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Feed and Feed Preheating Effect on MED-TVC Enhancement

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ABSTRACT

Rapid and significant growth of world installed capacity of Reverse Osmosis (RO) followed by Multi-Effect Distillation (MED) has taken place year after year. Efforts are made to improve the system performance through increasing productivity and lowering specific power consumption by utilizing waste heat for seawater feed preheat. The present work studies the importance of seawater preheating in MED by utilizing power plants condenser cooling water. A steady state mathematical model for Multi-Effect Distillation combined with Thermal Vapor Compression (MED-TVC) system and the governing equations are solved using a computer program to evaluate the MED-TVC system performance. The model validity is examined by data collected from two MED-TVC plants which showed good agreement. Furthermore; the study results show that an increase of seawater feed temperature from 32 to 46 °C enhances the system productivity. Also, it increases the Gain Output Ratio by 8.7%, and decreases the specific heat consumption and the heat transfer area by 9.6% and17.4% respectively.

Key words: Multi-effect** Distillation **/ Thermal vapor compression / Feed preheating / Steam jet ejector

INTRODUCTION

The world and also Egypt suffer from water shortage problem due to the rapid growth in population, limited fresh water resources, industry, and irrigation water consumptions. Egyptian population at home increased to 85 million in August of 2013 at a rate of growth of one million per six months (1). The statistical analysis has indicated that the freshwater resources per capita per year in Egypt are 810 CM which are less than the poverty limit (1000CM/Capita/Year) which is equal to about 13 % of the average world resources per capita-year(2). Water desalination is considered one of the main solutions to overcome fresh water shortage. The long term growth rate in the desalination market is around 12% per year. This reflects the fact that scarcity is growing faster than the global population growth rate and faster than global economy increase(3). Figure (1) shows the trends of world water desalination technologies installed capacities growth, in 2005 and 2012-2013. As shown in the figure, the rapid increase is mainly in the installed capacities Reverse Osmosis (RO) and MED systems, while there is a noticeable decrease in the Multi-Stage Flash (MSF) evaporation capacity(3,4). Desalination processes are intensive energy consuming processes. Therefore, Efforts have been made to improve desalination system performance through increasing productivity and lowering specific power consumption by utilizing waste heat for seawater feed preheating of MED desalination systems.

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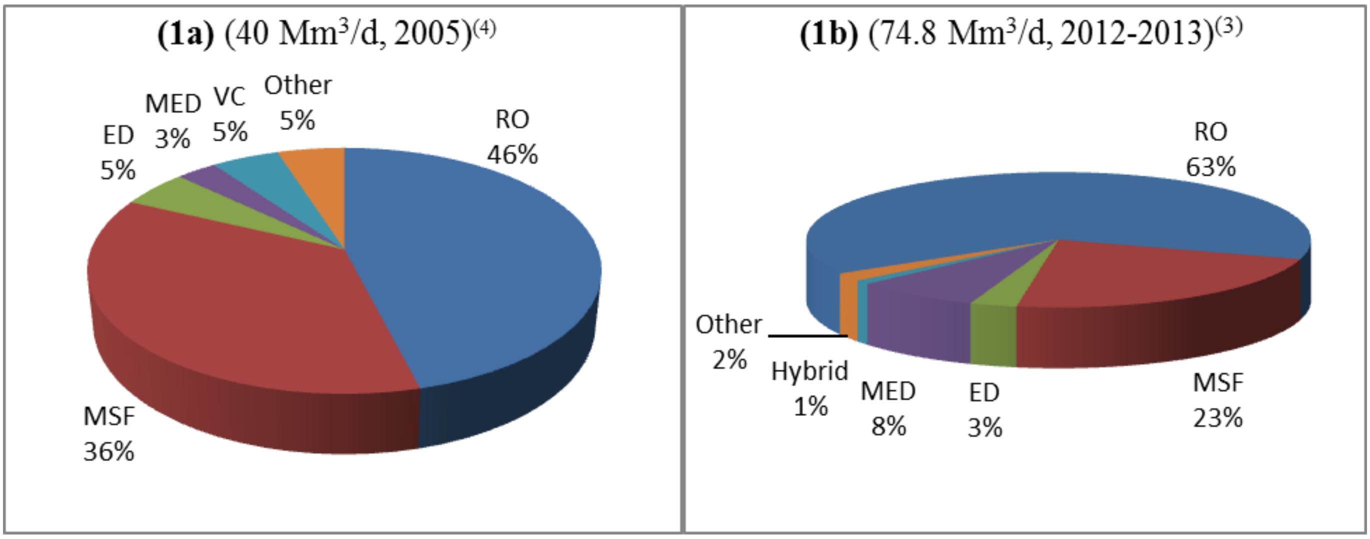

Fig. (1): World installed desalting capacity by process (3,4)

PREVIOUS WORK

Several studies have been carried out including studies about the effect of operating conditions on the performance of ME-TVC system.

Darwish et al(5), Alasfour et al(6), El-Dessouky et al(7), Kamali et al(8, 9), and Bin Amer(10), conducted thermal and performance analyses for the multiple effect evaporation system. A parametric study was preformed to investigate the impact of motive steam pressure, temperature difference per effect, top brine temperature, feed seawater temperature and motive steam flow rate on the system performance for each configuration. The results showed that the conventional multi-effects (MED) can produce desalinated water at a lower cost than the MSF system. Also, the decrease in exergy destruction is more pronounced than the decrease in the gain output ratio, GOR, at lower value of motive steam pressure.

Shih(11) conducted a detailed analysis of the technical developments and comparison regarding the use of waste heat recovery for the three types of thermal desalination. A comparative analysis of thermal desalination economics and the best utilization of waste heat was made. In utilizing waste heat, he showed that Multi-Effect Desalination (MED) is more flexible, consumes less energy, and allows for higher efficiency units. Meanwhile, Tewari and Rao(12) discussed the importance of utilizing waste heat from nuclear research reactors by coupling low-temperature evaporation (LTE) desalination units to improve system performance through increasing productivity and lowering specific power consumption by utilizing waste heat for seawater feed preheat. The results showed that increasing seawater feed temperature will increase the system water product and GOR.

The objective of the present work is to study the effect of feed preheating of contiguous MED-TVC on the system performance, through presenting and validating a mathematical model of steady state operation of the MED-TVC using an expandable computer program to evaluate the system performance. The computer program necessitates a subroutine to predict the entrainment ratio of steam jet ejector, which is the heart of MED-TVC process. The system performance must explore the effect of feed preheating on productivity, gain output ratio, specific heat consumption, heat transfer area, condenser cooling water flow rate, etc. to obtain the best possible operating conditions. The evaluation of number of effects on the MED-TVC performance is also studied.

MED-TVC MODEL $^{(6\text{-}10)}$

Figure (2) shows the processes and the main components of the conventional MED-TVC system with parallel cross flow configuration. The MED-TVC system to be analyzed is composed of evaporators (effects), a condenser, and a steam jet ejector. The evaporator (effect) represents the main part of the system. The number of evaporators depends on the required output capacity. The motive steam($M_m = S$) is used to compress part of the vapor generated in the last effect ($M_{ev}=D_r$) by the steam ejector, The expanded motive steam and the recompressed vapor leaving the steam ejector ($M_m + M_{ev}$) are directed to and condensed in the first effect. Part of the condensate returns to the boiler (M_m) and the other part (M_{ev}) joins the potable water product. The vapor formed in the first effect (D_1) by boiling is directed to the second effect where it acts as a heat source. This vapor heats the feed water (F_2) from (T_F) to boiling temperature (T_2), and generates vapor by boiling at a rate equal to (D_2). This continues up to the last effect where the vapor formed in the last effect (D_n) is divided into (M_{ev}) and (D_f) The stream (M_{ev}) is recompressed by the steam ejector to the first effect, and the other stream (D_f) is directed to the condenser where it gives its latent heat to the cooling water (M_{cw}) and raises its temperature from (T_{cw}) to (T_F)$^{(6)}$. Hot brine (B_i) from an effect (i) at a pressure of (P_i) (starting from i = 1) flows to the next effect (i + 1) at (P_{i+l}) and so on to last effect (n). Since $P_{i+1} < P_i$ flashing occurs in effect (i+1).

When deriving the energy balances for effects and condenser, the following assumptions have been made to simplify the mathematical model:

1- Equal temperature difference across each effect

$$\Delta T = T_1 - T_2 = T_2 - T_3 = T_{n-1} - T_n \tag{1}$$

2- The specific heat capacity for the feed seawater is equal to that of the brine and distillate water

$$C = C_f = C_b = C_d \tag{2}$$

3- Equal feed flow rate in all effects (parallel feed arrangement)

$$F_1 = F_2 = F_n = \frac{F_t}{n} \tag{3}$$

Temperature profile:

$$\Delta T = \frac{T_{ds} - T_{bn}}{n} \tag{4}$$

$$T_{b(1)} = T_{ds} - \Delta T \tag{5}$$

$$T_{v(1)} = T_{b(1)} - BPE \tag{6}$$

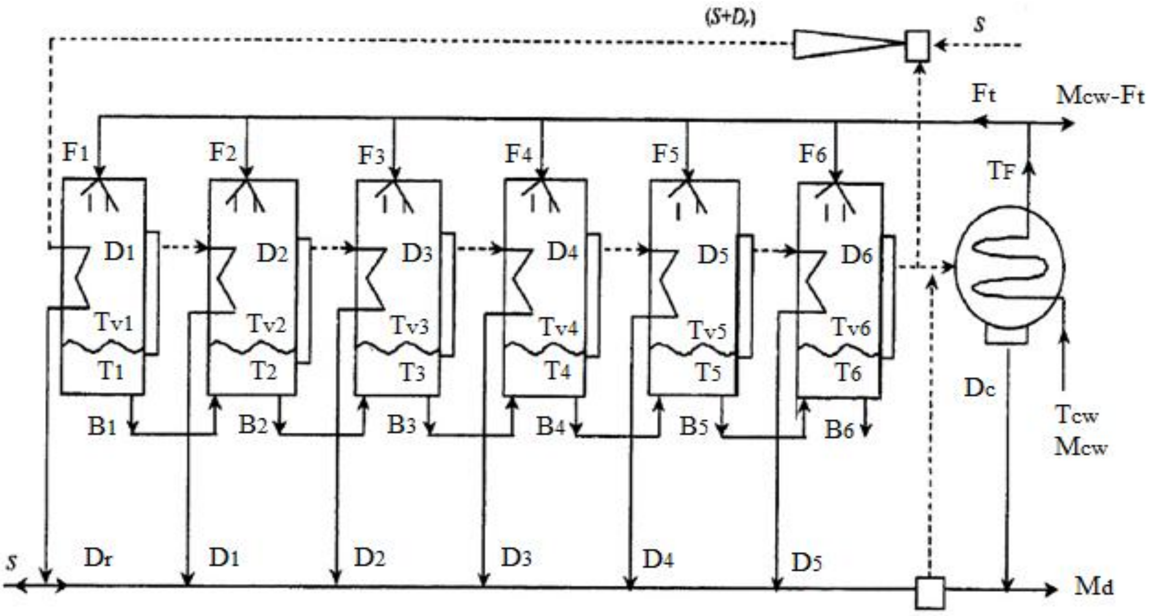

Fig. (2): MED-TVC unit with six effects [(6)].

Where ΔT is the temperature difference between each effect, BPE is the boiling point elevation and subscribes v, b, ds is the vapor, brine and discharged steam.

The Heat and Mass Balance of the First Effect:

$$M_s = M_{ev} + M_m \tag{7}$$

$$M_s \times L_s = F_{(1)} \times C \times (T_{b(1)} - T_F) + D_{(1)} \times L_{v(1)} \tag{8}$$

$$B_{(1)} = F_{(1)} - D_{(1)} \tag{9}$$

Where: $D_{(1)} = D_{b(1)} + D_{f(1)}$ $D_{f(1)} = 0$,

$D_{b(1)}$ is the amount of vapor generated by brine boiling in the first effect.

$D_{f(1)}$ is the amount of vapor generated by brine flashing inside the first effect.

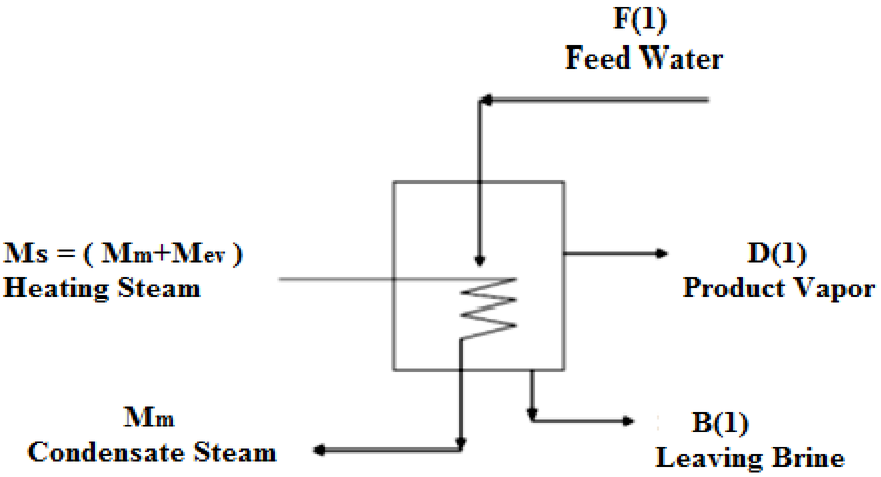

Fig. (3): First effect of MED-TVC mass balance diagram.

Energy balance in the first effect:

$$M_s \times L_s = U_{(1)} \times A_{(1)} \times (T_{ds} - T_{b(1)}) \tag{10}$$

Salt balance for the first effect:

$$X_{b(1)} = X_{f(1)} \times \frac{F_{(1)}}{B_{(1)}} \tag{11}$$

Where $X_{b(1)}$ is the salinity of the brine produced in the first effect.

$X_{f(1)}$ is the salinity of the feed water in the first effect

The Heat and Mass Balance of Effect (i):

$$F_{(i)} + B_{(i-1)} = D_{(i)} + B_{(i)} \tag{12}$$

Where: $D_{(i-1)}$ is the vapor from the previous effect.

$B_{(i-1)}$ is the brine leaving the previous effect.

$D_{(i)}$ is the produced vapor in the effect.

$B_{(i)}$ is the brine leaving the effect.

Also;

$$B_{(i)} = B_{(i-1)} + B'_{(i)} \tag{13}$$

$$D_{(i)} = D_{b(i)} + D_{f(i)} \tag{14}$$

Where, $B'_{(i)}$ is the amount of brine produced in the effect itself.

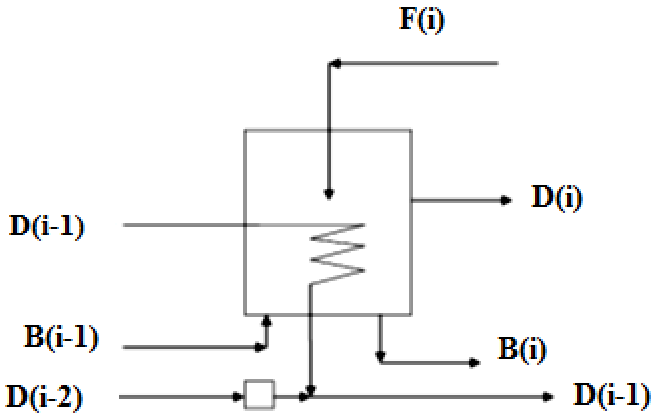

Fig. (4): Effect (i) mass balance.

Salt Balance of (i) Effect

The salinity of the distillate is negligible compared to the salinity of the seawater. The brine salinity is given by

$$X_{b(i)} = \frac{(X_{b(i-1)} \times B_{(i-1)} + X_{f(i)} \times F_{(i)})}{B_{(i)}} \tag{15}$$

Energy Balance:

Heat in: $D_{(i-1)} \times h_{v(i-1)}$ heat from the steam of the previous effect

Where

$h_{v(i-1)}$	is the enthalpy of vapor produced in effect (i-1).
$B_{(i-1)} \times h_{b(i-1)}$	heat of the brine leaving the previous effect
$h_{b(i-1)}$	is the enthalpy of the brine coming out of the effect (i-1).
$F_{(i)} \times h_{f(i)}$	heat of the make-up coming into the effect
$h_{f(i)}$	is the enthalpy of the makeup entering the effect(i).

Heat Out:

Where

$D_{(i)} \times h_{v(i)}$	heat of the produced steam leaving the effect
$h_{v(i)}$	is the enthalpy of the steam produced in effect (i).
$B_{(i)} \times h_{b(i)}$	heat of the brine leaving the effect (i)
$h_{b(i)}$	is the enthalpy of the brine leaving the effect (i).

This leads to:

$$D_{f(i)} = \frac{\left(B_{(i-1)} \times C \times (T_{b(i-1)} - T_{b(i)})\right)}{L_{v(i)}} \tag{16}$$

$$D_{b(i)} = \left[\frac{\left((D_{(i-1)} \times L_{v(i-1)}) - (F_{(i)} \times C \times (T_{b(i)} - T_F))\right)}{\left(L_{b(i)}\right)} \right] \tag{17}$$

$$D_{(i)} = \left(\frac{D_{(i-1)} \times L_{v(i-1)}}{L_{v(i)}} \right) - \left(F_{(i)} \times C \times \frac{(T_{b(i)} - T_F)}{L_{v(i)}} \right) + \left(B_{(i-1)} \times \frac{C \times \Delta T}{L_{b(i)}} \right) \tag{18}$$

Heat transfer area in effect (i) is expressed as follows

$$D_{(i-1)} \times L_{v(i-1)} = U_{(i)} \times A_{(i)} \times (T_{c(i-1)} - T_{b(i)}) \tag{19}$$

The effect of feed preheating process on the effect vapor temperature is considered in the following equations which depend on the general low for gases.

$$CF *_{(J,i)} = \left(\frac{D_{(0,1)}}{D_{(J,i)}} \right) \times \left(\frac{T_{v(0,i)}}{\left(\frac{p_{v(0,i)}}{100} \right)} \right) \tag{20}$$

$$a *_{(J,i)} = \left(\frac{79 \times CF_{(J,i)}}{500000} \right) \tag{21}$$

$$b *_{(J,i)} = - \left(\left(\frac{1671 \times CF_{(J,i)}}{200000} \right) + 1 \right) \tag{22}$$

$$C*_{(J,i)} = \left(\frac{29 \times CF_{(J,i)}}{200} \right) \quad (23)$$

$$Tv*_{(J,i)} = \left(-b_{(J,i)} + \sqrt{\frac{b_{(J,i)}^{\ 2} - 4 \times a_{(J,i)} \times C_{(J,i)}}{2 \times a_{(J,i)}}} \right) \quad (24)$$

The total distillate flow rate, M_d, is defined by

$$M_d = \sum_{i=1}^{n} D_{b(i)} + \sum_{i=2}^{n} D_{f(i)} \quad (25)$$

Balance Equations for the down Condenser:

The down condenser balance equations include the energy balance and heat transfer rate equation.

Energy Balance of the down Condenser

$$(D_{(n)} - M_{ev}) \times L_{v(n)} = (M_{cw}) \times C \times (T_F - T_{cw}) \quad (26)$$

Rating of the down Condenser

$$(D_{(n)} - M_{ev}) \times L_{v(n)} = U_c \times A_c \times (LMTD)_c \quad (27)$$

$$(LMTD)_c = \frac{(T_F - T_{cw})}{\ln\left(\frac{(T_{cn} - T_{cw})}{(T_{cn} - T_F)} \right)} \quad (28)$$

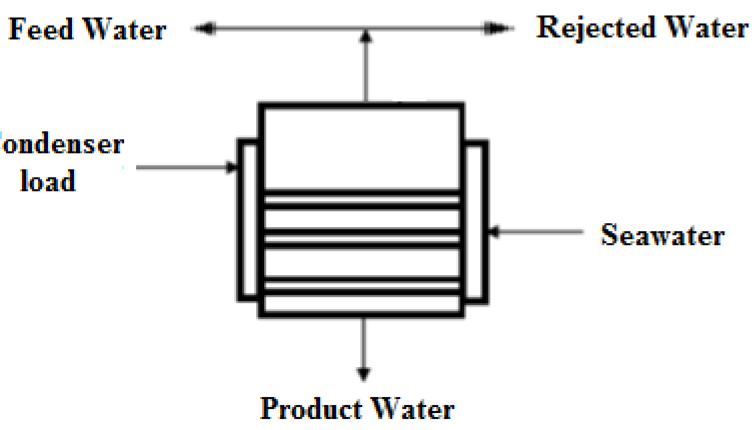

Fig. (5): Down condenser mass balance.

Where; Ac, U_c, and $(LMTD)_c$ are the heat transfer area, overall heat transfer coefficient, and logarithmic mean temperature difference respectively. In the presence of the steam jet ejector, the thermal load of the down condenser is lower since the part of the vapor formed in the last effect is entrained in the steam jet ejector.

STEAM JET EJECTOR

The main data required from analyzing the steam jet ejector is the determination of the entrained vapor mass flow rate required per unit mass of the motive steam (ER), given the pressure of the motive steam (P_m), discharge pressure (P_{ds}) and the suction pressure (P_{ev}). The expansion ratio (Ex) is defined as the ratio of the motive steam pressure to the entrained vapor pressure. The compression ratio (Cr) gives the pressure ratio of the compressed vapor to the entrained vapor.

Ejector correlations have a narrow range of applications with low accuracy**.** Correlations of steam jet ejectors depend on a chart designed by Power (13) with an accuracy of about 20%. Studies use Power chart to obtain the ejector entrainment ratio as a function of the compression ratio and expansion ratio in certain ranges. The study of El-Dessouky et al (14) used some experimental, actual, and power graph data to make two correlations of the entrainment ratio for compression ratio higher and lower than 1.8. These correlations are out of range in the present work and with low accuracy due to the wide range of data used.

A mathematical model developed by (15) investigates the effect of the operating parameters on the ejector performance. Based on this model (15), a correlation is presented in our case study to predict the entrainment ratio of the steam jet ejector in a definite rang of operation to facilitate the mathematical model simulation of MED-TVC plant. The equation is a function of the discharged vapor pressure and the expansion ratio which is defined as the ratio of the discharged vapor to the entrained vapor pressure.

$$Ex = \frac{P_m}{P_{ev}} \tag{29}$$

$$Cr = \frac{p_{ds}}{p_{ev}} \tag{30}$$

$$\mathbf{ER = 0.22617 + 1.43452*10^{-2} * (P_{ds}) - 2.14616*10^{-3} * (Ex) + 8.52517*10^{-6} * (Ex)^2} \tag{31}$$

Equation(31) (16) is valid in the range of entrained vapor pressure from 7.41 to 9.71 kPa, motive steam pressure 2500 kPa, and compression ratio 3.13.

MED-TVC MODEL VALIDATION

The developed MED-TVC model is solved by computer program and the flowchart for the program is mentioned in appendix A. Desalination plant design validations are important since different mathematical models have been developed each with different process (model) assumptions and configuration layouts. The model is used to estimate the performance of MED-TVC plant. The model is validated by using actual data of two desalination plants. The first plant is Mirfa in the United Arab Emirates with 4 effects (17). The second plant is Um El Nar which located in United Arab Emirates with 6 effects (17) .Table (1) presents the operating conditions data of both plants that were used as input data to the present model. Also, the output calculated performance values are compared with actual measured values, are presented in Table (1).

Table (1): Validation of MED-TVC model.

Desalination plant	**Mirfa**		**Um alnar**	
	Actual	**Model**	**Actual**	**Model**
Operating and design conditions				
Motive steam pressure P_s, kpa	2500	2500	2500	2500
Motive steam flow rate M_m, kg/s	6.8	6.8	10.65	10.65
Discharge steam temperature T_{ds},°C	62.8	62.8	65	65
Last brine temperature T_{bn},°C	46.8	46.8	42.8	42.8
Feed seawater temperature T_F,°C	40	40	40	40
Temperature drop per effect ΔT,°C	4	4	3.8	3.8
Number of effects, n	4	4	6	6
Ejector design				
Compression ratio, Cr	2.16	2.16	3.13	3.13
Expansion ratio, Ex	248	248	300	300
System performance				
Distillate production, M_d, kg/s	51.3	* 50.67	94.46	* 93.20
Gain output ratio, GOR	7.5	* 7.46	8.87	* 8.75
Specific heat consumption, shc	342.1	* 340.21	285.4	*288.8
Specific heat transfer area, sa	336.4	* 333.38	241	* 246
Ejector entrainment ratio, ER	1.11	* 1.11	0.735	*0.735

* calculated model output data.

RESULT AND DISCUSSION

The effect of feed preheating with fixed feed water mass flow rate for each effect on MED-TVC performance:

In this study an investigation of the impact of feed water temperature on the system performance is presented. As shown in Figure (6), the results showed that the water production of the first effect decreases with the increase of feeding water temperature. These results were achieved because the increase of feed water temperature increases the discharged vapor temperature of the ejector with constant compression ratio. The increase of the discharged vapor temperature increases the temperature difference between the boiling and the feeding temperatures in the first effect which reduces the amount of vapor generated in the first effect. The figure also shows that, the water product of the last effect increases with the feed temperature as shown in Figure (7). This increase is due to the decrease in the temperature difference between the boiling temperature and the feed temperature. The lowest sensible heat occurs at the higher feed temperature which, results in the increase of the vapor temperature and the mass flow rate and the increase of the amount of the flashed vapor in the last effect.

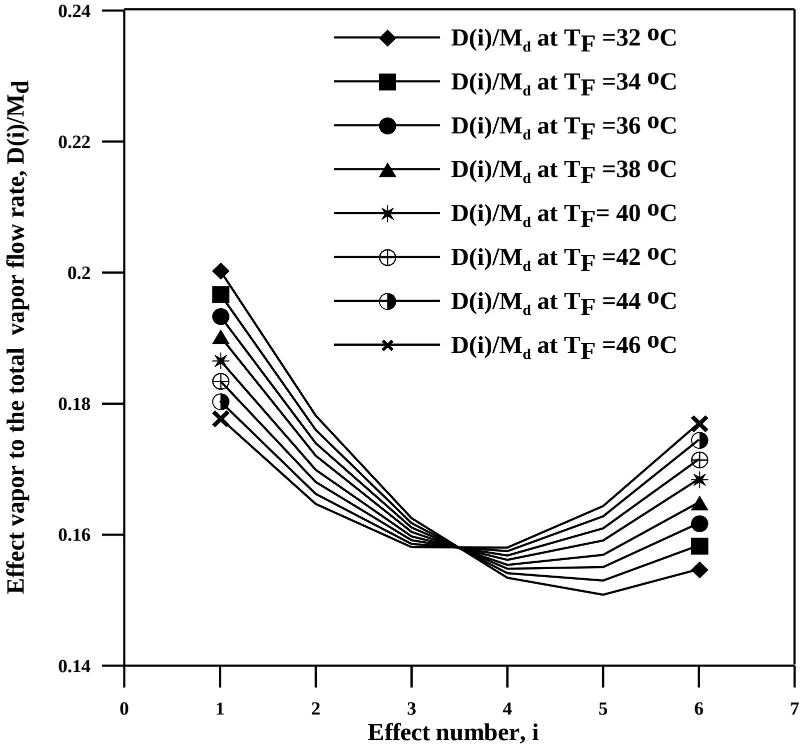

Fig. (6): Feed temperature with the ratio of effect vapor product to the total product vapor.

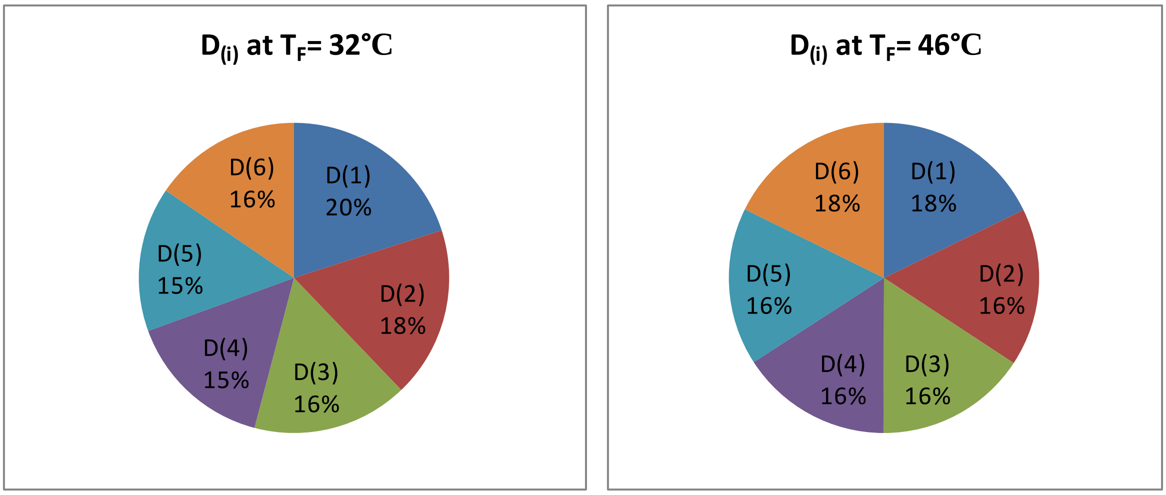

Fig. (7): Product vapor percentage at each effect at T_F=32 and 46°C.

As shown in Figures (8 and 9) results show that increasing feed water temperature, increases the fresh water productivity and the gain output ratio (GOR). The total water product increases from 86.2 kg/s at T_F =32°C to 93.64 kg/s at T_F =46°C .The gain output ratio increases from 8.08 at T_F =32°C to 8.79 at T_F = 46°C which represents an increase percentage of 8.73%.The reason behind that is that feed seawater with high temperature needs less heat to be saturated. As a result of that, more energy is used to generate additional amount of vapor which, is condensed as a water product. Thus, the total productivity of the plant and (GOR) increases.

Figure (10) illustrates that the vapor temperature profile of each effect, increase in the feeding water temperature and increases the vapor temperatures in each effect. This increase in vapor temperature is due to the increase of the amount of the produced vapor which increases the vapor temperature and the pressure in each effect. It is worse to mention that the temperature difference between feed water and vapor temperature in the last effect must be not less than 2.5°C, otherwise which would damage the feed water spray pattern outside the tube in evaporator and decrease the heat transfer coefficient.

Figure (11) illustrates the slight increase of the temperature difference in each effect with the increase in feeding water temperature. The increase in water feeding temperature increases the last effect vapor temperature and the pressure and increases also the discharge steam temperature of the ejector with a constant compression ratio. So, the total temperature difference across the effects increases. Therefore, a slight variation in the temperature difference in each effect occurs.

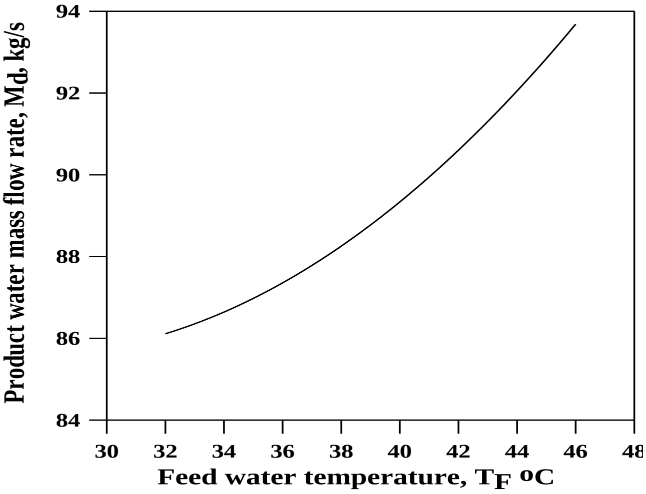

Fig. (8): Total Product water with feed water temperature.

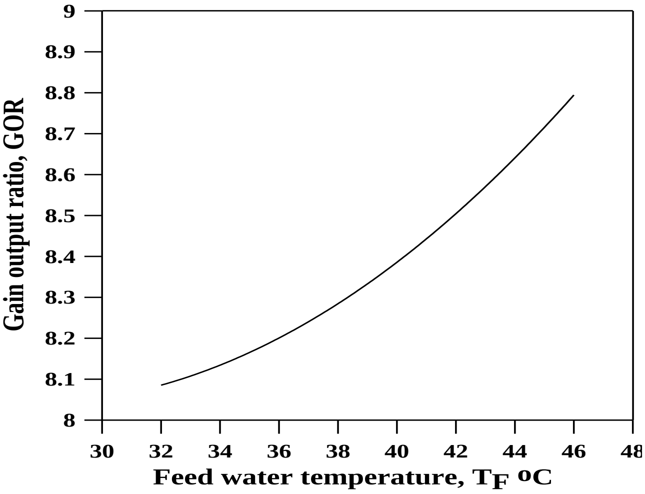

Fig. (9): Gain output ratio with feed water temperature.

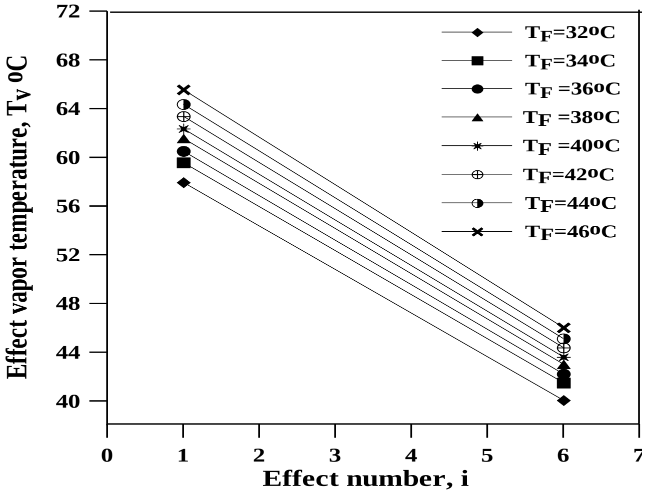

Fig. (10): Vapor temperature at each effect with feed water temperature.

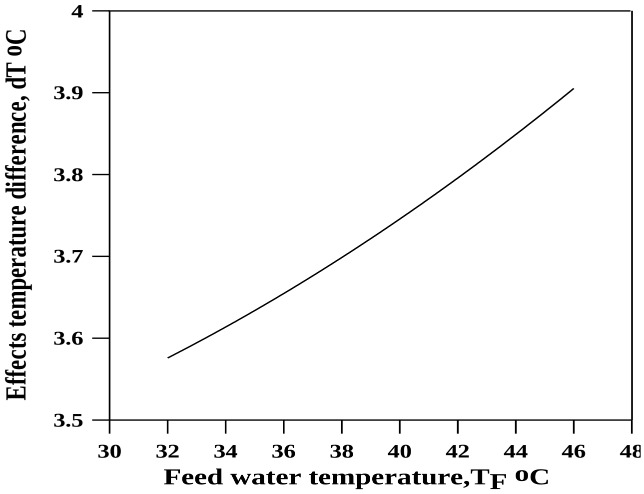

Fig. (11): Temperature difference with Feed water temperature

Figures (12 and 13) show that, the increase in feed temperature decreases the specific heat consumption and the specific total effects heat transfer area. From the definition of the specific heat consumption and the specific total effects heat transfer area, this decrease is due to the increase in the total water product M_d with feed preheating at the same amount of the motive steam flow rate and the same motive steam pressure. By preheating the feed water, the feed water temperature increases just outside the effects, so the total amount of required surface area remain constant but the ratio between the total amount of required surface area to the total water product which is called specific total effects heat transfer area (sa) is increased due to the water product increase. The specific heat consumption decreases from 313.31 at T_F =32°C to 284.74 kJ/kg.K at T_F =46°C which represents a reduction percent of 9.1%. The specific total effects area decreases from 314.53 at T_F =32°C to 259.62 m^2/(kg/s) at T_F =46°C which represents a reduction percentage of 17.45% .

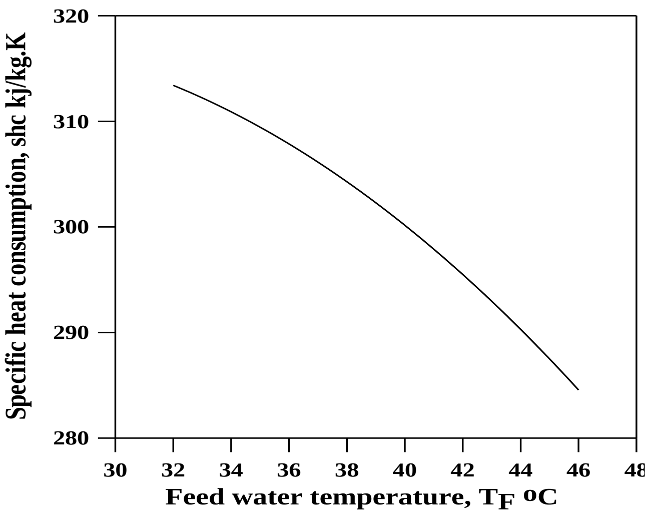

Fig. (12): Specific heat consumption with feed temperature.

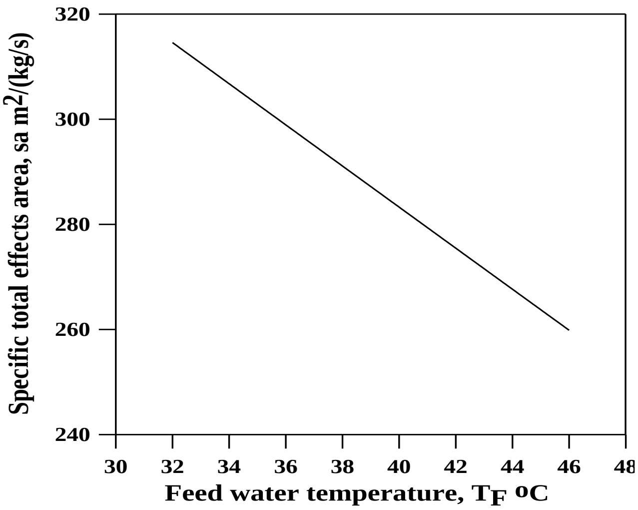

Fig. (13): Specific total effects area with feed temperature.

Effect of Varying Inlet Feed Water Temperature with Different Number of Effects on MED-TVC Performance

In the present case study, the effect of feed water preheating process is studied with varying the number of effects. The number of effects in MED-TVC system is limited by the temperature difference between the heating vapor in the first effect and the seawater inlet temperatures, which represent the hot and cold ends in the system.

Figures (14 and 15) show the effect varying the number of effects with feed preheating process on the total produced water and the gain output ratio. Increasing feed seawater temperature will increase the gain output ratio and increase the fresh water productivity due to the decrease in the temperature difference between the inlet feed water temperature and the effect temperature. These findings are in agreement with the work of Kamali (18). Moreover the total fresh water productivity and the gain output ratio are strongly affected by the number of effects. A larger number of effects increase the fresh water productivity and the gain output ratio. This is because increasing the number of effects causes redaction in the temperature difference across the effect as a result of that the number of vapor reuse increases and consequently the total amount of vapor formed increases.

Figure (16) shows the effect of varying the number of effects with feed preheating process on the specific heat consumption. The increase in the inlet feed temperature decreases the specific heat consumption. Moreover, increasing the number of effects decreases the specific heat consumption due to the increase in the total amount of the produced fresh water. Figure (16) illustrates that specific heat consumption reduction percentage decreases with increasing the number of effect. As shown in Figure (16) varying the number of effects from n=4 to n=6 has the greatest effect on the specific heat consumption reduction percentage. Furthermore, the number of effects in MED-TVC system is limited by the temperature difference between the heating vapor in the first effect and the seawater inlet temperatures. As a result of that the effect of varying the number of effects on the specific power consumption is decreased at high number of effects.

Figure (17) shows the effect of varying the number of effects with feed preheating process on the total area of effects. The increase in feed water temperature decreases the specific total heat transfer area of effects. This decrease is due to the increase in the total water product M_d with feed preheating at the same amount of the motive steam mass flow rate and the same motive steam pressure. It is clear that by changing the number of effects the heat transfer area will change as well .The heat transfer area will increase with increasing the number of effects. The increase in the heat transfer area increases the cost of the MED-TVC system.

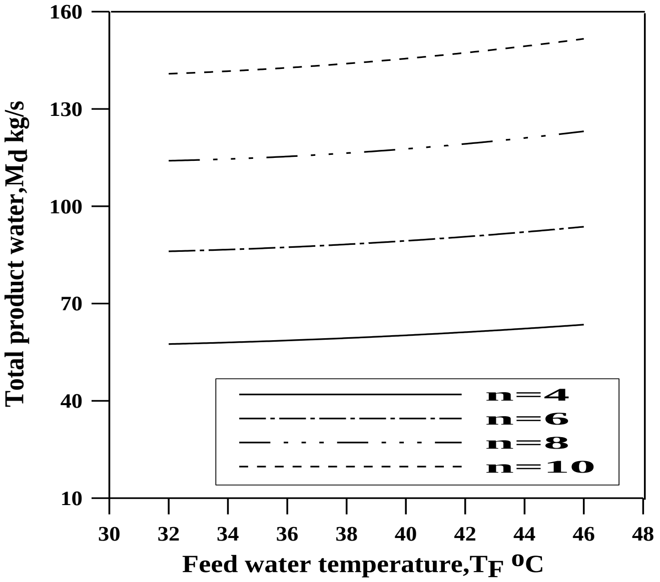

Fig. (14): Total product water with feed water temperature at different number of effects.

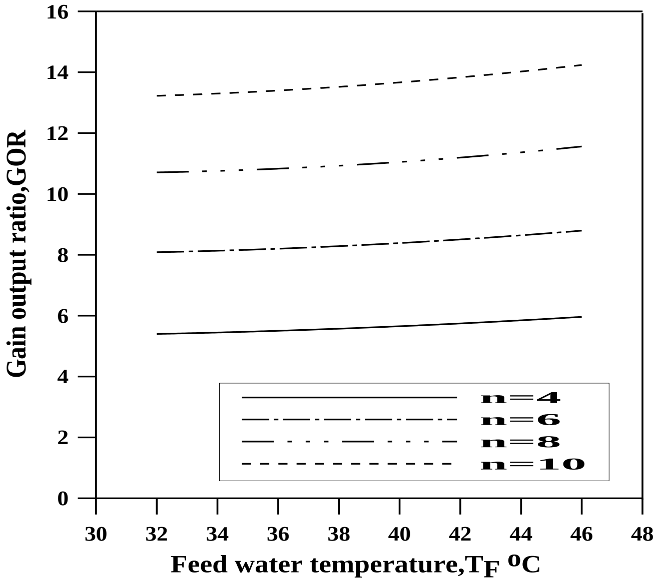

Fig (15): Gain output ratio with feed water temperature at different number of effects.

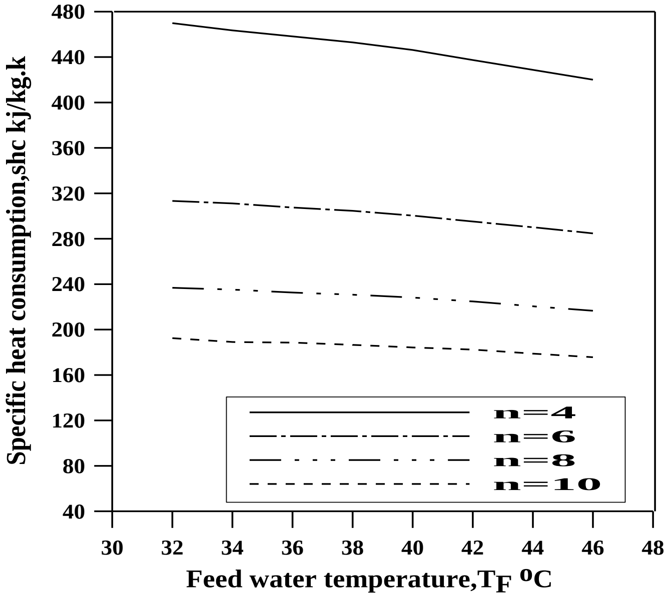

Fig. (16): Specific heat consumption with feed water temperature at different number of effects.

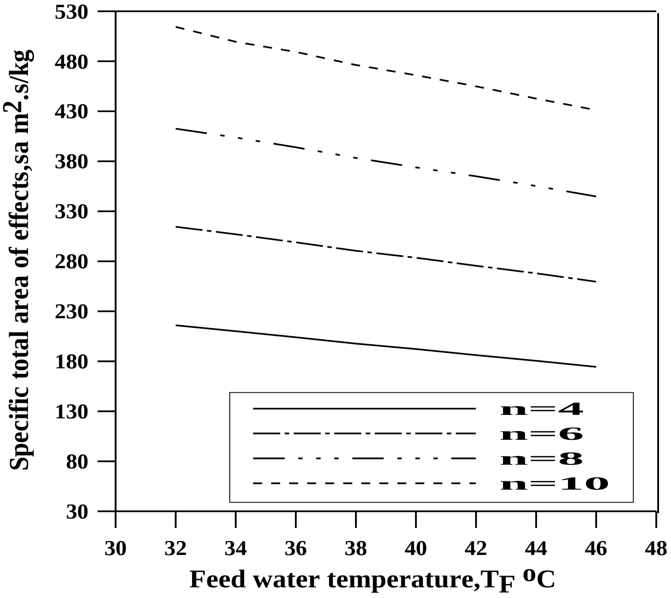

Fig. (17): Specific total area of effects with feed water temperature at different number of effects.

CONCLUSION

This paper outlines the multiple effect desalination thermal vapor compression study to enhance its performance. A computer program was developed from the literature studies and used to simulate MED-TVC system. A case study was made to evaluate the effect of seawater feed preheating using low grade heat source on system performance at fixed feed water mass flow rate. The seawater feed temperature has a crucial effect on the system performance, increase in total water product, increase in the GOR and decrease in the specific heat consumption and the specific total effect area. Furthermore, the effect of different number of effects with feed preheating was studied. A larger number of effects increases the fresh water productivity, the Gain Output Ratio and decreases specific heat consumption.

NOMENCLATURE TABLE

A	Heat transfer area,	m^2	T	Temperature, °C
B	Brine mass flow rate,	kg/s	TVC	Thermal vapor compression
BPE	Boiling point elevation,	°C	CF,a,b,C	Factors
C	Specific heat capacity of water,	kJ/kg.K	**Subscripts**	
Cr	Ejector compression ratio		b	Brine
D	Distillate,	kg/s	cw	Cooling water
D_r	Entrained vapor,	kg/s	c	Condenser
D_s	Discharged steam		d	Desalinated water
ER	Ejector entrainment ratio		ds	Discharge steam
Ex	Ejector expansion ratio		e	Evaporator
F	Feed water mass flow rate,	kg/s	ev	Entrained vapor
GOR	Gain output ratio		F	Feed water
L	Latent heat,	kJ/kg	f	Flashing vapor
LMTD	Logarithmic mean temperature difference		i	Effect number
M	Mass flow rate	kg/s	m	Motive steam
MED	Multiple effect desalination		n	Total number of effects
ΔT	Temperature difference between two effect		s	Steam
P	Pressure,	kPa	v	Vapor

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Appendix A
MED-TVC Mathematical Model Flow Chart