plant existed in Benghazi city. The comparisons show good agreement with these available data.

Keywords: *System performance, Energy balance, Mass balance, Desalination Plants, Modelling, MSF.*

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. Literature review

Helal et al. [1] used a tridiagonal matrix model for steady-state simulation of MSFD plants. The set of equations was solved in a global manner by arranging the stage energy relations in the form of a tridiagonal matrix. He found this method stable and showed fast convergence. Marina Rosso et al. [2] described a steady state mathematical model developed to analyze the MSF desalination processes. The model allows calculating the plant productivity together with the profiles of temperatures and flowing rates in all the stages of the unit. Husain et al. [3] described the work done on modeling and simulation of multistage plant containing 15 recovery and 3 rejection stages . He used 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 .He stated that the TDM formulation , represents a more realistic situation in which the makeup seawater is directly fed to the last rejection stage from which the total brine recycle is drown .Khawla A. Al – Shayji [4] explained how to apply modular and equation – solving approaches for steady state and dynamic simulations of large scale commercial MSF desalination plants using ASPEN PLUS (Advanced System for Process Engineering PLUS) and SPEEDUP (Simulation Program for Evaluation and Evolutionary Design of Unsteady Processes). His work illustrated the development of an optimal operating envelope for achieving a stable operation of a commercial MSF desalination plant using the SPEEDUP model.

This paper aims to model MSF plant using TDM formulation and to build a computer code that helps in evaluating the plant performance under design and operating parameters at steady state operation conditionsto provide plant-working envelope. This code could help in building the system control loop by implementing it as one of the control modulus.

3. Description of the MSF process

Figure1 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 [1].

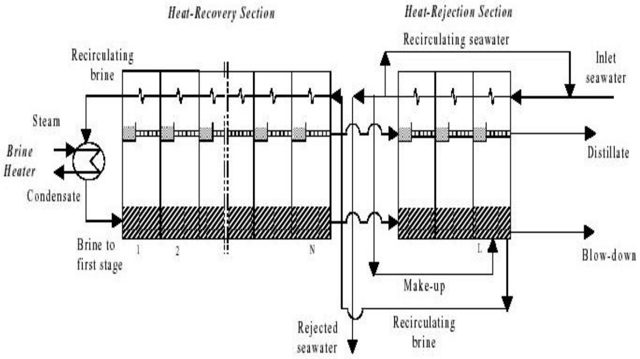

Fig.1: Recirculation brine multistage flash (MSF) desalination plant.

4. Mathematical model

The steady state mathematical model of the multi stage flash desalination process generally is developed under following simplifying assumptions:

- The product leaving any stage is salt free;
- The heat of mixing for brine solutions are negligible ;
- No heat lost in system;
- No subcooling of condensate leaving the brine heater.

The model equations are constituted of a set of mass and energy balances with their final form are given in the following. A detailed description of these equations is presented in reference [1].

The final form of the governing equation which is used to build TDM equation for any stage j, as shown in Figure 2,for the recovery and reject sections is:

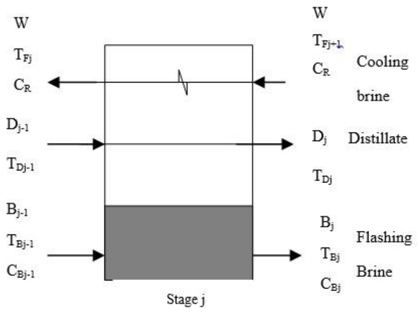

Fig. 2: General stage in an MSF plant.

$$(C_{1j})T_{F\,j-1} + (C_{2j} - 1)T_{F\,j} + (C_{3j} + 1)T_{F\,j+1} = b_{3j} \tag{1}$$

Where;

$$C_{1j} = \left[b_{1j} a_{j-1} \big/ (1 - a_{j-1}) \right] \tag{2}$$

$$C_{2j} = \left[b_{1j} \big/ (1 - a_{j-1}) \right] - \left[b_{2j} a_j \big/ (1 - a_j) \right] \tag{3}$$

$$C_{3j} = \left[b_{2j} \big/ (1 - a_j) \right] \tag{4}$$

The first and last stages have particular characteristics, which are to be taken into account for deriving the TDM. The first stage in the recovery section receives no distillate stream from an external source. Further, T_{b0} the temperature of the flashing brine entering the stage is calculated from steam temperature. Thus the equation for this stage will be as follows:

$$(C_{21} - 1)T_{F1} + (C_{31} + 1)T_{F2} = b_{31} \tag{5}$$

$$C_{21} = -\left[b_{21} a_1 \big/ (1 - a_j) \right] \tag{6}$$

$$C_{31} = \left[b_{21} \big/ (1 - a_1) \right] \tag{7}$$

The elements of the TDM in the last stage are such as:

$$C_{1J} T_{FJ-1} + (C_{2J} - 1) T_{FJ} = b_{3i} \tag{8}$$

Where,

$$C_{1J} = -\left[b_{1j} a_{j-1} \big/ (1 - a_{j-1}) \right] \tag{9}$$

$$C_{2J} = \left[b_{1j} \big/ (1 - a_{j-1}) \right] - \left[b_{2j} a_j \big/ (1 - a_j) \right] \tag{10}$$

$$C_{3J} = -\left[T_{SW} \left(b_{2j} \big/ (1 - a_j) + 1 \right) \right] - b_{3j} \tag{11}$$

5. System performance

The performance of the plant 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 k cal to brine heater or to the first effect .

$PR = (D_N / W_s)$; This ratio is dimensionless (12)

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

$q = W_s * \lambda_s / D_N$; (13)

6. Computer code structure and solution procedure

The mathematical model for a steady state simulation, as described above, is used to build computer code for performance analysis of MSF desalination systems.

In this code, all the temperature profiles TFj,TBj, and TDj, j=1, .N are initialized so the various properties, heat transfer coefficients and temperature losses can be calculated and, as a result, all the model equations become linear. A TDM is developed consisting of linear equations correlating each combination of three successive temperatures TFj, TFj-1, and TFj+1. By solving these equations simultaneously, an updated profile of TFj is obtained which is used through the heat transfer equation to update the TDj profile.

The convergence criterion used is:

$$\sum_{J=1}^{N} [\, T^{i+1}_{B\,j} - T^{i}_{Bj} \,]^2 \le 0.00001 \times N$$

Where i is the iteration index.

Figure 3 gives the flow chart of the computer code used for steady state simulation of the MSF desalination systems .The excision steps are as following:

1. Initialize all the variables , temperatures , flow rates and salinity
2. Solve enthalpy balance equations for flashing brine flow rate (B_j)
3. Solve overall mass balance equation for distillate flow rate (D_j).
4. Balance the mass on blow down splitter (relation between F,W, B_N).
5. Balance the overall salt for recycle concentration (C_R).
6. Balance the salt on brine heater.
7. Calculation of the stages temperature losses (BPEj, δj, Δj).
8. Solve the stage heat balance equations simultaneously (matrix equations) for the tube side temperatures and top brine temperature, TFj, TB0.
9. Solve the heat transfer equations simultaneously for updating distillated temperature profiles (TDj).
10. Solve equilibrium equations iteratively for a new temperature profile of flashing brine (TBj).
11. Test for convergence.
12. Use the converged values to obtain the other variables (Ws, q, PR).

7. Model Validation

Table1Compares the temperatures of the flashing brine (T_{Bj}), distillate (T_{Dj}), and recirculating brine (T_{Fj}) as well as the flash pressures (P_j) in 24 flash stages of actual data of plant in Kuwait and data obtained by [Ref 4] with values predicted by developed code. Table 2 compares actual and predicted values of the recirculating brine temperature entering the brine heater (T_{F1}), temperature of the final distillate produced (T_{DN}) and temperature of final flash stage (T_{BN}) as well as the flow rate of distillate produced (D_N), blow down (B_N), and steam to brine heater (W_S). In addition, this table shows the predicted and actual performance ratio, which is the ratio of distillate produced to steam consumed . While Table3 shows the profiles of temperature and distillate flow rate presented by [Ref 2] as compared with the predicted values. These two tables show the superiority of the current predictions over the available predicted data as compared with the real plant data.

Table1: Comparison of predicted values with actual plant data and [Ref.4].

Flash stage no.	$T_{B\,(j)}$[°C]			$T_{D\,(j)}$[°C]			$T_{F\,(j)}$[°C]			$P_{\,(j)}$[Bar]		
	Ref.4	Real data	Current study	Ref.4	Real data	Current study	Ref.4	Real data	Current study	Ref .4	Real data	Current study
1	88.36	88.90	88.23	87.16	87.70	87.27	82.22	83.20	85.02	0.63	0.66	0.63
3	83.09	84.40	84.17	81.89	83.20	83.14	76.97	78.80	80.69	0.52	0.55	0.54
5	77.83	79.60	79.99	76.63	78.40	78.95	71.77	74.00	76.49	0.42	0.45	0.45
7	72.62	75.00	75.77	71.42	73.80	74.73	66.68	69.40	72.27	0.33	0.38	0.38
9	67.52	70.50	71.53	66.32	69.30	70.49	61.75	64.80	68.02	0.27	0.31	0.32
11	62.59	66.20	67.29	61.39	65.00	66.23	57.01	60.50	63.77	0.22	0.26	0.26
13	57.91	61.90	63.05	56.61	60.60	61.98	52.56	56.20	59.52	0.17	0.21	0.22
15	53.58	57.70	58.84	52.18	56.30	57.73	48.47	52.00	55.29	0.14	0.17	0.18
17	49.55	53.60	54.66	48.15	52.20	53.51	44.70	47.90	51.10	0.12	0.14	0.14
19	45.96	49.70	50.53	44.36	48.10	49.33	41.36	44.00	46.95	0.10	0.12	0.12
21	42.82	45.90	46.61	41.10	44.20	45.32	38.44	40.34	42.87	0.08	0.10	0.10
23	40.11	42.60	43.01	38.21	40.70	41.65	34.23	35.30	38.43	0.07	0.08	0.08
24	38.44	40.50	40.75	36.54	38.60	39.35	32.22	32.22	35.57	0.06	0.07	0.07

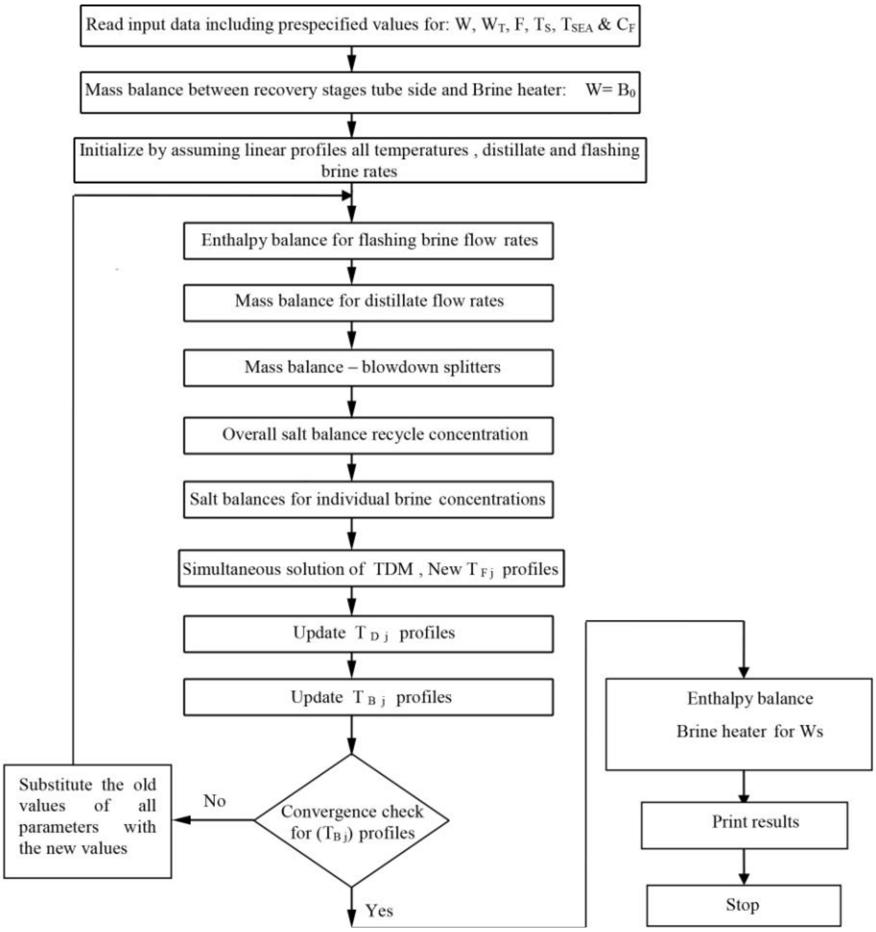

Fig. 3: Flow chart of the computer code.

Table 2: Comparison of predicted performance variables with design data and Ref.4.

Performance variables	**Unit**	**Ref.4**	**Real data**	**Current study**
$T_{F(1)}$	°C	84.43	84.89	85.00
$T_{D\,(N)}$	°C	36.54	38.60	39.46
$T_{B\,(N)}$	°C	38.44	40.50	40.50
$D_{(N)}$	T/min	19.33	18.80	18.69
$B_{(N)}$	T/min	29.43	29.96	29.93
W_S	T/min	2.50	2.35	2.36
Performance Ratio	kg/540 kcal	7.76	8.00	7.93

Table 3: Comparison of predicted performance variables with design data and Ref.2.

Flash stage no.	$T_{B\,(j)}$[°C]		$T_{D\,(j)}$[°C]		$T_{F\,(j)}$[°C]		$D_{\,(j)}$[T/hr]	
	Ref .2	Current study	Ref .2	Current study	Ref .2	Current study	Ref .2	Current study
0	89.74	89.32	0.00	0.00	0.00	0.00	0.0000	0.00
1	86.89	86.31	85.75	85.69	83.33	83.07	59.40	61.62
2	84.01	83.45	82.87	82.82	80.41	80.19	118.70	119.63
3	81.08	80.57	79.95	79.93	77.44	77.28	178.40	177.50
4	78.11	77.67	76.97	77.02	74.43	74.36	238.50	235.19
5	75.09	74.76	73.94	74.10	71.37	71.43	298.90	292.62
6	72.04	71.84	70.88	71.17	68.28	68.49	359.50	349.72
7	68.95	68.92	67.78	68.23	65.16	65.54	420.10	406.44
8	65.84	65.99	64.65	65.29	62.01	62.60	480.60	462.70
9	62.70	63.07	61.49	62.33	58.84	59.65	541.00	518.43
10	59.55	60.15	58.32	59.39	55.65	56.71	601.00	573.57
11	56.39	57.25	55.13	56.45	52.46	53.78	660.60	628.03
12	53.24	54.36	51.93	53.51	49.27	50.86	719.70	681.73
13	50.09	51.50	48.74	50.60	46.09	47.96	778.00	734.56
14	47.28	48.45	45.87	47.51	44.06	45.08	829.60	790.28
15	44.42	45.30	42.95	44.28	41.10	41.82	881.60	847.59
16	41.51	42.07	39.98	40.97	38.07	38.44	934.10	905.40

8. Case study

In this case study the performance calculations is solved using the developed computer code. The design data used for this purpose belong to the North Benghazi (Libya) MSF desalination plant .The capacity of the plant is 6000 ton/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 4 and 5. The heat balance diagram of the plant is shown in Figure 4.

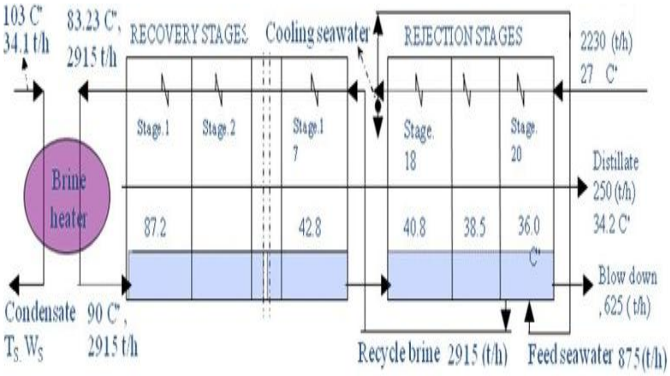

Fig.4: Heat balance diagram for multistage flash desalination plant presented by contractor.

To demonstrate the capability of the code for predicting the performance parameters, the seawater feed flow rate (W_T), the recycle stream flow rate (W) and the steam temperature (Ts) are input to the code. On the basis of these information the model is run to calculate the plant productivity together with the profiles of temperatures and flow rates of in all the stages of the unit . The main parameter used to quantify the process performance is the ratio between the distillate product and the steam flow rate. The results of this calculation are reported in Table 6.

Table 4: Design and operational data of North Benghazi desalination plant [5].

Process variables	**Units**	**Specification**
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
Blowdown flow rate	T/h	625
Steam temperature to brine heater	°C	103
Top brine temperature	°C	90

Table 5: Design and dimensional details of North Benghazi desalination plant [5].

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	m^2	842	840	703.33
(U_D)	kcal/m^2.°c /hr	1700	2453	2100
F. F	(kcal/m^2.°c /hr)$^{-1}$	3.5819	1.667	1.945
V of brine	m/s	2.0	2.0	2.1

9. Comparison between actual and predicted results

To evaluate the accuracy of the predicted data presented in Table 6, Table 7 is constructed from the manufacture data and predicted values. The comparison is made for the recirculating brine temperature entering the brine heater (T_{F1}), temperature of the final distillate produced (T_{DN}), final brine temperature (T_{BN}) and the top brine temperature (T_{B0}), as well as the flow rate of distillate produced (D_N), blow down (B_N) and steam to brine heater (W_S). In addition , this table shows the performance ratio and energy necessary to produce 1 kg of distillate (q). Inspection of data presented in Table 7 reveals that the predicted values are very close to the referenced values.

Table 6. Output results for the MSF desalination plant

Stage No	B ,T/h	D , T/h	C_B %	T_F,°C	T_D,°C	T_B ,°C	p, bar	V, m/s
0	2915	0	0.0544			91.04	0.70	2.060
1	2901.99	13.00	0.0546	84.52	87.56	88.35	0.63	2.081
2	2888.68	26.32	0.0549	81.70	84.89	85.67	0.57	2.077
3	2875.40	39.61	0.0551	78.99	82.19	82.97	0.51	2.074
4	2862.20	52.88	0.0554	76.26	79.48	80.25	0.45	2.070
5	2848.88	66.11	0.0557	73.52	76.76	77.52	0.41	2.067
6	2835.70	79.30	0.0559	70.76	74.02	74.78	0.36	2.064
11	2770.81	144.20	0.0572	56.89	60.18	60.94	0.19	2.049
12	2758.20	156.88	0.0575	54.11	57.40	58.17	0.17	2.046
13	2745.54	169.46	0.0578	51.33	54.61	55.40	0.15	2.043
14	2733.09	181.91	0.0580	48.56	51.83	52.63	0.13	2.041
15	2720.78	194.22	0.0583	45.80	49.06	49.88	0.11	2.038
16	2708.62	206.40	0.0585	43.04	46.30	47.14	0.10	2.036
17	2703.58	211.43	0.0587	40.30	45.04	45.99	0.095	2.033
18	2703.58	228.70	0.0589	37.54	41.21	42.05	0.079	2.104
19	2674.60	240.40	0.0593	34.46	38.44	39.35	0.069	2.102
20	2661.64	254.47	0.0596	30.93	35.42	36.22	0.058	2.100

Table 7: Comparison between actual and predicted principal operating parameters.

Operating parameters	Unit	Contractor's design data	Predicted	Error %
T_{F1}	°C	83.23	84.52	1.55
T_{DN}	°C	34.20	35.42	3.56
T_{BN}	°C	36	36.22	0.61
T_{B0}	°C	90	91.04	1.15
T_m (make up)	°C	37	37.65	1.73
D_N	T/h	250	254.47	1.78
B_D	T/h	625	621.64	0.537
W_S	T/h	34.10	35.67	4.60
Performance ratio	kg/540 kcal	7.33	7.17	2.18
Specific heat consumption	kcal/kg ofdistillate	75.5	75.28	0.30

10. Conclusion

The following conclusions are subtracted from the present study:

1. The developed model can be used adequately to analyze the MSF water desalination process at steady state operation conditions.
2. The developed computer code can be used adequately to perform the performance analysis of MSF desalination plants by calculating the plant productivity together with profiles of temperatures and flow rates in all stages of the unit.
3. The present code is valid when compared with commercial softwares used for the same purpose.
4. North Benghazi desalination plant was used as a case study, and good agreement was found when comparing the predicted data with the plant design data.

References

[1] A. M. Helal, M.S. Medani, M. A. Soliman, and J. R. Flowers. (1986). A tridiagonal matrix model for multistage flash desalination plants.Comput. Chem. Engg. Vol. 10, 327-34.

[2] Marina Rosso, Angelo Beltarmini , Marco Mazzotti , and Massimo Morbidelli.(1996). Modeling multistage flash desalination plants. Desalination Vol.108, 365- 374.

[3] A. Husain , A. Woldai, Al – Radif, A. Kesou, R. Borsani, and P. B. Dshphandey. (1994). Modelling and simulation of a multistage flash desalination plant. Desalination Vol. 97, 555- 586.

[4] Khawlaabdulmohsen Al – shayji. (1998). Modeling , Simulation , and Optimization of large scale commercial desalination plants. PhD Thesis, Virginia Polytechnic Institute and State University, Virginia.

[5] Operating manual of MSF desalination plant at north-Benghazi station.

APENDIX: Nomenclature

Symbol	Description
a_{1i}, a_{2i}, a_{2i}	Temporary constants for stage j
b_{1i},b_{2i}, b_{3i}	Temporary variables
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_{1i}, c_{2i}, c_{3i}	Temporary constants at the conditions of stage j
C_{Bj}	Salt concentration in the flashing brine leaving stage j
C_{B0}	Salt concentration in the flashing brine leaving the brine heater
C_F	Feed seawater salt concentration
C_R	Salt concentration in the cooling brine to the recovery section
C_W	Rejected sea water mass flow rate
D_j	Distillate flow rate leaving stage j
D_N	Plant productivity
F	Make-up seawater mass flow rate
N	Total number of stages , N=NR+NJ
NR	Number of stages in the heat recovery section
NJ	Number of stages in the heat rejection section
P_j	Pressure at stage j
PR	Performance ratio of the plant, PR = DN/Ws
T_{B0}	Temperature of flashing brine leaving the brine heater
T_{Bj}	Temperature of flashing brine leaving stage j
T_{Dj}	Temperature of distillate leaving stage j
T_{Fj}	Temperature of cooling brine leaving stage j
T_m	Temperature of make up seawater flow rate
T_{SEA}	Seawater temperature
T_S	Steam temperature
W	Recirculating brine mass flow rate To the heat recovery section
W_S	Steam mass flow rate
W_T	Sea water mass flow rate to the heat rejection section
Greek letters	
Δ_j	Temperature loss at stage j
δ_j	Non equilibrium allowance at stage j
λ_s	Latent heat of steam to brine heater