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THERMAL PERFORMANCE AND EXERGY ANALYSIS OF A THERMAL VAPOR COMPRESSION DESALINATION SYSTEM

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Abstract—A thermodynamic analysis based on the first and second laws is conducted to evaluate the performance of a thermal vapor compression (TVC) desalination system. The performance of the analytical model is compared with operational data obtained from tests performed on a four-effect, low temperature TVC desalination system with performance ratios of 6.5–6.8, located in the U.A.E. The effect of the process variables on the plant's performance ratios is investigated. The exergy losses due to irreversibilities in different subsystems of the TVC system are evaluated and compared with those of the conventional multi-effect boiling (MEB) and mechanical vapor compression (MVC) desalination systems. The TVC system yields the least exergy destruction among the three systems. Subsystem exergy analysis shows that most of the exergy destruction in the TVC system occurs in the first effect and in the thermo-compressor. Overall exergy losses can be significantly reduced by increasing the number of effects and the thermo-compressor entrainment ratio, and by decreasing the top brine and heating steam temperatures.

Water desalination   Exergy   Thermal compression desalination   Thermodynamics

NOMENCLATURE

E = Energy (kJ)
$E_{j,\text{in}}$ = Input energy of stream j (kJ)
$E_{j,\text{out}}$ = Output energy of stream j (kJ)
ER = Entrainment ratio = (kg/h vapor taken from evaporator and compressed by ejector)/(kg/h driving stream)
h = Specific enthalpy (kJ/kg)
h_1 = Enthalpy of high pressure steam (kJ/kg)
h_2 = Enthalpy of steam after isentropic expansion in nozzle to pressure of entrained vapor (kJ/kg)
h_3 = Enthalpy of mixture at start of compression in diffuser section (kJ/kg)
h_4 = Enthalpy of mixture after isentropic compression to discharge pressure (kJ/kg)
I = Rate of exergy loss (kJ/h)
I_i = Irreversibility rate of subsystem i (kJ/h)
I_T = Rate of loss of exergy, or irreversibility rate, of process (kJ/h)
M = Mass flow rate (kg/h)
N = Number of effects
P = Pressure (bar)
PR = Performance ratio = $(M_d\lambda)/Q_s$
Q = Heat (kJ)
Q_s = Heat supply rate to desalination plant (kJ/h)
R = Gas constant for H_2O (kJ/(kg K))
s = Specific entropy (kJ/(kg K))
T = Temperature (K)
W = Work (kJ)
X_m = Mole fraction of salt in brine
X_{om} = Mole fraction of salt in sea water

Greek

β = Constant (equation (10))
δ = Exergy defect (equation (7))
η = Overall thermal efficiency of thermo-compressor (equation (11))
λ = Latent heat of evaporation of water (kJ/kg)
Σ = Summation

ϕ = Exergy rate (kJ/h)
ϕ_{br} = Reject brine exergy rate (kJ/h)
ϕ_c = Chemical exergy of brine (kJ/h)
ϕ_{cond} = Condensate exergy rate (kJ/h)
ϕ_{in} = Exergy flow rate associated with input streams (kJ/h)
ϕ_{out} = Exergy flow rate associated with outlet streams (kJ/h)
ϕ_{steam} = Thermal exergy flow associated in motive steam to thermo-compressor and steam ejector (kJ/h)
$\phi_{sw,in}$ = Exergy flow rate associated with sea water feed (kJ/h)
ϕ_{pumps} = Exergy of pumping energy inputs (kJ/h)
ψ = Exergy efficiency (equation (6))

Subscripts

d = Distillate
f = Feed
0 = The "dead state"

INTRODUCTION

Desalination processes are energy intensive, and there is recent interest in reducing the energy requirement by using vapor compression distillation processes for small or medium scale desalination plants [1–8]. The unique characteristic of vapor compression is the energy re-use of the vapor generated in the last effect (by compressing it either thermally in a steam ejector or mechanically in a compressor) to act as a heat source for the first effect. The compression process raises the steam pressure and, consequently, its saturation temperature slightly higher than the temperature of the vapor generated in the first effect.

Mechanical vapor compression requires the installation of the expensive compressor with all its limitations (low capacity), accessories, and operational and maintenance disadvantages [2]. In contrast, the thermo-compressor consists of a simple ejector without any moving parts and with hardly any maintenance requirements, but it has a lower efficiency. Commercial thermo-vapor-compression units of low capacities are being used successfully (see [3, 5, 7, 8]). In the U.A.E., there are four vapor compression desalination plants in operation in the remote areas of western Abu Dhabi. Each plant has a capacity of one million gallons per day. These plants have been characterized by proven reliability under the Gulf conditions, low temperature operation (top brine temperature lower than 60°C), lowering corrosion and scaling problems, low energy consumption (thermal and electrical), easy operation and maintenance and good economics, including erection, civil work and sea water intake. It has been reported [8] that such plants are 35% cheaper than the multi-stage flash plants.

Most of the thermodynamic analysis performed so far on the TVC system is based on the first law of thermodynamics [1, 4, 9]. Although the first law is an important tool in evaluating the overall performance of the desalting plant, such analysis does not take into account the quality of energy transferred. This is an issue of particular importance when both thermal and mechanical energy are employed, as they are in vapor compression plants. First-law analysis cannot show where the maximum loss of available energy takes place and would lead to the conclusion that the energy loss to the surroundings and the blowdown are the only significant losses. Second-law (exergy) analysis is needed to place all energy interactions on the same basis and to give relevant guidance for process improvement. In related areas, exergy analysis has been applied to multi-stage flash distillation (see [10–13]) and cogeneration plants (see [14–16]) but not noticeably to vapor compression distillation processes. In this paper, we apply exergy analysis to the TVC process, using actual plant operating data. The effects of the main process variables on the performance ratio of the plant, as well as the exergy efficiency of the primary plant subsystems, are examined. (The performance ratio PR is defined in the nomenclature section.) The energy/exergy performance of the TVC system is then compared with mechanical vapor compression and conventional multi-effect boiling desalination systems.

METHOD OF ANALYSIS

The mass, species, energy, and exergy accounting equations are solved for each of the process subsystems.

Energy balance equation

From the first law,

$$\Sigma E_{j,\mathrm{in}} + Q = \Sigma E_{j,\mathrm{out}} + W. \tag{1}$$

The mass, species, and energy balance equations for all the plant subsystems, and a few associated state and effect related functions yield a set of n independent equations. This set of simultaneous equations is solved by matrix algebra assuming equal temperature intervals for all effects, and assuming that all effects have adiabatic walls.

The boundary conditions are (1) the specified sea water feed conditions (flow rate, salinity, temperature), (2) the desired distillate production rate, and (3) the specified maximum brine salinity and temperature. The matrix solutions obtained determine the distillation rates in the individual effects, the steam requirements, and hence the performance ratio.

Exergy analysis

The steady state exergy balance equation may be written as

Total exergy transported into system

= Total exergy transported out of system + Energy destroyed within system.

In other words,

$$\Sigma\phi_{\mathrm{in}} = \Sigma\phi_{\mathrm{out}} + I_{\mathrm{T}}, \tag{2}$$

where

$$\Sigma\phi_{\mathrm{in}} = \phi_{\mathrm{sw,in}} + \Sigma\phi_{\mathrm{steam}} + \Sigma\phi_{\mathrm{pumps}}, \tag{3}$$

and

$$\Sigma\phi_{\mathrm{out}} = \Sigma\phi_{\mathrm{cond}} + \Sigma\phi_{\mathrm{br}}. \tag{4}$$

The system overall irreversibility rate can be expressed as the summation of the subsystem irreversibility rate [17]:

$$I_{\mathrm{T}} = \sum_{j} I_i, \tag{5}$$

where J is the number of subsystems in the analysis and I_i is the irreversibility rate of subsystem i. The exergy ("rational" [17]) efficiency ψ, given by

$$\psi = \frac{\Sigma\phi_{\mathrm{out}}}{\Sigma\phi_{\mathrm{in}}} \tag{6}$$

is used as a criterion of performance, with ϕ_{out} and ϕ_{in} defined by equations (4) and (3), respectively. The total loss of exergy is made up of the individual exergy losses of the plant subsystems. The exergy efficiency defect δ_i of each subsystem is defined by

$$\delta_i = \frac{I_i}{\Sigma\phi_{\mathrm{in}}}. \tag{7}$$

Combining equations (6) and (7) gives

$$1 = \psi + \delta_1 + \delta_2 + \cdots + \delta_J. \tag{8}$$

The exergy of the working fluid at each point, calculated from its properties, is

$$\phi = M[(h - h_0) - T_0(s - s_0)], \tag{9}$$

where the subscript 0 indicates the "dead state". In this study, the dead state is defined by $T_0 = 298.15$ K and $P_0 = 1$ atm, and X_{om} is based on a sea water salt concentration of 47,800 ppm.

The brine exergy consists of two parts: the thermo-mechanical part (due to temperature and pressure), which is calculated from equation (9), and the chemical part (due to the brine's salt concentration), which is calculated from (cf. [18])

$$\phi_c = \beta MRT_0\left(\frac{X_m X_{om}}{X_m - X_{om}}\right)\ln\left(\frac{X_m}{X_{om}}\right), \tag{10}$$

where β is a dimensionless constant evaluated from the chemical exergy data in [15].

The exergy losses of the thermo-compressor have been calculated assuming that it will have an overall thermal efficiency of 0.75, as suggested in Refs [2] and [19]. The ejector efficiency can be expressed in terms of entrainment ratio by using the relationship [19]

$$\eta_e = (\mathrm{ER} + 1)\frac{h_4 - h_3}{h_1 - h_2}. \tag{11}$$

PROCESS DESCRIPTION

A simplified diagram of the analyzed multiple effect thermal vapor compression system is illustrated in Fig. 1. The system consists of N horizontal falling film evaporators. The incoming sea water is first preheated in a distillate cooler and a terminal condenser. A fraction of the feed water is rejected to the sea when necessary and the rest is divided into N equal streams that form the water feed to the N effects.

A small fraction of the live steam from the boiler is passed to the vacuum ejector and the remaining steam is passed to the thermo-compressor as the motive steam. The flow of motive steam leaving the nozzle creates a vacuum which withdraws the vapor generated in the last effect. The combined vapor streams are then compressed in a diffuser to a pressure that meets the thermal requirements in the first effect. The condensate leaving the first effect is divided into two streams. An amount equivalent to the withdrawn vapor flows down into the multiple effect boiling system, while the remaining condensate returns to the boiler loop. The heating vapor causes evaporation of the feed brine being fed from the top. The vapor generated in the first effect is then passed to the tube side of the next effect, where the same process of condensation and evaporation is repeated. The brine produced in one effect is cascaded down to the next effect for flashing. The sea water from the last effect is discharged as rejected brine. The condensate collected from the N effects is passed to a distillate cooler where it serves to preheat the incoming sea water.

More detailed information about the dimensions and materials of the plant, design conditions and seawater characteristics are available in [8].

SIMULATION RESULTS AND DISCUSSION

Thermal analysis

The analytical performance was first compared with actual test data obtained from a four-effect, low temperature TVC desalination plant operating in the U.A.E. The plant operating conditions, with all experimental data used here having been collected during one year of operation, are summarized in Table 1 (from [8] and [20]). The measured performance ratios range between 6.5 and 6.8, almost twice the values normally obtained from a conventional four-effect boiling distillation unit. The performance ratios predicted by the model agree favorably well with the measured values, with deviations ranging from 0.1 to 3.3% only.

The effects of the top brine temperature (TBT) and the thermo-compressor entrainment ratio (ER) on the performance ratio (PR) of the TVC system are shown in Fig. 2. The performance ratio is seen to be highly dependent upon the entrainment ratio. As ER is increased, the demand for driving steam is reduced, resulting in an increase in PR. Increasing the TBT (while leaving the number of effects constant) leads to a decrease in the performance ratio because of the increase in the required thermal energy.

For comparison, the variations of the performance ratios with TBT of the conventional multi-effect boiling (MEB) and mechanical vapor compression (MVC) desalination systems are also

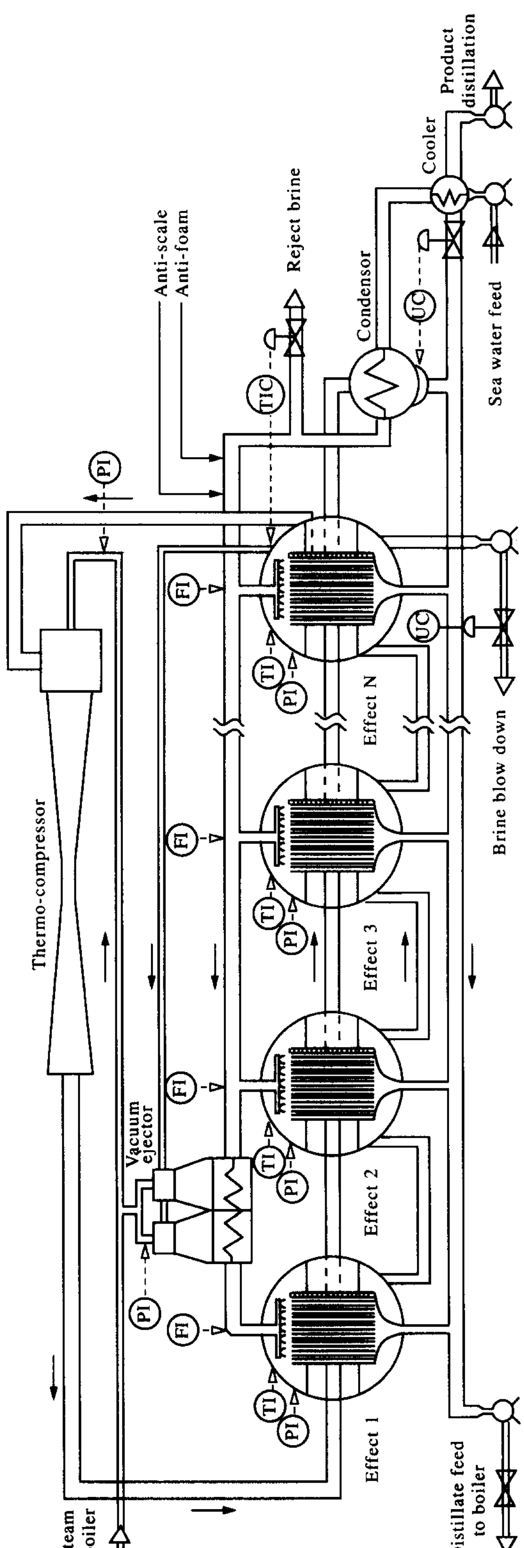

Fig. 1. Schematic diagram of the thermal vapor compression system.

Table 1. Range of the plant operating variables (from [8] and [20])

Parameter/variable	Range
Number of effects	4
Water production flow rate (m^3/h)	120–185
Sea water flow rate (m^3/h)	600–650
Sea water feed temperature (°C)	20–36
Salinity of sea water feed (ppm)	47,800
Temperature of motive steam (°C)	210–220
Pressure of motive steam (bar)	18–22
Temperature in the last effect (°C)	43–50
Thermocompressor entrainment ratio	0.8
Brine temperature rise vacuum ejector condenser (°C)	5
Temperature of steam condensate leaving 1st effect (°C)	60–62
Brine temperature leaving 1st effect (°C)	53–61
Brine temperature leaving 2nd effect (°C)	49–57
Brine temperature leaving 3rd effect (°C)	45–54
Brine temperature leaving 4th effect (°C)	43–50
Performance ratio	6.4–6.8

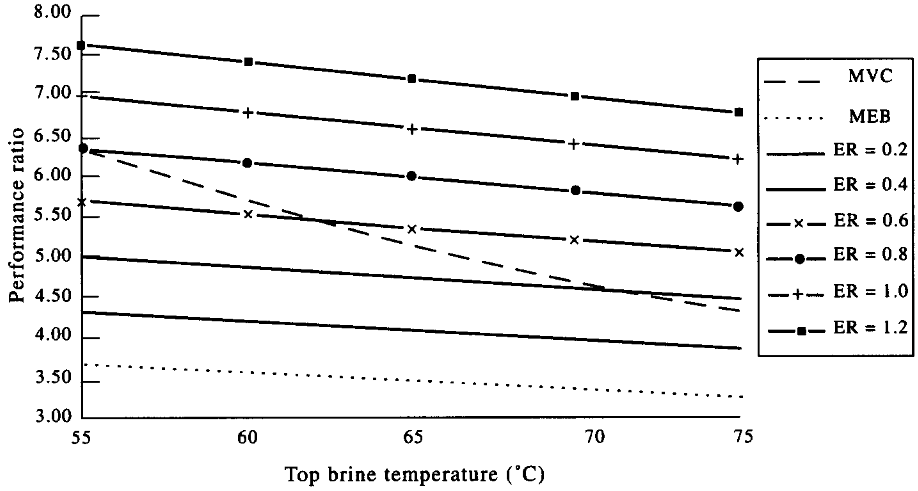

Fig. 2. Dependence of the performance ratio on the top brine temperature (TBT) and the entrainment ratio (ER). (Number of effects = 4, recovery ratio = 0.214.)

shown in Fig. 2. The thermal energy requirement of the MVC system is calculated assuming that the isentropic efficiency of the compressor is 80% and that the work delivered to drive the compressor is produced with a thermal efficiency of 30%. It can be seen that the TVC system has higher performance than the MEB system under all conditions. For example, a TVC system operating with an ER of 1.0 produces a performance ratio that is almost twice that produced by a conventional MEB system. The MVC system performance is more strongly affected by the TBT

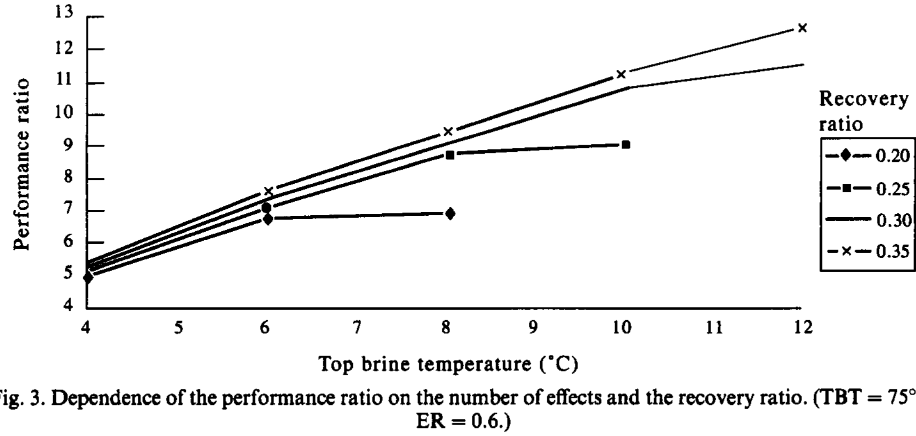

Fig. 3. Dependence of the performance ratio on the number of effects and the recovery ratio. (TBT = 75°C, ER = 0.6.)

than is the performance of the TVC and MEB systems. The MVC system has lower performance ratios that the TVC system when the ER and TBT are above a certain value. For example, the TVC system has a higher performance ratio that the MVC system for all the TBT values considered here if ER > 0.8.

The influence of the number of effects and the recovery ratio (M_d/M_f) on the performance ratio of the TVC system is shown in Fig. 3. It can be seen that the performance ratio is affected by both the number of effects and the recovery ratios. For a specified ER, TBT, and recovery ratio, there exists, as expected in this constrained situation, a maximal number of effects beyond which the performance ratio would not increase. This maximum decreases as the recovery ratio becomes smaller.

Exergy analysis

Calculations of the losses of exergy, and of the irreversibilities, provide useful information for pinpointing the units that are responsible for these losses and for the energy consumption. The exergy losses due to the irreversibilities of a TVC system are compared with those of MEB and MVC desalination systems working under the same boundary conditions.

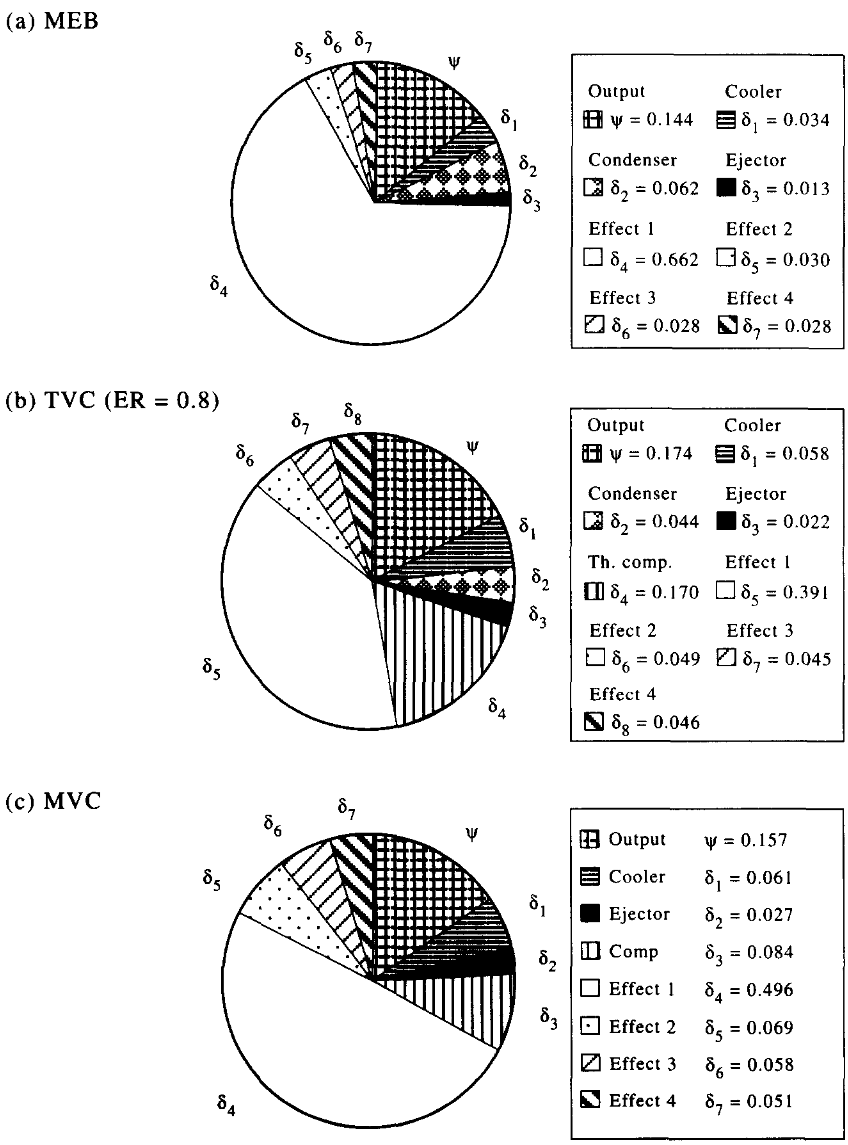

Fig. 4. Breakdown of the exergy efficiency defects of the multi-effect boiling (MEB), thermal vapor compression (TVC) and mechanical vapor compression (MVC) desalination systems. (TBT = 60°C, number of effects = 4.)

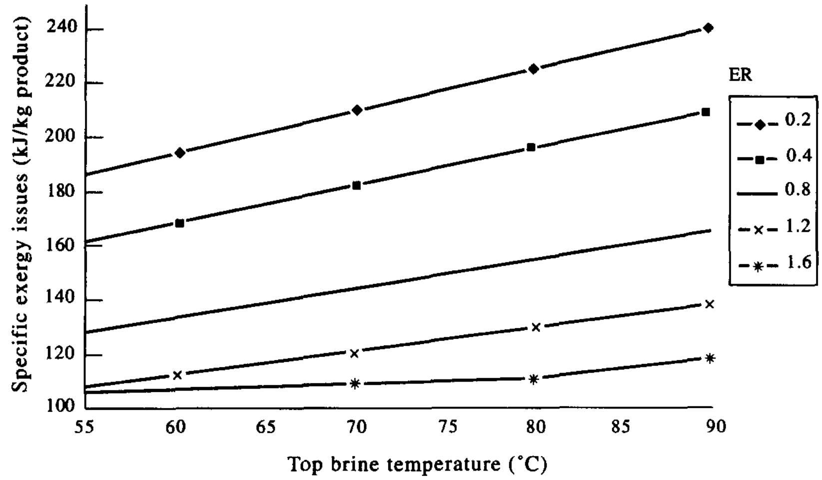

Fig. 5. Dependence of the specific exergy losses on top brine temperature (TBT) and entrainment ratio (ER). (Number of effects = 4.)

The overall specific exergy losses in the TVC, MVC and MEB systems are 135, 142, and 227 kJ/kg, respectively. Although the TVC system destroys the least amount of exergy when compared with the other two systems, it would also be useful to compare its real, irreversible performance with that of a hypothetical reversible desalination process which, though impractical, serves as a guide for the highest theoretically achievable performance. Spiegler [21] reported that the minimum exergy requirement for such a process with a recovery ratio of 0.5 is about 7.2 kJ/kg. This represents only 5.3% of the exergy destruction in a practical TVC unit, with the difference being lost due to real process irreversibilities.

A breakdown of the exergy losses among the major subsystems of the TVC, MEB and MVC configurations considered here, using their subsystem efficiency defects δ_i and the exergy efficiency ψ for the full system, is illustrated in the pie charts (a), (b), and (c) shown in Fig. 4. For all three examined systems, the highest efficiency defects, by far, are associated with the first effect, primarily because of the high temperature of the steam used to supply heat to that effect. The magnitude of that temperature and the first-effect efficiency defect are closely related: 215°C, 0.662 for MEB, 153°C, 0.496 for MVC, and 113°C, 0.391 for TVC, respectively, while the top brine temperature for all is only about 60°C. This demonstrates well the fact that the use of the high temperature steam heat source (at 215°C for all) is most exergetically efficient in the TVC system, because a part of its exergy is first used for generating compression (mechanical energy) and only the remainder, at lower temperature now, is used for heat transfer, the more exergy-destructive process. The thermo-compressor of the TVC system generates an efficiency defect of 0.17, with the

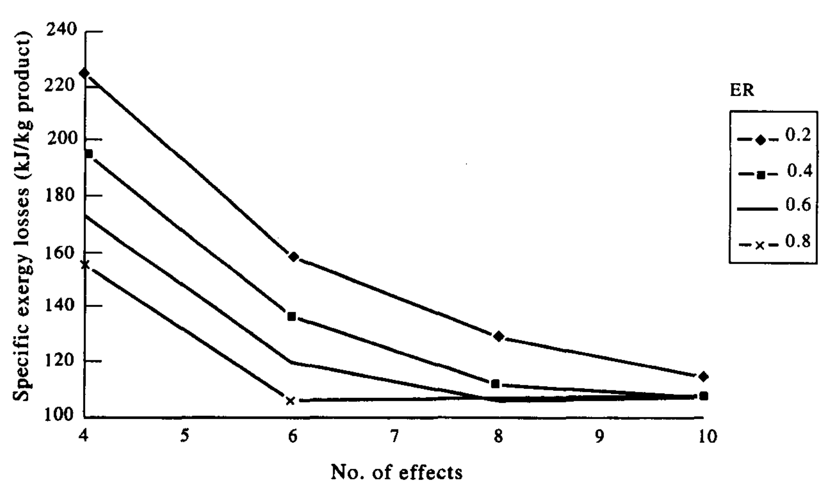

Fig. 6. Dependence of the specific exergy losses on the number of effects and the entrainment ratio (ER). (Top brine temperature (TBT) = 80°C.)

irreversibilities arising due to losses in the nozzle, mixing and diffuser sections. Remarkably, the more efficient use of the heating steam described above renders the TVC process more efficient than the MVC process despite the fact that the thermo-compressor efficiency defect is about twice as high as that of the mechanical vapor compressor.

The influences of the TBT and of the number of effects on the overall specific exergy losses for different values of ER are shown in Figs 5 and 6, respectively. The figures reveal that the overall specific exergy losses decrease as TBT is decreased, and as the number of effects and ER are increased. Decreasing the TBT or increasing the number of effects results in a lowering of the temperature drop per effect, thus diminishing irreversibility. It should be mentioned that the minimal inter-effect temperature difference is limited by the boiling point elevation and capital investment, and the determination of the optimal temperature drop per effect therefore requires also a detailed cost analysis. The reason for the reduction of exergy loss with increasing ER is due to the reduction of the driving steam requirement and its associated exergy content.

CONCLUSIONS

(1) Operational data of a four-effect, low temperature thermal vapor compression desalination plant revealed that performance ratios of 6.5 to 6.8 can be attained. Such ratios are almost twice those of a conventional four-effect boiling desalination plant.

(2) The performance ratios of the TVC system increase with the number of effects and with the entrainment ratio of the thermo-compressor and decrease with the top brine temperature.

(3) Exergy analysis reveals that the thermal vapor compression desalination plant (TVC) is the most exergy-efficient when compared with the mechanical vapor compression (MVC) and multi-effect boiling (MEB) ones.

(4) The subsystem most responsible for exergy destruction in all three desalination systems investigated is the first effect, because of the high temperature of its heat input. In the TVC system, this amounts to 39%, with the second highest exergy defect being that of the thermo-compressor, equal to 17%.

(5) Exergy losses can be significantly reduced by increasing the number of effects and the thermo-compressor entrainment ratio, or by decreasing the top brine and first-effect heat input temperatures.

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