THERMAL MODEL FOR MSF DISTILLATION PLANT

نموذج حرارى لوحدة تقطير بالتبخير متعددة المراحل

Hesham M. Mostafa and Abdel-Hamid M. Torki

Higher Technological Institute, Ramadan 10th City, Egypt

خلاصة: يعتبر التقطير من أبسط الطرق للحصول على الماء العذب. ولد تم عمل نموذج حرارى لوحدة تقطير متعددة المراحل وذلك لعمل حسابات مبدئية لعوامل التصميم المختلفة، وهى عدد المراحل، المساحة التى يتم خلالها إنتقال الحرارة، معامل الأداء وكذلك درجات الحرارة ومعدل التدفق. وقد تم حساب عوامل التصميم هذه لماء مالح معلوم درجة حرارته ونسبة ملوحته وذلك لإنتاج ١ كجم/الثانية من الماء العذب. ولإتمام هذه الدراسة بعد إنشاء النموذج الحرارى المقترح للمحطة فقد تم حل مجموعة المعادلات الآنية غير الخطية بالطرق العددية. وقد أجريت مقارنة النتائج الحالية مع مثيلاتها من الأبحاث السابقة وذلك لإختبار صلاحية النموذج الحرارى المقترح حيث ثبت توافق النتائج وصلاحية النموذج.

ABSTRACT

Distillation is the simplest technique for producing fresh water. A thermal model for a Multi-Stage Flash (MSF) distillation plant is constructed to calculate the preliminary values for different design parameters. For a specified values of input heat per unit mass flow rate of distilled water, sea water temperature, sea water concentration, and maximum brine temperature, the values of most important design parameters are obtained. These parameters are the total number of stages, total heat transfer surface area, performance ratio, temperatures and mass flow rates for MSF distillation plant.

To perform this study, a set of non-linear simultaneous equations is developed and solved by iteration methods. Then the values of the design parameters are evaluated for the specified requirements of the MSF distillation plant to produce unit mass flow rate of distilled water.

1. Introduction

The adequate solution for the fresh water shortage problem in arid areas is achieved by adopting the distillation techniques, which is the simplest techniques for producing fresh water.

In MSF distillation plant, sea water or brine is heated under pressure to just below the saturation temperature (i.e. boiling is not allowed). Then, hot sea water is discharged through heat recovery and heat rejection sections. The pressure of each stage is reduced compared with the previous stage. Hot sea water is evaporated or flashed due to the reduction in pressure to obtain thermal equilibrium with stage saturation conditions prevailing in each

individual stage. Input sea water is wormed inside condenser tubes due to the condensation of the released vapor on the outside of condenser tubes, as shown in Fig. 1. Brine heater raises the sea water temperature to the required maximum temperature, T_{max}.

Mostafa, H. M. [1] introduced a theoretical analysis of MSF evaporator plant. This analysis was achieved by applying the mass and energy balance for every stage. The plant performance was predicted for different operating parameters. Fath, E.S.H. [2], developed a computer program to calculate the main performance parameters, such as performance Ratio, flash range and heat transfer coefficient. Also, the analysis indicated that increasing the capacity of the MSF plant up to 50 MIG/D (called the Jambo size) would reduce the capital operational and other water production costs. A model for MSF desalination plant has been developed by Ali, A.H. [3] to simulate the behavior of MSF distillation plant. A stage to stage interactive procedure was carried out to solve this model. Also, mathematical models for MSF distillation plant were proposed by Ali et al [4] and El-Doussouky et al [5]

The main objective of this work is to optimize the design parameters of MSF distillation plant by construction a thermal model for the specified requirements of the MSF distillation plant.

2. Thermal Model

Thermal model represents the formulation of the governing equations of mass, concentration and energy for MSF distillation plant. The solution technique required to solve the resulting nonlinear simultaneous equations is also introduced.

2.1. Mass, concentration and Energy Balance

To obtain the unit mass flow rate of distilled water ($m_D = 1$ kg/s), the mass balance for rejection section is given by:

$$M_{DN} = M_{BD} + M_R - M_{BN} + 1 \tag{1}$$

Also, the mass balance for recovery section is given by:

$$M_{BO} = M_{BN} + M_{DN} \tag{2}$$

To perform complete condensation for the vapor flashing in rejection section, the mass flow rate of sea water inside condenser tubes has to be greater than the mass of sea water which passes to the recovery section by a certain value as follows:

$$M_{SW} = M_{SI} + M_{SO} \tag{3}$$

Recirculated sea water flow rate to the recovery section is given, (as shown in Fig.1) by the following equation:

$$M_R = M_{BO} - M_{SI} \tag{4}$$

The concentration balance for node (b), which is in between rejection and recovery sections, (as shown in Fig. 1) is given by:

$$M_{SI} \cdot X_{SW} = M_{BO} \cdot X_{BO} - M_R \cdot X_{BO} \tag{5}$$

The concentration balance for rejection and recovery sections are formulated as follows:

$$M_{BN} \cdot X_{BN} = (M_{BD} + M_R) \cdot X_{BD} \tag{6}$$

$$M_{BO} \cdot X_{BO} = M_{BN} \cdot X_{BN} \tag{7}$$

The energy balance for rejection section is formulated as follows:

$$(M_{BD} + M_R) \, C_{P,BD} \cdot T_{BD} + M_{SW} \, C_{P,SW} \cdot T_{SO} + M_D \, C_{P,D} \cdot T_D =$$
$$M_{SW} \cdot C_{P,SW} \cdot T_{SW} + M_{BN} \, C_{P,BN} \cdot T_{BN} + M_{DN} \, C_{P,DN} \cdot T_{DN} \tag{8}$$

Brine and distilled water temperatures outlet from rejection section are given by:

$$T_D = T_{BO} - L_J \tag{9}$$

Where, L_J is sum of boiling point elevation of the brine and brine temperature loss in rejection section and defined as follows[1]:

$$L_J = 0.6872 - 0.185 \cdot X_{BD} - 0.01 \cdot T_{BD} \tag{10}$$

The energy balance for recovery section is obtained as follows:

$$M_{BO} \cdot C_{P,BO} \cdot T_R + M_{BO} \, C_{P,BO} \cdot (T_{MAX} - T_{IN}) = M_{DN} \, C_{P,DN} \cdot T_{DN} + M_{BN} \, C_{P,BN} \cdot T_{BN} \tag{11}$$

And the total input heat to brine heater per unit mass flow rate of distilled water is given by:

$$Q = M_{BO} \, C_{P,BO} \cdot (T_{MAX} - T_{IN}) \tag{12}$$

Brine and distilled water temperatures outlet and inlet from recovery section are given by:

$$T_{BN} = T_{DN} + L_R \tag{13}$$

Where, L_R is sum of boiling point elevation of the brine and brine temperature loss in recovery stages and defined as follows [1]:

$$L_R = 0.6872 - 0.185 . X_{BN} - 0.01 . T_{BN} \qquad (14)$$

Evaporation in recovery section is defined as:

$$M_{DN} . h_{fg,r} = M_{BO} . C_{P,BO} . T_{MAX} - M_{BN} . C_{P,BN} . T_{BN} \qquad (15)$$

Where, $h_{fg,r}$ is the latent heat calculated at the average temperature, $\dfrac{T_{MAX} + T_{DN}}{2}$

Also, condensation over condenser tubes in recovery section is given by:

$$M_{DN} . h_{fg,r} = M_{BO} . C_{P,BO} . (T_{IN} - T_R) \qquad (16)$$

Evaporation in rejection section is defined as:

$$(1 - M_{DN}) . h_{fg,J} = M_{SW} C_{P,SW} . (T_{SO} - T_{SW}) \qquad (17)$$

Where $h_{fg,J}$ is the latent heat calculated at the average temperature, $\dfrac{T_{BN} + T_{BD}}{2}$.

Also, condensation over condenser tubes in rejection section is given by:

$$(1 - M_{DN}) . h_{fg,J} = M_{BN} C_{P,BN} . T_{BN} - (M_{BD} + M_R) C_{P,BD} . T_{BD} \qquad (18)$$

The heat balance of node (b) is given as follows:

$$M_{SI} C_{P,SO} . T_{SO} + M_R C_{P,BD} . T_{BD} = M_{BO} C_{P,R} . T_R \qquad (19)$$

The total input heat to the condenser tubes ($Q = U . A . LMTD$) is equal to the total input heat which is defined in equation 12. Then, the total surface area is defined as follows:

$$A = M_{BO} . C_{P,BO} (T_{MAX} - T_{IN}) / U . (LMTD) \qquad (20)$$

Where, LMTD is the logarithmic mean temperature difference calculated as:

$$LMTD = [(T_{MAX} - T_{IN}) - (T_{BN} - T_R)] / Log[(T_{MAX} - T_{IN}) / (T_{BN} - T_R)]$$

Where, U is the overall heat transfer coefficient, and the approximate value is about 3000 W/m^2 °C [3].

Plant thermal performance ratio is defined as:

$$PR = h_{fg} / M_{BO} . C_{P,BH} (T_{MAX} - T_{IN}) \qquad (21)$$

Total input heat per unit mass of distilled water is defined as follows [1]:

$$Q = \dot{M}_{BO} \, C_P \, (L_R + \frac{T_{MAX} - T_{BD}}{N}) \, . \, \{1 \, / \, [1 - EXP(-\frac{U\,A}{\dot{M}_{BO}\,C_P})]\} \tag{22}$$

Then, the total number of stages for a specified value of input heat per unit mass flow rate of distilled water is found to be:

$$N = \frac{T_{MAX} - T_{BD}}{[(Q \, / \, \dot{M}_{BO} \, . \, C_P) - LR)] \, . \, [1 - EXP(-U \, A \, / \, \dot{M}_{BO}. \, C_P)]} \tag{23}$$

2.2 Solution Technique

The set of simultaneous nonlinear equations 1 through 19 represents a thermal model for MSF distillation plant. The solution for this set of equations produces the values of mass flow rates, concentrations and temperatures at inlet and outlet from rejection and recovery sections. The values of the design parameters are obtained for different values of input heat per unit mass flow rate of distilled water at known inlet sea water temperature, concentration and maximum brine temperature.

3. Results and Discussion

3.1 Optimization of the Design Parameters for the Specified Requirements of MSF Plant:

Figure 2 shows the variation of the required total surface area with the total input heat for different number of stages to produce unit mass flow rate of distilled water. It is noticed that for higher values of input heat the effect of heat transfer area is negligible. Also, for lower values of Q the required A is very high. For both cases it is expensive, so that there is an optimum or economic values for Q and A. The variation of A with N for different input heat Q is represented in Fig. 3. It is noticed that A decreases with increasing the total number of stages N and can be ignored for N greater than 40 stage for all values of total input heat to produce unit mass flow rate of distilled water. Also, it is known that for higher values of N the temperature drop per stage will be too small. For example if the total number of stages equal to 40, T_{MAX} equal to 90 °C, and blow-down temperature equal to 30 °C, the temperature drop per stage will equal to 1.5 °C. This is in good agreement with practical designs of MSF evaporators [6].

Figure 4 shows that the required total surface area increases sharply for the higher values of PR for different values of N.

From the discussion given above, it could be found that to obtain 1 kg/s of distilled water with an input 250 kW, the required surface area for MSF distillation plant is about 153 m^2 for total number of stages about 40 and PR equal to 9. This plant operates at inlet sea water temperature 20 °C, concentration 4% and maximum brine temperature 90 °C.

3.2   Effect of the Specified Requirements for MSF Plant on the Design Parameters

The variation of the mass flow rate inlet to the recovery section per unit mass flow rate of distilled water, M_{BO} with inlet sea water temperature, T_{SW} for different salt concentration, X_{SW} is shown in Fig. 5. Most sea water concentration lies between 3-5%, then it is noticed that the variation in M_{BO} is ignored for different values of X_{SW} for the same values of Q and N. Increasing T_{SW} needs more pumping power due to increase in M_{BO}. As long as, the temperature of sea water decreases in deeper positions, then it is recommended to pump the inlet sea water through a submerged tube in a deeper position where temperature level is desired.

Figure 6 shows that decreasing T_{SW} decreases the required surface area for the same value of Q and N. Also it is noticed that decreasing X_{SW} decreases the required A for fixed values of T_{SW}.

Figures 7 and 8 show that Increasing maximum brine temperature decreases the required pumping power due to decrease of M_{BO} and decreases the required total surface area. Also, decreasing X_{SW} decreases the required total surface area, A for fixed values of T_{MAX}.

It is known that T_{SW} and X_{SW} are restricted by a specified values according to the position of the MSF plant, but a suitable value for T_{MAX} can be chosen to adequate the above mentioned specified values.

3.3 Validity of the Proposed Thermal Model

The data of a reference MSF plant (Doha, West Plant in Kuwait) are operated at maximum temperature 90 °C, PR = 8, brine recirculation to distillation rate ratio equal to 12.67, specific heat transfer area 292 m^2/kg/s and input heat 280 kW/kg/s [6]. Fig. 9 shows that the data for both the reference plant and the proposed thermal model are in good agreement.

4. Conclusions

A proposed thermal model for a MSF distillation plant is constructed and solved. Predetermination of the most important design parameters is performed. The design parameters are evaluated and selected to provide the optimum performance for the specified requirements of the MSF distillation plant. It is found that to produce 1 kg/s of distilled water from sea water at 20 °C, x=4% and maximum brine temperature 90 °C, a MSF distillation plant with 40 stage, total surface area is about 153 m^2, input heat 250 kW and performance ratio equal to 9 is proposed. A comparison was made between the results of the present work and that of the previous studies to validate the present model.

References

1. Hesham,M.Mostafa, "Theoretical Analysis of Multi-Stage Flash Evaporator", Mansoura Engineering Journal, Vol. 23, No.3 pp 1-16, Sep., 1998

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3. Ali, N.H., "Simulation of MSF Desalination Plant", Alzahar Engineering Second International Conference, PP. 108, 1991.

4. Ali, S.E., and Fath-Allah, K., "MSF Mathematical Model", IDA World Congress on Distillation and Water Science, PP. 203, Vol. IV, Abou Dahbi, Nov. 18-24, 1995.

5. El-Doussoky, H, and Bingulac, S., "A Stage-BY-Stage algorithm for Solving the Steady State Model of Multi-Stage Flash Desalination Plant", IDA World Congress on Desalination and Water Science, PP. 251, Vol. IV, Abou Dahbi, Nov 18-24, 1995.

6. Darwish, M.A., and El-Doussoky, H., "Desalination by Distillation process: A Technical Comparison", IDA World Congress on Desalination and Water Science, PP 219, Vol. IV, Abou Dahbi, Nov. 18-24, 1995.

Nomenclatures

A   Total heat transfer surface area per unit mass flow rate of distilled water, [m^2/(kg/s)]

C_P Specific heat, [kJ/kg °C]

H_{fg} Latent heat of evaporation, [kJ/kg]

m   Mass flow rate, [kg/s]

M   Mass flow rate per unit mass flow rate of distilled water,[-]

N   Total number of stages,[-]

PR   Performance ratio [-]

Q   Total input heat per unit mass flow rate of distilled water, [kW/(kg/s)]

T   Temperature [°C]

X   Salt concentration   [%]

Subscripts

BD   Brine blow-down

BN   Brine outlet from recovery section

BO   Brine inlet to the recovery section

D   Distilled outlet from MSF distillation plant

DN   Distilled outlet from recovery section

J   Rejection

IN   Inlet brine to the brine heater

MAX   Maximum brine

r   Recovery

R   Recirculated Brine

SI   Make-up water

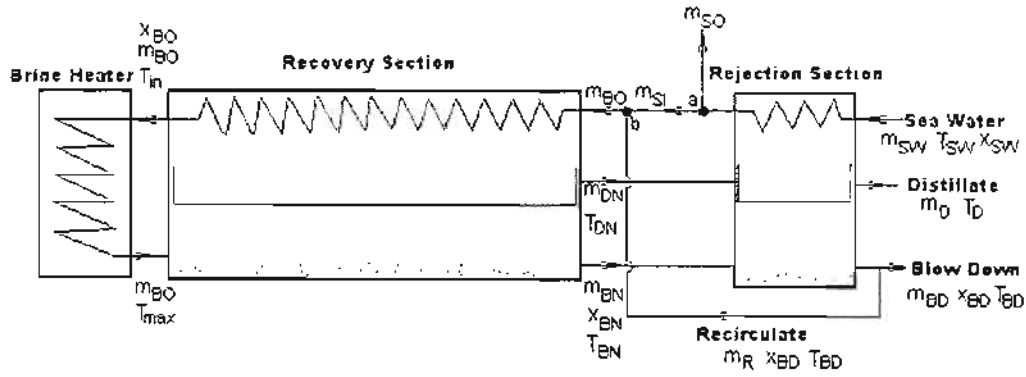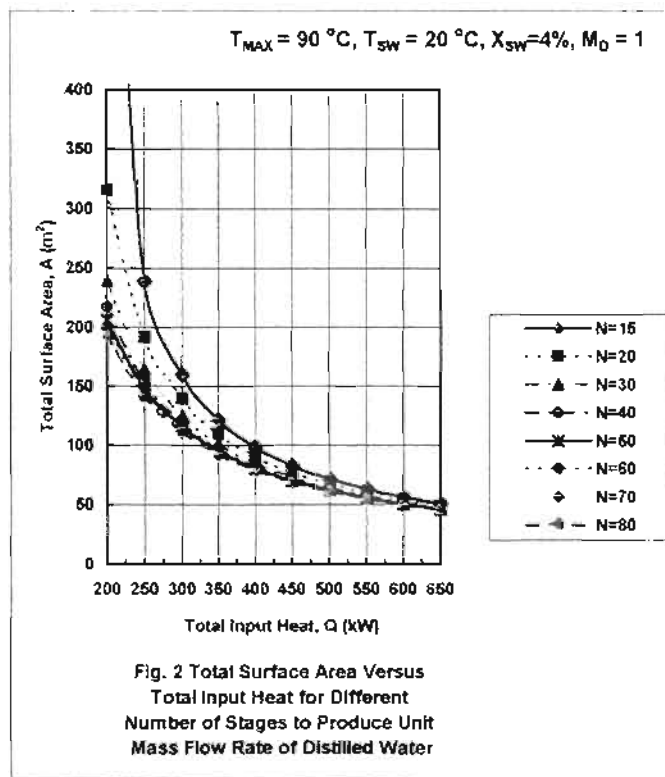SO   Outlet sea water

SW   Inlet sea water

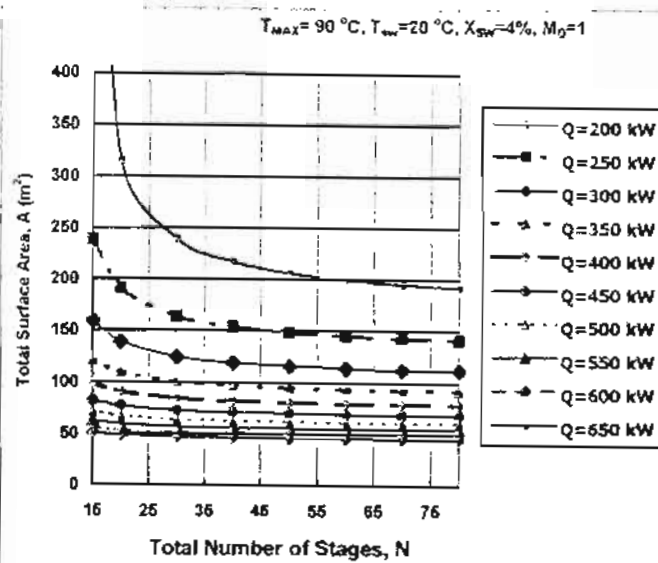**Fig. 1 The Basic components of MSF Distillation Plant**

Fig. 2 Total Surface Area Versus
Total Input Heat for Different
Number of Stages to Produce Unit
Mass Flow Rate of Distilled Water

$T_{MAX}= 90\ ^\circ C,\ T_{sw}=20\ ^\circ C,\ X_{SW}=4\%,\ M_D=1$

Fig. 3 Total Surface Area Versus Total Number of
Stages for Different Total Heat Input to Produce Unit
Mass Flow Rate of Distilled Water

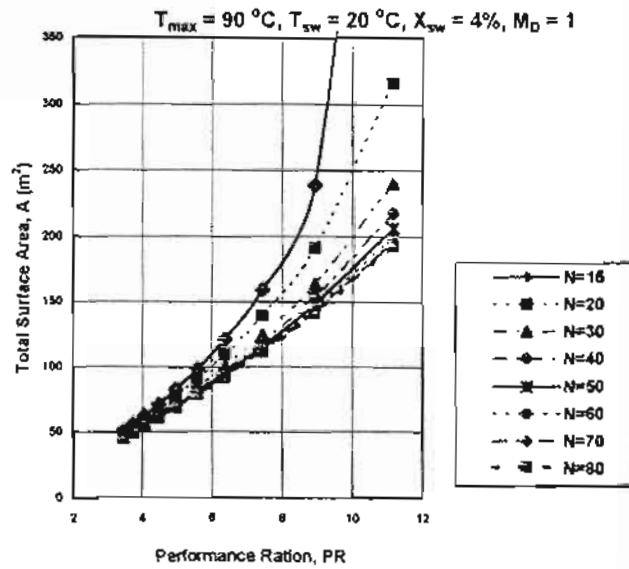$T_{max} = 90\ ^\circ C,\ T_{sw} = 20\ ^\circ C,\ X_{sw} = 4\%,\ M_D = 1$

Fig.4 Total Surface Area versus
Performance Ratio for Different Number
of Stages to Produce Unit Mass Flow
Rate of Distilled Water

Q = 250 kW, T_{MAX} = 90 °C, N = 40 stages, M_0 = 1

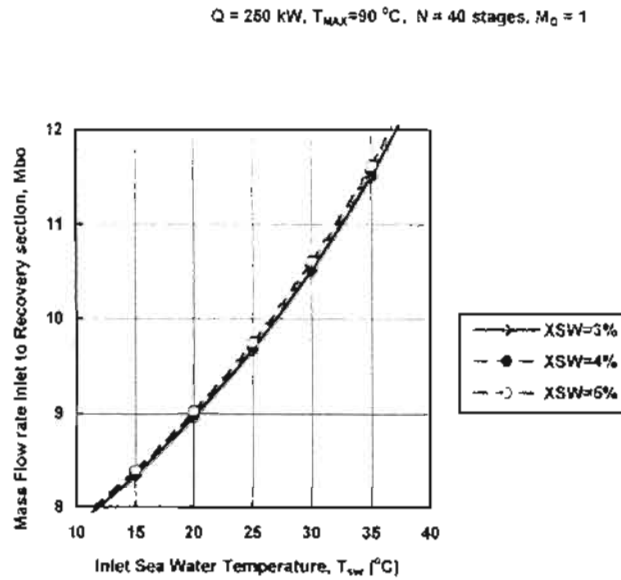Fig. 5. Variation of Mass Flow Rate Inlet to Recovery
Section with Inlet Sea Water Temperature for
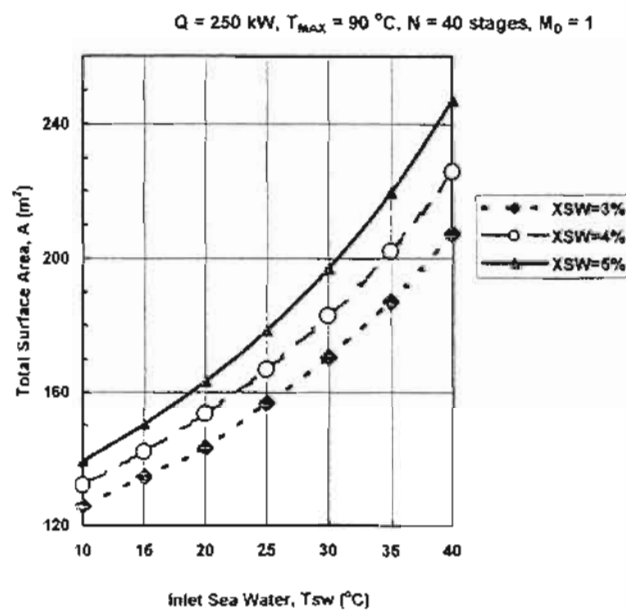Different Inlet Sea Water Concentrations

Q = 250 kW, T_{MAX} = 90 °C, N = 40 stages, M_0 = 1

Fig. 6 Variation of Total Surface Area with Inlet Sea Water
Temperature for Different Inlet Sea Water Concentrations

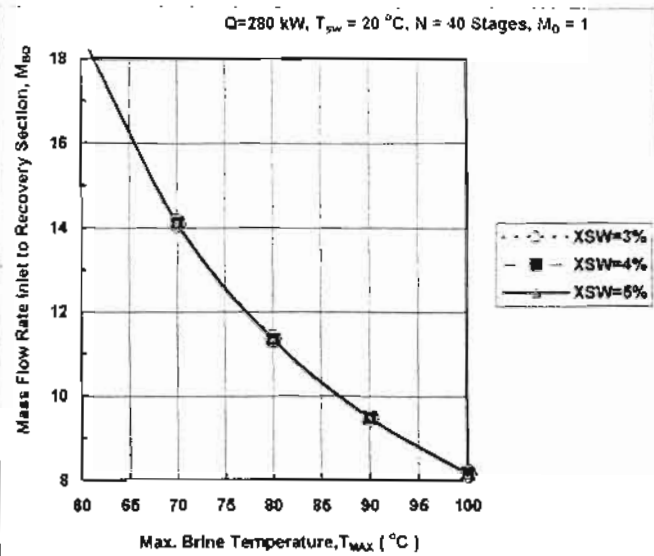Q=280 kW, T_{sw} = 20 °C, N = 40 Stages, M_0 = 1

Fig. 7 Variation of Mass Flow Rate Inlet to Recovery Section per Unit Mass Flow Rate of Distilled Water with Maximum Brine Temperature for Different Inlet Sea Water Concentrations
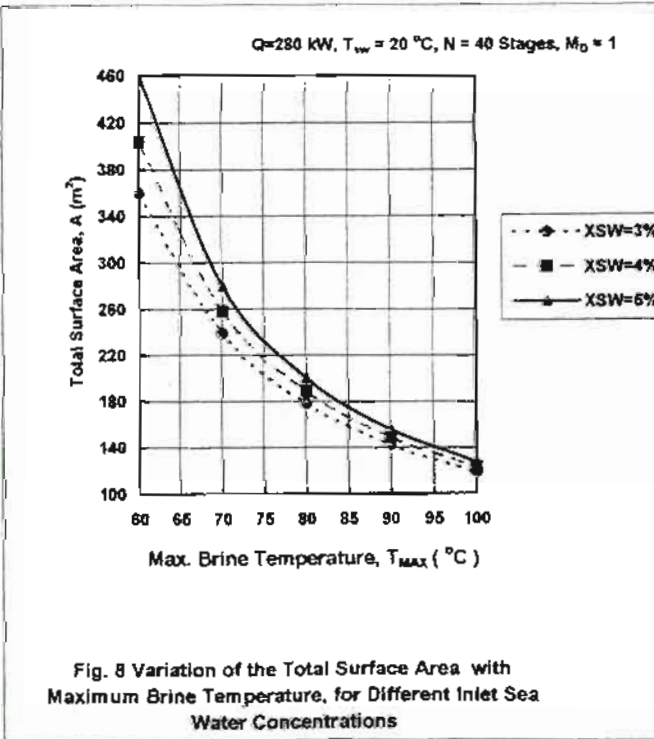
Q=280 kW, T_{sw} = 20 °C, N = 40 Stages, M_0 = 1

Fig. 8 Variation of the Total Surface Area with Maximum Brine Temperature, for Different Inlet Sea Water Concentrations

$Q=280$ kW .T_{sw} = 20 $^\circ$C, N=24 Stages, M_D = 1, T_{BD}=30 $^\circ$C

Fig. 9 Comparison between the Present Work for Recirculated Mass Flow Rate per Unit Mass flow Rate of Distilled Water, M_R with Darwish et al [6]